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A Select Bibliography with Abstracts of Reports Related to Waste Isolation Pilot Plant Geotechnical Studies (1972 - 1990)*

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ABSTRACT

This select bibliography contains 941 entries. Each bibliographic entry contains the citation of a report, conference paper, or journal article containing geotechnical information about the Waste Isolation Pilot Plant (WIPP). The entries cover the period from 1972, when investigations began for a WIPP Site in southeastern New Mexico, through December 1990.

Each entry is followed by an abstract. If an abstract or suitable summary existed, it has been included; 316 abstracts were written for other documents. For some entries, an annotation has been provided to clarify the abstract, comment on the setting and significance of the document, or guide the reader to related reports. An index of key words/phrases is included for all entries.

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Acknowledgments

Wendell Weart and Dan Garber of Sandia National Laboratories (SNL) encouraged the authors in this project, thinking that it would be a unique source of information about geotechnical work for the Waste Isolation Pilot Plant (WIPP) Project. However, they are not culpable for any mistakes.

Glenda Sweatt and Elisa Monnet of the SNL Waste Management and Transportation Library supplied bibliographic lists and worked many hours searching for, checking, assembling, and shipping documents. Lata Desai of the Westinghouse WIPP Site Library provided similar services.

Carol Crawford of Tech Reps, Inc. (TRI) checked every citation for accuracy and completeness against existing compendia, and her expertise as a technical librarian contributed greatly to the usefulness of this bibliography.

Ed Lorusso (TRI) served as lead editor, assisted by Tim Peterson, Julie Coffey, Frances Forrest, and Virginia Gilliland. All deserve recognition for this often thankless but extremely important task.

The reviewers and referee are thanked for their contributions in cross-checking the accuracy of abstracts written for this bibliography and in verifying that abstracts represent reasonably well the content of each document. For their willingness to undertake this tedious task, we are grateful to Rick Beauheim (SNL), David Borns (SNL), Chris Francke (Westinghouse), Bob Guzowski (SAIC), Norbert Rempe (Westinghouse), Peter Swift (TRI), Wolfgang Wawersik (SNL), and David Zeuch (SNL).

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1.0 INTRODUCTION

1.1 Background

The Waste Isolation Pilot Plant (WIPP), located about 26 miles east of Carlsbad, NM, is a research and development facility proposed as a repository for transuranic waste from US defense programs. The rocks in which the waste is to be disposed are bedded evaporites, mainly halite. Research about the WIPP Site has necessitated the development and production of hundreds of geotechnical documents.

1.2 Purpose

This bibliography is intended to benefit a broad readership that includes specialists in the field, interested parties in other disciplines, managers, and the general reader interested in geotechnical information about the WIPP. Documents prepared during the early years of the WIPP Project were not always published via the channels that have since become standard to the project (e.g., SAND reports). Because such early documents may be relatively obscure to some readers, the authors have included abstracts for these and all other entries.

1.3 Criteria for Inclusion

All documents included in the bibliography are WIPP-related, have geotechnical content, were mostly funded by the US Department of Energy (DOE), are available in the open literature or as specified, and were printed and distributed between 1972 and December 1990. These criteria were intended to be more inclusive than exclusive. For example, documents on waste/rock interactions are included, as are documents on borehole plugging that served both the WIPP and other possible repositories in salt for disposal of radioactive waste. Also, documents are included from the period prior to the involvement of Sandia National Laboratories and before the present location was selected (1972 through 1975) to show the direct succession from this early work to the present. A few documents are included for which only the basic work was funded directly or indirectly by the DOE.

1.4 Abstracts and Titles

Approximately two-thirds of the abstracts were written by the authors of the cited document. Existing abstracts have been retained fundamentally as written by original authors. Obvious typographical and grammatical errors have been corrected. Some editing has been done to make the bibliography more cohesive as a whole, and acronyms and abbreviations have been clarified within each abstract to the extent practicable. In a few cases, a word or phrase has been inserted in an existing abstract for the sake of clarity; such insertions are enclosed in brackets []. Formulas have been eliminated from a few abstracts during editing, and some symbols are replaced by words.

Titles and authors are presented exactly as given on the title page of each document. Typographical and other errors are noted by [sic], and punctuation or other material added for clarification is enclosed in brackets []. The format of each citation was revised by C. Crawford (TRI) to match the style in Garber et al. (1992).

The remaining abstracts were either adapted from existing material or written by Powers and/or Martin and are identified by "DWP" and/or "MM/DWP" and flush right on the last line of the abstract. When conclusions, summaries, or executive summaries provided the basis for an abstract, key material was sometimes used verbatim from the source and quoted directly; some technical editing may have subsequently occurred, changing punctuation etc. Abstracts written solely by Powers may differ slightly in focus from the original document because of the temporal scope of this bibliography, since early work was often followed by much more detailed study. No offense is intended to the authors of such early documents. The original document must be regarded as definitive in all cases.

1.5 Annotations

The abstracts of 43 entries are followed by an annotation. Some annotations provide cross-references, and the rest provide a scientific and historical context for documents deemed to have special significance in the development of geotechnical concepts for the WIPP. These documents were selected by Powers and reflect his perspective on the geotechnical work at the WIPP. Some excellent technical work may not have been annotated due to time constraints.

1.6 Methodology

After an initial list was compiled and cross-checked, it was circulated to WIPP Project participants with a request that they add or delete items. Copies of each document were subsequently obtained in order to verify its existence, confirm the title and authors' names, and derive an abstract.

Readers are encouraged to contact Powers concerning any corrections or additions for a later version or addendum. For additions, readers are requested to supply a complete copy of the document to either Powers or the Waste Management and Transportation Library at Sandia National Laboratories in Albuquerque, NM.

1.7 Organization

The bibliography is ordered alphabetically by author. Same-author documents are ranked by date of publication. Documents with multiple authors are sorted alphabetically by the second author's name, or by the number of coauthors. Smith and Jones comes before Smith, Jones, and Brown, but Smith and Brown (1990) comes before Smith and Jones (1978). Likewise, Smith, Jones, and Brown (three authors) comes before Smith, Brown, Jones, and Green (four authors), despite the second author alphabetical order.

1.8 Index

Standard indexing systems such as GEOREF were found unsuitable for making an index of key words/phrases for this bibliography. Therefore, Powers created a WIPP-specific index that contains at least one reference to each entry in the bibliography.

1.9 Document Sources

The locations of the documents listed in this bibliography are generally self-evident from each citation. Thus, journal articles and similar documents may be examined at libraries or purchased from publishers. However, some less-obvious sources are given below.

For SAND reports and some other government documents, the National Technical Information Service, US Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161, can provide printed or microfiche copies. DOE employees and DOE contractors can

obtain these documents from the Office of Scientific and Technical Information, PO Box 62, Oak Ridge, TN 37831.

Some WIPP reports by the DOE and DOE contractors are available through the Department of Energy, WIPP Project, PO Box 3090, Carlsbad, NM 88221-3090.

Reports by and to the Environmental Evaluation Group are available through the Environmental Evaluation Group, Suite F-2, 7007 Wyoming Blvd., NE, Albuquerque, NM 87109.

1.10 Reference Cited

Garber, D.P., M.M. Gruebel, and E.N.S. Lorusso. "The Concise Format Guide for Waste Isolation Pilot Plant Program SAND Reports.

2.0 BIBLIOGRAPHY AND ABSTRACTS

A

Abitz, R., J. Myers, P. Drez, and D. Deal. 1990. "Geochemistry of Salado Formation Brines Recovered From the Waste Isolation Pilot Plant (WIPP) Repository," *Waste Management 90, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 25 - March 1, 1990*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 881-892.

ABSTRACT: Intergranular brines recovered from the repository horizon of the Waste Isolation Pilot Plant (WIPP) have major- and trace-element compositions that reflect seawater evaporation and diagenetic processes. Brines obtained from repository drill holes are heterogeneous with respect to composition, but their compositional fields are distinct from those obtained from fluid inclusions in WIPP halite. The heterogeneity of brine compositions within the drill-hole population indicates a lack of mixing and fluid homogenization within the salt at the repository level. Compositional differences between intergranular (drill hole) and intragranular (fluid inclusions) brines are attributed to isolation of the latter from diagenetic fluids that were produced from dehydration reactions involving gypsum and clay minerals.

Modeling of brine/rock equilibria indicates that equilibration with evaporite minerals controls the concentrations of major elements in the brine. Drill-hole brines are in equilibrium with the observed repository minerals halite, anhydrite, magnesite, polyhalite, and quartz. The equilibrium model supports the derivation of drill-hole brines from near-field fluid, rather than large-scale vertical migration of fluids from the overlying Rustler or underlying Castile Formations.

Acton, R.U. 1978. "Thermal Conductivity of S.E. New Mexico Rocksalt and Anhydrite," *Thermal Conductivity 15, Proceedings of the Fifteenth International Conference on Thermal Conductivity, Ottawa, Ontario, Canada, August 24-26, 1977*. Ed. V.V. Mirkovich. SAND77-0962C. New York, NY: Plenum Press. 263-276.

ABSTRACT: The thermal conductivity of several rocksalt materials has been determined. Some of the materials were core samples from well AEC 8, Carlsbad, NM. These samples ranged from nearly pure halite (NaCl) to nearly pure anhydrite (CaSO₄). Core sample crystallite size ranged from about 3 cm to essentially packed salt sand (≈ 0.5 mm). The samples exhibited thermal conductivities from ≈ 1.5 to 7.5 W/mK because of variations in purity and grain size.

A 1-m cube of rock salt from the Mississippi Chemical Company's southeast New Mexico potash mine was obtained for other experiments. The thermal conductivity of one sample from each of the orthogonal directions of the cube was measured. This material had a high conductivity of ≈ 8.5 W/mK and was very isotropic. A core of rock salt from the Morton Salt Co., Paynesville, Ohio had a thermal conductivity of 6 W/mK, which is in the upper band of the results on cores from well AEC 8.

Finally, a concrete made with salt-sand and rocksalt aggregate was determined to have a conductivity of ≈ 2 W/mK.

A longitudinal heat flow apparatus was used to determine the thermal conductivity. An analysis of the experiment gave an accuracy within $\pm 15\%$ on geological samples and within $\pm 10\%$ on 304 stainless steel.

Alderman, S.S., Jr., W.A. Seedorff, Jr., and C.O. Rodriguez. 1978. *Preliminary Report. Resource Study Waste Isolation Pilot Plant Eddy County, New Mexico.* Working Draft. San Carlos, CA: Agricultural & Industrial Minerals, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This preliminary report fulfills the first phase of the contract for this study, reporting work and results completed by April 15, 1978. The purpose of this study is to estimate the potash ore reserves and resources within the Waste Isolation Pilot Plant (WIPP) site. Basic data have been gathered, including core logs, geophysical logs, and chemical analyses for government and industry drill holes within the area, data on lithology and correlation of specific units within the Carlsbad district, and data about mineralization within ore zones.

Samples from the fourth ore zone from four WIPP holes were tested in the laboratory for potash leaching. Minimum product grade of 22% K_2O was attained in four of seven tests.

The Carlsbad district is estimated to include 415 million t of recoverable ores/resources within current properties and undeveloped properties. A total of 250 million t of recoverable ores/resources of langbeinite are estimated, and these ores/resources would result in about 72 and 74 million t, respectively, of recoverable product. DWP

ANNOTATION: The final report on potash resources is also available. It is included in the bibliography under Seedorff, 1978.

Anderson, H.M., J. Pietz, and D. Smith. 1983. *Solutions to Radionuclide Migration with Nonlinear Retardation Mechanisms in Backfill Material. Interim Progress Report, June-December 1982.* SAND82-7089. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Previous models of the backfill barrier have incorporated a linear isotherm with a single valued retardation term, R_d , for predicting the retardation effect of bentonite clays on radionuclide transport. The failure of this modeling approach to accurately predict radionuclide migration has prompted the development of more comprehensive phenomenological models for retardation.

This paper advances a conceptual framework for modeling retardation in the backfill with any of a number of complex physiochemical processes including sorption, chemical precipitation/dissolution, ion or isotope exchange, chemical substitution reactions, or entrapment. These processes are accounted for by the inclusion of a general retardation sink term in a model for diffusion-controlled flow through a porous medium. Nonlinearities in the retardation mechanism may render an analytic solution to the resultant differential equation unattainable. However, semianalytic monotone iterative schemes described in this paper are shown to provide an effective technique for the necessary integrations.

No attempt has been made to calibrate the model to reflect the backfill barrier's potential or to provide quantitative estimates of effectiveness in an actual repository. Comparisons between models with different retardation mechanisms and estimates of potential delay time effectiveness in an actual repository will be the subject of future reports.

Anderson, R.Y. 1978. *Report to Sandia Laboratories on Deep Dissolution of Salt, Northern Delaware Basin, New Mexico.* (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Deep-seated dissolution in the Delaware Basin has developed in association with the Capitan Reef and the underlying Bell Canyon (Delaware) aquifers and at a more permeable horizon between the Castile and Salado Formations. The uplift, erosion, and exposure of the reef in the Guadalupe and Glass Mountains has channeled meteoric waters through the reef aquifer. These waters gained access to the salt through fractures around the reef margin and dissolved overlying and superjacent salt by means of brine density flow. This type of deep dissolution moved into the salt beds laterally at a horizon of increased permeability between the Castile and Salado Formations and dissolved a wedge that undercut the overlying evaporites. The deep-seated dissolution also produced a number of large-scale collapse structures along the basin margin and along the western edge of salt. This wedge-like effect, combined with surface dissolution, has removed 50% of the original salt from the basin and 70% of the original salt at the lower Salado horizon.

The waters in the aquifers, by gaining access to overlying salt through fractures, have also dissolved smaller scale localized chambers in overlying salt beds that subsequently collapsed to form breccia pipes, deep-seated sinks, and other collapse structures. These features have been exhumed to different stratigraphic levels in the tilted and eroded basin, resulting in surface expression as limestone buttes (castiles), collapsed outliers, domal structures with collapsed centers (breccia pipes), and deep-seated sinks. Many of the deep-seated sinks are associated with salt anticlines, which probably formed as a result of differential stress from unloading related to dissolution. Localized collapse, as well as regional dissolution, is an ongoing process.

The Waste Isolation Pilot Plant (WIPP) Site lies in a corner of the Delaware Basin that has been relatively protected from regional but not localized effects of deep dissolution. Deep seated, wedge-like dissolution, however, has progressed from north to south in the basin and salt in the northern part of the Delaware Basin will eventually be dissolved at the lower Salado horizons before overlying salt has been removed from the basin by processes of near-surface dissolution (suberosion).

ANNOTATION: Anderson prepared this report for Sandia National Laboratories (SNL) specifically to summarize data and concepts about dissolution in the Delaware Basin as background for a geological characterization report (Powers et al., 1978). During late 1976 and 1977, Anderson was asked to develop more detailed information on highly deformed evaporites at borehole ERDA-6 and testable concepts about the overall extent and processes of salt dissolution. This earlier work, in letter and memo form, became the basis for drilling ERDA-10 several mi south of the WIPP Site to determine if salt beds in the upper Castile Formation would be reduced or absent because of dissolution. The ERDA-10 core indicated that these units were absent because of depositional events during the time when the Castile was formed.

Anderson presented a theory and laboratory model of brine density flow and invoked it as an important part of the dissolution process. Anderson and Kirkland published this separately in *Geology* (Vol. 8, no. 2, 66-69).

Some concepts and data presented in Anderson (1978) were further tested or examined. Individual anomalies that were considered evidence of deep-seated dissolution by Anderson were drilled, and many surficial features were mapped in detail (e.g., Bachman, 1980, 1981; Snyder and Gard, 1982). Wood et al. (1982) calculated the significance of the Bell Canyon aquifers and brine density flow for removing halite. Robinson (1989) and Robinson and Powers (1987) examined some alleged dissolution breccias in the Castile and basin margin to margin halite deposition. Holt and Powers (1984, 1986b, 1988) reexamined concepts of Rustler dissolution, though these are little treated in Anderson (1978). Lambert (1983a) also extensively critiqued the views expressed by Anderson; Anderson (1981, 1982) expanded some of his earlier concepts.

Subsequent studies by other workers generally review the processes or limit the apparent extent of dissolution. The report was very useful as a broad summary of anomalies, processes, and upper limits to the extent of dissolution. Earlier work focused more on surficial indicators of stability for the area and indications of solution of the upper Salado, especially in the Nash Draw area.

Anderson, R.Y. 1979a. *Evaluation of Potential Environmental Hazards Related to Dissolution Effects in the Vicinity of the WIPP Site.* Santa Fe, NM: Environmental Evaluation Group. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Four potential geologic hazards or problems, related to salt dissolution, may affect geologic stability of the Waste Isolation Pilot Plant (WIPP) Site: rate of regional near-surface dissolution (subrosion), rate of regional deep-seated dissolution, reef-margin structural and dissolution features, and breccia pipes and deep-seated dissolution in the basin. For each of these, differences in interpretation are reviewed, a possible failure mode is presented, and current and further work are discussed.

Near-surface dissolution and erosion might discharge groundwater with radioactive material in surface drainage after a protracted period. Cores from the salt basin and Delaware Basin could provide a chronology of dissolution events. Deep-seated dissolution is attacking the lower Salado within the basin. The erosion-dissolution contact between the Castile and Salado Formations is partly responsible. Brine could migrate through a dissolution zone into the Capitan aquifer. Cores from San Simon Swale and Sink and the Salt Basin could help establish migration rates of the dissolution wedge. Brine in Castile structures is meteoric in origin. These structures favor flow between the reef or basin aquifers and the site. Geophysical data and cores should be obtained to determine if a suspected "sink" 2 mi north of the WIPP Site is in a dissolution or flowage feature. WIPP-12 should be deepened to test for brine/gas in the anticlinal structure. Brine density flow explains the process of developing solution features in the western part of the basin. The features are nearly randomly distributed. Some may exist in the eastern part of the basin (e.g., Bell Lake, Slick Sink, "sink" 2 mi north of the WIPP site. Water might rise to the surface carrying waste, but it is more likely to move down to the basin aquifer. Several possible sinks should be drilled and cored to determine the origin of collapse and obtain a climatic record.

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Anderson, R.Y. 1979b. *Mechanism and Rates of Development of Regional and Localized Dissolution Features in and Below Evaporites.* Santa Fe, NM: Environmental Evaluation Group. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Dissolution in evaporite basins progresses through different stages. The Delaware Basin has progressed to a mature stage with dissolution features nearly at a maximum. These features include reef margin dissolution depressions, reef margin wedges, basin collapse structures, and a basin dissolution wedge.

Uplift of the western basin margin began active dissolution along the reef margin about 2-3 million years ago with substantial dissolution by 1 million years ago. Active dissolution reached the northeastern corner of the Delaware Basin in the past 100,000 years and is still active. Within the basin, westernmost collapse structures are probably Pleistocene in age. Central basin structures predate 0.5 million-year-old caliche. Sinks in the eastern part of the basin probably formed in the last 60,000 years.

Reef margin depressions and wedges can be expected to extend from the northeast to the site area of the disposal horizon. Depressions will probably develop northeast of the site along the reef within 100,000 years, and it is conceivable that a wedge could penetrate the site in the same time. The deformed evaporites north and east of the site may be predisposed to dissolution along fractures.

Basin wedge dissolution is temporarily stabilized 12-14 mi from the site because basin geometry directed water away from the northern basin. The reef margin wedge will probably reach the site before the basin wedge. Bell Lake Sink indicates the area is actively subject to localized dissolution that may be obscured by shifting dune sand. Uncollapsed or partly stopped local solution chambers could be present below the site or could develop, affecting isolation.

Geologic uncertainty is increased in the Delaware Basin because dissolution is at a mature stage and because all dissolution features may not have been discovered or correctly interpreted.

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Anderson, R.Y. 1979c. *Notes on Dissolution and Brine Chambers Related to the WIPP*. Santa Fe, NM: Environmental Evaluation Group. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Clear replacement halite in core from borehole WIPP-11 reflects brine mobility and replacement of laminated calcite-anhydrite of the Castile Formation in a manner similar to core from borehole ERDA-6. WIPP-11 is dry; ERDA-6 produced brine. Generalized cross-sections show that WIPP-11 has salt flow in Halite II. WIPP II is located between structures at ERDA-6 and near the Waste Isolation Pilot Plant (WIPP) Site that are thought or assumed to have Halite I cores. A similar feature exists east of the WIPP Site in T22-23S, R33E. Anhydrite II trapped pressurized brine at ERDA-6 and other locations but was not folded at WIPP-11. Anhydrite II may have permitted water from the Capitan aquifer to intrude and pass through fractures into the deformed area. Faulting and fracturing may extend to the Bell Canyon, thereby providing sources and pathways for brine.

Water intruded continuously to form brine chambers during or after the development of anticlinal structures. Structures are probably associated with 3- to 8-million-year-old period of extension in the Rio Grande Rift. Brine may have been emplaced in the last few million years and cannot be assumed to represent long-abandoned flow systems.

Young faulting near San Simon appears related to rift extension and uplift. Faults cutting evaporites may also be Pleistocene-Wisconsin. Inferred faults at the WIPP Site anticline could be rejuvenated and brine, if present, could move.

Breccias from anhydrite beds of the lower Salado at ERDA-10 may be caused by dissolution of indeterminate age. These "show that there are unexplained examples and evidence of a previous episode of dissolution at the [ERDA]-10 locality."

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Anderson, R.Y. 1981. "Deep-Seated Salt Dissolution in the Delaware Basin, Texas and New Mexico," *Environmental Geology and Hydrology in New Mexico*. Eds. S.G. Wells, W. Lambert, and J.F. Callender. New Mexico Geological Society Special Publication No. 10. [Roswell, NM]: New Mexico Geological Society. 133-145.

ABSTRACT: Patterns of salt dissolution in the Delaware Basin are related to the bedrock geometry and hydrology that developed following uplift, tilting, and erosion in the late Cenozoic; the greatest volume of salt has been removed since that time. During the Permian, some salt was dissolved from the top of the Castile Formation before deposition of the Salado

Formation and from the top of the Salado before deposition of the Rustler Formation. In addition, some salt dissolution occurred after the Permian and before the Cretaceous. Post-uplift surface dissolution has progressed across the Delaware Basin from south to north and west to east and generally down the regional dip. Deep-seated dissolution has occurred around the margin of the basin where the Capitan limestone aquifer is in contact with the Permian evaporites and within the basin where selective dissolution in the lower Salado has undercut the overlying salt beds of the middle and upper Salado. Dissolution has not advanced down regional dip uniformly but has left outliers of salt and has progressed selectively into structurally predisposed areas. This selective advance has significance for the stability of the US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) Site.

Anderson, R.Y. 1982. "Deformation-Dissolution Potential of Bedded Salt, Waste Isolation Pilot Plant Site, Delaware Basin, New Mexico," *Scientific Basis for Nuclear Waste Management V, Proceedings of the Materials Research Society Fifth International Symposium on the Scientific Basis for Nuclear Waste Management, Berlin, Germany, June 7-10, 1982*. Ed. W. Lutze. New York, NY: North-Holland. Vol. II, 449-458.

ABSTRACT: The origin of deep-seated collapse and brecciation, common to bedded salt in a number of evaporite basins, is poorly understood. Young uplift and exposure of evaporites in the Delaware Basin and an active hydrologic system provide a unique opportunity to examine the pathways of water movement related to collapse features and salt dissolution. Salt deformation is also closely associated with brine reservoirs, dissolution, and collapse. This report briefly discusses evidence for deep-seated dissolution; considers relationships between deformation, dissolution, and brine; and examines the potential for dissolution at the Waste Isolation Pilot Plant (WIPP) with respect to stages in the deformational-dissolution process.

Depressions around the basin margin are caused by dissolution of evaporites by the Capitan reef aquifer. Within the basin, wedge-like fronts, depressions, and isolated lows show the effects of dissolution. Brine density flow is an important mechanism in dissolution. Deformed Castile around the basin edge and near the WIPP Site are also associated with pressurized brine and gas. Continuing deformation and water recharge are necessary to account for reservoir pressures. Salt deforms more readily in the presence of water, and the most likely source of water is under the evaporites. Density foundering of anhydrite further drives deformation.

It is proposed here that dissolution progresses by steps. Meteoric water recharges the basin aquifer (Delaware Mountain Group) and may be involved in salt flowage and forming brine reservoirs. The Salado is dissolved above Castile deformation, which causes overlying beds to collapse and accumulate alluvial fill. Salado dissolution is incorporated into the regional dissolution wedge and later into surface drainage.

The WIPP Site is in an area predisposed to deep-seated dissolution. Surface sinks and depressions on marker beds in the vicinity of the site may indicate that the area is in the second dissolution stage.

DWP

Anderson, R.Y. 1983a. *Evidence for Deep Dissolution in the Delaware Basin. Prepared for the State of New Mexico Environmental Evaluation Group.* (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Because of contentions that data do not support the concept of deep dissolution, it is necessary to present the evidence that explains, "feature by feature and step by step, the conclusion that great quantities of salt have been selectively removed by dissolution from the lower part of the Salado Formation." The geophysical contrasts between halite and anhydrite

and the many boreholes present in the basin provide excellent data on the distribution of these rocks.

An unconformity between the Castile and Salado Formations successively truncates deeper Castile salt beds from south to north, resulting in stacked anhydrite units. This feature is best understood by "hanging" the geophysical logs on the basal salt in the Halite III member of the Castile. Salt beds in the upper Castile can be traced with little change in thickness until they encounter the unconformity. The basin was apparently tilted about 6 ft/mi to the south by the end of the Castile deposition. The Castile/Salado contact can be estimated by thickness of accumulated beds compared to areas with salt and by a natural gamma signature at that point in most logs.

In northern Loving County, TX, geophysical logs show disrupted lower Salado units in an area east of the Pecos River. Upper Salado marker beds are traceable into part of this area without change in thickness, but are lowered relative to the Castile/Salado contact. The Rustler Formation is traceable through this area without change in thickness. Salt is lost along the edges of this area at a rate of about 200 ft/mi, about an order of magnitude greater than for depositional facies variations. DWP

Anderson, R.Y. 1983b. *Review Comments Related to Dissolution of Evaporites in the Delaware Basin. Prepared for State of New Mexico Environmental Evaluation Group.* (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Three documents are reviewed that relate to dissolution of evaporites and the integrity of the Waste Isolation Pilot Plant (WIPP) Site. Lambert's conclusions about dissolution in the lower Salado Formation are almost completely wrong because the contact between the Castile and Salado Formations was not correctly understood. The key to this contact is that the Castile was exposed before the Salado was deposited. Upper salt units were dissolved across exposed beds, stacking anhydrite beds along a modest angular unconformity. If this is not recognized, the compensating thickness of the Salado is not recognized, and the evidence for dissolution is lost. The most important general point is that arguments about geochemistry, lack of a sink for brine, and strata-bound dissolution are irrelevant if no deep dissolution is recognized by Lambert. Weart errs in concluding deep dissolution does not operate in the Delaware Basin. The evidence for deep dissolution is strong and compelling. If the pathways and sinks considered have been shown not to exist, it means the site cannot be considered properly evaluated, and the future effects of dissolution cannot be predicted. The WIPP Site cannot be said to be "qualified with respect to dissolution." In addition, Weart did not consider the possible relationship between brine in pressurized reservoirs in Castile anhydrite and areas of deep dissolution. Possible sources of water and solutes, such as lithium, may be alluvium in deep depressions containing volcanic ash. The sources and pathways for the brines clearly are not known. These uncertainties make it more important to understand the possible relationship to deep dissolution because the implications would be highly significant for a repository. Other documents on dissolution that appear to eliminate the Delaware Mountain Group (DMG) as a sink for brines indicate that deep dissolution has not been taken seriously by the Department of Energy (DOE); more serious problems exist if the DMG is not the sink for brines. Despite evidence for deep dissolution presented more than six years ago, no research program has been designed or implemented to explain the process. It is recommended that evidence for deep dissolution be independently evaluated. New Mexico should withhold consent until research demonstrates the hydrology of deep dissolution and validates failure scenarios and consequence analysis. A panel of state geologists and Environmental Evaluation Group (EEG) personnel should evaluate evidence and participate in designing a research program.

DWP

ANNOTATION: The papers reviewed by Anderson (Lambert, 1983a; Weart, 1983c; and Wood et al., 1982) are included in this bibliography.

Anderson, R.Y. 1987. *Report to New Mexico Environmental Evaluation Group (EEG) on Evaluation of Drillhole DOE-2.* (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: DOE-2 was drilled to test the origin of a local depression on Salado marker beds about 2 mi north of the Waste Isolation Pilot Plant (WIPP) Site. The feature was alternately suggested to be caused by deformation or dissolution.

Original contacts of Castile halite and anhydrite units may not be present. Some deformed anhydrite and breccia above Halite I are not an original contact. The breccia generally resembles a dissolution residue, except fragments are not suspended in a "paste" typical of dissolution. Pull-apart structures indicate deformation.

No definitive evidence of dissolution was found, and the Castile is similarly deformed nearby. The simplest explanation is that halokinetic deformation, initiated at depth, has moved upward and involved the Salado as well as the Castile Formation.

Large halite crystals and associations with H₂S and hydrocarbons are similar to locations with brine. WIPP-12 brine may have been partly derived from the area of DOE-2. Brine chemistry establishes that the evaporites are the most likely source of brines through deformation and recrystallization. "[T]he untested anticlinal structure beneath the site remains a candidate for a brine reservoir."

Deformation of underlying beds may predispose higher units to dissolution. WIPP-14, east of DOE-2, shows anomalies that may be genetically related to structures at DOE-2. Increased fracturing of higher beds may permit water penetration and dissolution as early stages of large-scale solution depressions. This would be similar to Poker Lake and Big Sinks. DWP

Anderson, R.Y., and D.W. Powers. 1978. "Salt Anticlines in the Castile-Salado Evaporite Sequence, Northern Delaware Basin, New Mexico," *Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, Carlsbad, NM, May 4, 1977.* Ed. G.S. Austin. New Mexico Bureau of Mines and Mineral Resources Circular 159. SAND77-0431C. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 79-83.

ABSTRACT: A number of structures have been encountered within the body of the Castile-Salado evaporites that can reasonably be interpreted as salt anticlines. One such structure, associated with brine, H₂S, and dissolution effects, was found during exploratory coring for the proposed nuclear waste disposal site near Carlsbad, NM. Correlation of stratigraphic units in the recovered core with cores and logs from nearby boreholes shows that the middle anhydrite unit (A-II) of the Castile Formation, which attains dips of as much as 70°, has been displaced vertically by as much as 950 ft (290 m). Extension fractures in the A-II unit suggest that it has been stretched above a pod of exceptionally thick salt of the lower halite unit (H-I) of the Castile Formation that moved into the axis of the anticlinal structure. Exceptionally thick and thin units of lower salt (H-I) occur in other nearby boreholes in a zone of deformation marginal to the reef. Suspected salt anticlines also occur at scattered localities in the northern part of the Delaware Basin. The association of extension fracturing to microfolding in the middle anhydrite unit (A-II) suggests that salt deformation accompanied or followed Cenozoic uplift and tilting of the basin.

Anderson, R.Y., K.K. Kietzke, and D.J. Rhodes. 1978. "Development of Dissolution Breccias, Northern Delaware Basin, New Mexico and Texas," *Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, Carlsbad, NM, May 4, 1977*. Ed. G.S. Austin. New Mexico Bureau of Mines and Mineral Resources Circular 159. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 47-52.

ABSTRACT: Beds of dissolution breccia are persistent in the Castile-Salado evaporites in the western part of the Delaware Basin. Dissolution breccia consists of subangular to somewhat rounded and elongate fragments of individual laminae of calcite-laminated anhydrite set in an anhydrite matrix. Collapse breccias consisting of angular fragments of laminated anhydrite with little or no matrix often overlie dissolution breccias or may occur separately within the anhydrite some distance above dissolution horizons. Correlation of individual calcite-laminated anhydrite laminae associated with dissolution breccias with the same laminae associated with halite beds shows that dissolution breccias are equivalent to halite beds. Even the thinnest halite beds in the eastern part of the basin once extended west of their present distribution, probably to near the western margin of the basin. The tracing of identified dissolution horizons to large areas of deep dissolution west of existing halite beds shows that it is removal of salt from the lower part of the Salado and upper part of the Castile Formations that has caused collapse of the depressions.

Argüello, J.G. 1988. *WIPP Panel Entryway Seal - Numerical Simulation of Seal Composite Interaction for Preliminary Design Evaluation*. SAND87-2804. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents the results of a series of structural analyses performed to evaluate the structural interaction of the components of a potential two-component panel entryway seal configuration with each other and with the rock salt formation at the repository horizon of the Waste Isolation Pilot Plant (WIPP). A two-dimensional axisymmetric geomechanical model was used to numerically simulate the interaction of the components of a 30.48 m (100 ft) long seal, consisting of concrete end caps and a crushed salt core, with each other and with the surrounding formation. Issues addressed in this report pertain to the consolidation of the crushed salt in terms of how much of the seal core reaches effective consolidation in the presence of the stiff concrete end caps because these could conceivably cause bridging (retardation of closure around the core) to occur. In addition, the stress field in the end caps is evaluated to determine if the concrete component maintains its integrity. The stresses induced in the surrounding formation are also evaluated to determine if the presence of the concrete component in the seal system results in a "tightening" of the formation around the seal.

Argüello, J.G. 1990. "Analysis of WIPP Disposal Room and Entryway Drift Intersection," *Rock Mechanics, Contributions and Challenges: Proceedings of the 31st US Symposium, Colorado School of Mines, Golden, CO, June 18-20, 1990*. Eds. W.A. Hustrulid and G.A. Johnson. Brookfield, VT: A.A. Balkema. 329-336.

ABSTRACT: A three-dimensional (3-D) finite element structural analysis of the intersection of a typical disposal room and entryway drift at the Waste Isolation Pilot Plant (WIPP) has been performed. This analysis reveals how complicated underground openings, truly 3-D in nature, respond in a creeping medium, and the response may appear anomalous to those with a "hard rock" background. Computed closures at the intersection are presented and compared to available in situ data. A qualitative agreement between measured and computed closures is seen.

Argüello, J.G., and R. Beraún. 1987. "Numerical Simulation of Drift Response in Rock Salt Resulting From the Emplacement of RH-TRU Waste in an Array of Horizontal Long Boreholes in a Separate Panel at the WIPP," *Rock Mechanics: Proceedings of the 28th US Symposium, University of Arizona, Tucson, AZ, June 29-July 1, 1987.* Eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman. SAND86-2224C. Boston, MA: A.A. Balkema. 643-652.

ABSTRACT: A series of thermal/structural analyses was performed to assess the feasibility of the Horizontal Long Borehole Concept for the emplacement of remotely handled transuranic (RH TRU) waste at the Waste Isolation Pilot Plant (WIPP). Results from the study indicate a strong sensitivity to power output per canister and to borehole spacing. This suggests that the feasibility of implementing the concept at the site will be highly dependent on the maximum power output per canister and on the spacing at which the boreholes containing these canisters might be placed.

Argüello, J.G., and H.S. Morgan. 1986. *Numerical Simulation of the Creep Response of Model Salt Pillars.* SAND85-2429. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A series of model pillar creep response calculations has been performed using a cylindrical model pillar configuration with the reference creep law and material properties for the Waste Isolation Pilot Plant (WIPP). Pillar shortenings obtained from these calculations using the finite-element code SANCHO are presented and compared to measurements obtained from laboratory model pillar experiments performed by Lomenick in the 1960s. The calculations generally underpredict the measured responses for early parts of the tests. For many tests, the computed responses are greater than the measurements near the end of the test durations. The underpredictions at early times are similar to the underpredictions obtained when data and calculations for the South Drift portion of the WIPP are compared.

Argüello, J.G., and T.M. Torres. 1987. *WIPP Panel Entryway Seal - Numerical Simulation of Seal Component/Formation Interaction for Preliminary Design Evaluation.* SAND87-2591. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents the results of a series of structural analyses performed to evaluate the interaction of a potential two-component panel entryway seal configuration with the rock salt formation at the repository horizon of the Waste Isolation Pilot Plant (WIPP). A two-dimensional plane strain geomechanical model of the configuration is used to numerically simulate and compute the interaction of each component with the formation. The structural response of the component itself and that of the formation, resulting from this interaction, is then evaluated. Issues addressed in this report pertain to the consolidation of the crushed salt component in terms of when effective consolidation is reached and to the stresses induced by the concrete component in terms of whether its presence in the seal system results in a "tightening" of the formation around the seal.

Argüello, J.G., and T.M. Torres. 1988. *Thermal Effects of RH-TRU Waste Emplacement on WIPP Storage Room Thermal/Structural Response.* SAND88-2217. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents the results of a series of two-dimensional (2-D) thermostructural analyses performed to evaluate the effects of emplacing remotely handled transuranic (RH TRU) waste in the ribs of a typical waste storage room at the Waste Isolation

Pilot Plant (WIPP). A "reference" or baseline case, in which 60 watt (W) canisters of RH TRU waste are emplaced at 2.44 m (8 ft) centers, is first investigated. Variations to the power output per canister and to the spacing of the canisters are then evaluated to determine their effects on room response. An overall 2-D geomechanical model, consisting of two separate 2-D idealizations of the configuration, one thermal and one structural, is used to numerically simulate the response of a typical waste storage room at the repository horizon. Results show that for the "reference" condition, the added thermal load has no significant effect on room response and is comparable to the room response for the isothermal case. Furthermore, in varying the power output per canister, a moderate increase in power output, to 100 W per canister, resulted in a small increase in room closure, when compared to the baseline response, while a large increase in power output, to 300 W per canister, resulted in a very large increase in room closure. A small increase in canister spacing, from the baseline value, to 3.66 m resulted in a large decrease in room closure, whereas a larger increase in spacing to 6.10 m resulted in only a moderate additional decrease in room closure.

Argüello, J.G., M.A. Molecke, and R. Beraún. 1989. "3D Thermal Stress Analysis of WIPP Room T RH TRU Experiments," *Rock Mechanics as a Guide for Efficient Utilization of Natural Resources: Proceedings of the 30th US Symposium, West Virginia University, Morgantown, WV, June 19-22, 1989.* Ed. A.W. Khair. SAND88-2734C. Brookfield, VT: A.A. Balkema. 681-688.

ABSTRACT: A three-dimensional finite-element thermal stress analysis of the remotely handled transuranic (RH TRU) waste experiments in the Waste Isolation Pilot Plant (WIPP) Room T has been performed. This analysis aids in the interpretation of the bore-hole closure results being obtained from the Room T experiments and helps in assessing potential performance impacts in a typical storage room during the waste retrieval period. Computed results are presented and compared to available in situ data, and a qualitative agreement between measured and computed closures is seen.

Argüello, J.G., D.E. Munson, and D.S. Preece. 1987. "Preliminary Results of the Three-Dimensional Modeling of the WIPP Room D Excavation Sequence," *Rock Mechanics: Proceedings of the 28th US Symposium, Tucson, AZ, June 29-July 1, 1987.* Eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman. SAND86-2380C. Boston, MA: A.A. Balkema. 863-872.

ABSTRACT: A three-dimensional finite-element analysis of the creep deformations occurring during excavation of a room in salt is presented. Comparisons with in situ data show that the equivalent response of the excavation process can be captured with current computational tools. Results of the analysis further suggest that because of the very small influence introduced by the mining process, the current practice of modeling drift response with two-dimensional models, assuming instantaneous excavation, is appropriate.

Avis, J.D., and G.J. Saulnier, Jr. 1990. *Analysis of the Fluid-Pressure Responses of the Rustler Formation at H-16 to the Construction of the Air-Intake Shaft at the Waste Isolation Pilot Plant (WIPP) Site.* SAND89-7067. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The construction of the Air-Intake Shaft (AIS) at the Waste Isolation Pilot Plant (WIPP) Site in 1987 and 1988 initiated fluid-pressure responses, which were used to estimate the hydrologic properties of the Culebra Dolomite, Magenta Dolomite, and Forty-niner Members of the Rustler Formation. Fluid-pressure responses were monitored with downhole transducers at observation well H-16, about 17 m northwest of the AIS, and water-level

responses were observed and measured in observation wells H-1, ERDA-9, and WIPP-21, the closest observation wells to the AIS.

The AIS pilot hole, with a 0.25-m diameter, was drilled to a depth of 650 m and reamed to a diameter of 0.37 m. The pilot hole remained open and draining to the underground facility for about three months. The pilot hole was then upreamed (raise bored) to a 6.17-m diameter shaft from the underground facility to land surface. The pilot hole was drilled and reamed using a bentonite-mud-based brine as a drilling fluid. During the construction period, the fluid-pressure responses of the Culebra Dolomite were also affected by grouting and sealing of the Rustler Formation in the waste-handling shaft (WHS), by a multipad/tracer test at the H-11 hydropad in the southern WIPP Site, and by water quality sampling at WIPP-19 and H-15.

The well-test simulator GTFM [graph-theoretic-field model] was used to analyze the fluid-pressure responses of the Culebra and Magenta Dolomites and the Forty-niner claystone. The AIS was modeled as a test well with a zero-wellbore-pressure boundary condition. H-16 was modeled as an observation well. The pilot-hole drilling/reaming period was modeled as a well-bore history period and was simulated separately for each unit whose fluid-pressure responses were analyzed. A cement-invasion skin was used in simulating the Culebra dolomite's drilling/reaming period. A mud-filter-cake skin was used to create reduced wellbore pressures in simulating the pilot-hole drilling/reaming periods of the Magenta dolomite and Forty-niner claystone.

The estimated Culebra transmissivity ranged from 1.3×10^{-7} to 6.6×10^{-7} m²/sec. The most representative transmissivity of the Culebra between H-16 and the AIS was estimated to be 6.6×10^{-7} m²/sec. This estimate was obtained by calibrating the simulation of the Culebra's H-16 fluid-pressure response to a measurement of the flow rate from the Culebra to the AIS made 133 days after the upreaming of the Culebra. The transmissivity of the Culebra between the AIS and observation-wells H-1, ERDA-9, and WIPP-21 was estimated to range from 1×10^{-6} m²/sec to 1×10^{-7} m²/sec.

Radial formation-heterogeneity boundaries were employed to simulate the H-16 fluid-pressure responses in the Magenta Dolomite and the Forty-niner claystone. The formation-heterogeneity boundary for the Magenta Dolomite was estimated to be 40 m from the AIS with a near-field transmissivity of 8.0×10^{-8} m²/sec and a far-field transmissivity of 3.5×10^{-8} m²/sec. The formation-heterogeneity boundary for the Forty-niner claystone was also estimated to be 40 m from the AIS with a near-field transmissivity of 9.0×10^{-9} m²/sec and a far-field transmissivity of 1.3×10^{-9} m²/sec.

GTFM was used to simulate the flow rates of ground water draining from the Culebra Dolomite, the Magenta Dolomite, and the Forty-niner claystone to the open AIS. The simulated Culebra flow rate on the day of the water-ring measurement in the AIS was 0.058 L/sec and is in excellent agreement with the measured rate of 0.056 L/sec indicating an acceptable model calibration. One hundred days after upreaming, the simulated Culebra flow rate was 0.06 L/sec, the simulated Magenta flow rate was 0.007 L/sec, and the simulated Forty-niner flow rate was 0.0004 L/sec. The simulated Forty-niner flow-rate curve indicated a transition to the less-permeable, far-field system after 15 days.

B

Baca, T.E., 1983. *An Evaluation of the Non-Radiological Environmental Problems Relating to the WIPP.* EEG-20. [Sante Fe, NM:] Environmental Evaluation Group. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) project is designed to receive, inspect, emplace, and store defense-generated transuranic wastes in a retrievable fashion in an underground salt medium and to conduct studies and perform experiments in salt with high-level wastes. While not unique in its individual components, the entire operation presents some inherent environmental problems. Six major nonradiological environmental problems for the WIPP have been identified: air pollution, water pollution and sanitary waste, solid waste, domestic drinking water, occupational health and safety, and toxic chemicals.

These non-radiological concerns were evaluated by identifying the apparent specific environmental concerns, evaluating the control strategies for ameliorating these concerns, and identifying the Federal or State regulatory mechanism for ensuring that proposed control strategies are complied with during the construction and operation of the WIPP Facility.

These non-radiological concerns are adequately addressed by WIPP plans. State monitoring will ensure air quality conditions for permits to be maintained. A permit will be required for a sewage lagoon system. Federal agencies will monitor occupational health and safety. Toxic chemicals used in the Health Physics Laboratory need to be identified and quantified.

The WIPP Site is located in an area of low population density. A low onsite employment population is expected during construction and operation. These factors allow for a low population/problem exposure rate. DWP

Bachman, G.O. 1973. *Surficial Features and Late Cenozoic History in Southeastern New Mexico.* USGS-4339-8. Denver, CO: US Geological Survey.

ABSTRACT: Since deposition of the Ogallala Formation during Pliocene time, southeastern New Mexico has been subjected to erosion, solution, subsidence, and widespread eolian activity. These processes have combined to influence the formation and morphology of major drainage systems. Aligned drainage patterns resulted from solution of caliche localized by longitudinal sand dunes. San Simon Swale appears to have formed by processes of erosion and solution subsidence of Permian evaporites and was formerly an important tributary to the Pecos River. The combination of processes that formed San Simon Swale was similar to the combination of erosion and coalescing sinks that formed the lower Pecos Valley in southern New Mexico.

ANNOTATION: Bachman (1973) examined surficial features of a large area in southeastern New Mexico, continuing the discussion of stability of evaporites begun in Bachman and Johnson (1973). Bachman says relatively little about rocks older than the Ogallala Formation (Pliocene) compared to his later reports. He interpreted linear, oriented depressions on the Querecho Plains as troughs etched in caliche by rainwater that collected between long linear dunes that have since disappeared.

Bachman (1973) interpreted the Gatuña Formation as post-Ogallala because it contains Ogallala clasts. This contrasted with some interpretations of the deposition of the Gatuña Formation as being earlier than the time of the Ogallala deposition. Bachman also clearly separated the unit informally called the Mescalero caliche from the Ogallala. The Mescalero caliche has since

been determined to be less than 0.5 million years old, and it has been used extensively by Bachman to develop a more precise chronology of dissolution events in southeastern New Mexico.

Bachman also proposed that San Simon Swale formed by subsidence and erosion following salt solution (interpreted by C.L. Jones) in the San Simon Sink area. This preceded the summary by Anderson (1978).

Bachman, G.O. 1974. *Geologic Processes and Cenozoic History Related to Salt Dissolution in Southeastern New Mexico*. Open-File Report 74-194. Denver, CO: US Geological Survey.

ABSTRACT: Salt of Permian age in the subsurface of an area near The Divide, east of Carlsbad, NM, is being considered for a nuclear waste repository. The geologic history of the region indicates that dissolution of salt has occurred in the past during at least three distinct epochs: after Triassic but before middle Pleistocene time; during middle Pleistocene time; and during late Pleistocene time. Thus, destructive geologic processes have been intermittent through more than 100 million years.

Nash Draw, near The Divide, formed during late Pleistocene time by the coalescing of collapse sinks. The rate of its subsidence is estimated to have been about 10 cm (0.33 ft) per thousand years. The immediate area of The Divide adjacent to Nash Draw has not undergone stress by geologic processes during Pleistocene time and there are no present indications that this geologic environment will change drastically within the period of concern for the repository.

ANNOTATION: In this report, Bachman specifically considers the geological stability of the area including the present site of the Waste Isolation Pilot Plant (WIPP). The report is significant as the first relatively complete treatment of the geology and relationships of Pleistocene age deposits, especially the Gatuña Formation and Mescalero caliche. Other later reports develop different aspects of the latest geological history of southeastern New Mexico, but this report is an important beginning.

Bachman (1974) considers that salt was dissolved from the western Delaware Basin as early as Triassic. The long interval, mainly of exposure, from Triassic to the late Tertiary also should have been a time of salt dissolution. Bachman associates the Gatuña Formation with the most humid Pleistocene interval more than 600,000 years ago, a time when major dissolution in the Delaware Basin is thought to have occurred. This observation and correlation for the uppermost Gatuña is consistent with radiometric based ages available later (Bachman, 1980), though data now available demonstrate some rocks assigned to the Gatuña in southeastern New Mexico and west Texas are Miocene in age. Bachman also examined the Mescalero caliche in detail as evidence of arid climate conditions and recognized that the unit develops on stable surfaces. More recent dissolution has disturbed the Mescalero, identifying areas of dissolution and providing a maximum age. Bachman shows evidence of modern collapse and concludes that dissolution and erosion continue. Bachman (1974) estimated that dissolution had lowered the surface within Nash Draw about 180 ft since the end of Gatuña deposition (about 600,000 years ago), though he has since reconsidered that estimate and believes it is too high.

Though some interpretations (age of uppermost Gatuña) were subsequently borne out and others (dissolution in Nash Draw) seem high, this report served as a clear initial statement of the stability of the Los Medaños area with respect to dissolution. On the basis of the US Geological Survey (USGS) studies, an initial site was chosen and investigated by Oak Ridge National Laboratory (ORNL) in 1974. In 1976, when the current WIPP Site was chosen to replace the original site, it fell within the same area recommended by these studies.

Bachman, G.O. 1976. "Cenozoic Deposits of Southeastern New Mexico and an Outline of the History of Evaporite Dissolution," *Journal of Research, US Geological Survey*. Vol. 4, no. 2, 135-149.

ABSTRACT: Sedimentary records of Cenozoic history in southeastern New Mexico begin with the Ogallala Formation of Miocene and Pliocene age. Later records include the Gatuña Formation of early or middle Pleistocene age, Mescalero caliche (an informal term) of middle Pleistocene age, and fluvial deposits of late Pleistocene age, but there are many gaps in the record. The modern landscape is the result of erosion and deposition in climates that have ranged from semihumid to semiarid as well as dissolution of soluble rocks in Permian formations in the subsurface. This dissolution may have begun as early as Jurassic time and has continued intermittently to the present.

Bachman, G.O. 1980. *Regional Geology and Cenozoic History of Pecos Region, Southeastern New Mexico*. Open-File Report 80-1099. Denver, CO: US Geological Survey.

ABSTRACT: This report summarizes the Cenozoic history of the Pecos drainage in the Delaware Basin, southeastern New Mexico, and incorporates an outline of the dissolution and karst development in Permian evaporites in the region.

Evaporites include anhydrite, gypsum, halite, and related minerals. They are included in the Castile, Salado, and Rustler Formations of Late Permian age, the time of the Ochoan deposition. These formations have been transgressed by strata of the Dockum Group of Late Triassic age and unnamed formations of Early Cretaceous age.

Complex karst features include collapse sinks, karst mounds (new term), karst domes (new term), and caves. Karst mounds are erosional remnants of regional breccia. Karst domes are structural features that have formed on a very irregular dissolution surface. They are analogous to towers, kegelkarst, or mogotes in tropical regions, except that karst domes are almost buried by their own dissolution residue.

Breccia chimneys are collapse sinks that have formed over the Capitan aquifer system. They appear to be the result of unsaturated water rising under a strong hydraulic head through fractures and dissolving upward into the evaporite sequence.

Breccia chimneys, karst mounds, and karst domes studied during this work were formed during middle Pleistocene time.

Dissolution has been an active process in the Delaware Basin at least since Triassic time and it is impractical to attempt to calculate a rate of dissolution for the basin. Earlier estimates of the rate of dissolution are considered to be conservative. Subsurface evidence does not suggest that deep dissolution is presently an active process in the Castile Formation beneath the thick beds of Salado salt.

Pleistocene glaciation in the northern and central United States was probably accompanied by "pluvial" periods in southeastern New Mexico. Pluvials are characterized by less extreme temperatures, less evaporation, and more effective moisture than at present.

ANNOTATION: Bachman (1980) adds considerable information about surficial features in southeastern New Mexico to the framework of Quaternary history he previously presented (Bachman and Johnson, 1973; Bachman, 1974). The report is significant as a rational, field-based examination and explanation of surficial dome and collapse features in the Delaware Basin postulated (Anderson, 1978) to have formed by dissolution of Castile Formation halite.

Anderson proposed that water rises through fractures from the underlying Delaware Mountain Group because of higher pressures, dissolves halite in the Castile, and then sinks because of increased density (brine density flow). This specific process is not a significant cause of Castile dissolution (see annotation regarding Wood et al., 1982).

Bachman (1980) interpreted two important sets of dissolution features: the "breccia pipes" (Hills A-D) and karst dome/mound features. He hypothesizes that breccia pipes formed as fluid pressures decreased in the underlying Capitan Reef. Collapse in the Capitan propagated upward, forming a columnar feature with a sink at the surface. After the Mescalero caliche formed, salt was dissolved regionally from the Rustler and/or Salado, and the surface rocks around the breccia pipe core subsided to form pseudodomal structures. Snyder and Gard (1982) agreed with this interpretation (see annotation).

Bachman also defined two new features, karst domes and karst mounds, based on his study in the Queen Lake-Malaga Bend area south of Malaga, NM. Bachman interpreted these as near-surface features; Anderson (1978) suggested that they were seated in the Castile. WIPP-32 was drilled in Nash Draw, as a test of this interpretation, in the karst mound or dome closest to the site. Solution and collapse were restricted to the upper Salado and Rustler, demonstrating the Castile was not involved.

A test hole in the Malaga Bend-Queen Lake area near Malaga, NM, was discussed, but it was never drilled. No feature could be agreed upon as a satisfactory test of the hypothesis that the feature was caused by dissolution driven by the hydrology of the Delaware Mountain Group as opposed to near-surface hydrology.

This report was an important milestone in understanding regional effects of dissolution, though several other important reports followed that still addressed dissolution as a regional (e.g., Lambert, 1983a; Robinson and Powers, 1987) or WIPP Site process (Holt and Powers, 1984, 1986b).

Bachman, G.O. 1981. *Geology of Nash Draw, Eddy County, New Mexico*. Open-File Report 81-31. Denver, CO: US Geological Survey.

ABSTRACT: Nash Draw is a partially closed depression about 29 km (17 mi) east of Carlsbad, Eddy County, NM. It has been mapped geologically in conjunction with detailed studies to evaluate the proposed nuclear Waste Isolation Pilot Plant (WIPP). Maps at scales of 1:24,000 accompany this report.

The stratigraphic section exposed in Nash Draw includes the Rustler Formation and Dewey Lake Red Beds of Late Permian (Ochoan) age, the Dockum Group of Late Triassic age, and the Pleistocene Gatuña Formation. Other deposits of middle to late Quaternary age include the Mescalero caliche, spring deposits, and windblown sand.

Dissolution of evaporites has been a major process in the formation of Nash Draw. Nash Draw formed before, and during, Gatuña time about 600,000 years ago. Near-surface dissolution of gypsum in the Rustler Formation is presently active and is responsible for numerous collapse sinks and related karst features.

Bachman, G.O. 1983. *Regional Geology of Ochoan Evaporites, Northern Part of Delaware Basin*. New Mexico Bureau of Mines and Mineral Resources Open File 184. [Socorro, NM: New Mexico Bureau of Mines and Mineral Resources]. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Ochoan Series (Permian) in the northern part of the Delaware Basin, southeastern New Mexico, includes in ascending order the Castile, Salado, and Rustler Formations, and the Dewey Lake Red Beds. The Castile and Salado Formations comprise a sequence of evaporites that include anhydrite, gypsum, halite, and associated potash salts. The Rustler Formation contains some halite and minor amounts of potash minerals. These evaporites were deposited within the basin formed by the Capitan barrier reef, as well as across the reef. The evaporites, as well as the Capitan reef, are all subject to dissolution with resulting karst features analogous to those formed in limestone regions.

An ancestral Pecos River was the major drainage system in the western part of the Delaware Basin, New Mexico, during late Cenozoic time. That ancient river system was responsible for the formation of an extensive karst terrain along the east side of the present Pecos River in New Mexico and southward into Texas. During late Cenozoic time extensive dissolution occurred in the Salado Formation within the karst area as a result of the groundwater regime. The dissolution front was perched on the upper anhydrite member of the Castile Formation.

On the eastern side of the Delaware Basin in New Mexico, a large collapse sink—San Simon sink—overlies the Capitan reef, which is a prominent aquifer system in that area. So-called "breccia pipes" are ancient sinks that collapsed into the caverns in the reef on the northern margin of the basin. These have since been partially exhumed. The San Simon sink is presumed to be a modern analog of these breccia pipes.

Bachman, G.O. 1985. *Assessment of Near-Surface Dissolution At and Near the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico.* SAND84-7178. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The area at and near the Waste Isolation Pilot Plant (WIPP) Site was examined for evidence of karst development on the geomorphic surface encompassing the site. Certain surficial depressions of initial concern were identified as blowouts in sand dune fields (shallow features unrelated to karstification). An ancient stream system active more than 500,000 years ago contained more water than any system since. During that time (Gatúña, middle Pleistocene), many karst features such as Clayton Basin and Nash Draw began to form in the region. Halite was probably dissolved from parts of the Rustler Formation at that time. Dissolution of halite and gypsum from intervals encountered in borehole WIPP-33 west of the WIPP Site occurred during later Pleistocene time (i.e., <450,000 years ago). However, there is no evidence of active near-surface dissolution within a belt to the east of WIPP-33 in the vicinity of the WIPP shaft.

Bachman, G.O. 1987a. "Stratigraphy and Dissolution of the Rustler Formation," *The Rustler Formation at the WIPP Site, Report of a Workshop on the Geology and Hydrology of the Rustler Formation As It Relates to the WIPP Project, Carlsbad, NM, March 1985.* Ed. L. Chaturvedi. SAND86-7077C; EEG-34. Santa Fe, NM: Environmental Evaluation Group. 16-25.

ABSTRACT: The Rustler Formation consists of five members that are regionally persistent. The Culebra and Magenta Dolomite Members maintain their characteristics and thickness, while the evaporite and clastic members vary in facies and thickness. Clastic sediments increase southwest from the Waste Isolation Pilot Plant (WIPP) Site.

The Rustler has been modified by dissolution, forming karst features on a variety of scales and characterized by disorderly drainage. Nash Draw, Remuda Basin, and Burton Flat are major karst features developed in response to dissolution within the Rustler. Nash Draw began to form as a Pleistocene drainage system. Collapse sinks developed along the strike of the Rustler

as it was exposed. The sinks coalesced and Nash Draw subsided, disrupting drainage. The Mescalero caliche then formed on the surface east of Nash Draw. Nash Draw still expands slowly as a karst valley. Remuda Basin is a blind valley that drains into an open cave system in the Rustler. Burton Flat is a karst plain with many closed depressions, collapse sinks, and caves. The Mescalero caliche is not observed here because the surface is not stable enough for such a soil to develop or be preserved.

Karst features develop in an orderly manner. Paleokarst features are preserved in Pierce Canyon and southern Nash Draw. The Pleistocene Gatuña Formation shows collapse. Collapse sinks and caves in other areas show continuing karst processes. Evidence of perennial lakes indicates significant climatic variation during the Pleistocene. Rates of dissolution calculated assuming constant dissolution and subsidence are invalid. Many karst features apparently formed during times of greater rainfall. DWP

Bachman, G.O. 1987b. "Evaporite Karst in the Pecos Drainage, Southeastern New Mexico," *Geology of the Western Delaware Basin, West Texas and Southeastern New Mexico*. Eds. D.W. Powers and W.C. James. El Paso Geological Society Guidebook 18. El Paso, TX: El Paso Geological Society. 118-123.

ABSTRACT: Hundreds of karst features are present in evaporites in southeastern New Mexico. Most of these features are collapse sinks or elaborate drainage systems associated with collapse sinks. Many of these features formed during the middle to late Pleistocene. Breccia pipes are present along the northern part of the Delaware Basin. These are unique, deep-seated collapse sinks that formed during the middle Pleistocene.

Bachman, G.O. 1987c. *Karst in Evaporites in Southeastern New Mexico*. SAND86-7078. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Permian evaporites in southeastern New Mexico include gypsum, anhydrite, and salt, which are subject to both blanket and local, selective dissolution. Dissolution has produced many hundreds of individual karst features including collapse sinks, karst valleys, blind valleys, karst plains, caves, and breccia pipes. Dissolution began within some formations during Permian time and has been intermittent but continual ever since. Karst features other than blanket deposits of breccia are not preserved from the early episodes of dissolution, but some karst features preserved today (such as breccia pipes) are remnants of karst activity that was active at least as early as mid-Pleistocene time. Rainfall was much more abundant during late Pleistocene time, and many features visible today may have been formed then. The drainage history of the Pecos River is related to extensive karstification of the Pecos Valley during mid-Pleistocene time. Large-scale stream piracy and dissolution of salt in the subsurface resulted in major shifts and excavations in the channel. In spite of intensive groundwater studies that have been carried out in the region, major problems in groundwater in near-surface evaporite karst remain to be solved. Among these are determination of recharge areas and time of recharge.

Bachman, G.O. 1989. *Annotated Bibliography of Paleoclimate Studies Relevant to the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-7087. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A selective, partially annotated bibliography on paleoclimate literature (through 1984) presents the various interpretations of the nature of past climate in New Mexico and adjacent areas in the Southwest. Groundwater flow and concomitant dissolution of evaporites

in the Delaware Basin of southeastern New Mexico, the geologic setting of the Waste Isolation Pilot Plant (WIPP) Site, has occurred since Permian deposition and may be continuing at some places in the basin. An understanding of patterns of past rainfall may contribute to an understanding of the history of groundwater flow and evaporite dissolution at and near the WIPP Site and may help to predict the relative magnitudes of groundwater flow and evaporite dissolution to be expected during the required period of repository performance. Although most references in this list are annotated and pertain to paleoclimate in the vicinity of New Mexico, other references have been included that place the Southwest in the context of world climatic change, pertain to principles and methods of collecting climatic data for past geologic time, and complement such a collection of references because of their historic interest.

Bachman, G.O., and R.B. Johnson. 1973. *Stability of Salt in the Permian Salt Basin of Kansas, Oklahoma, Texas, and New Mexico, With a Section on Dissolved Salts in Surface Water*, by F.A. Swenson. USGS-4339-4. Denver, CO: US Geological Survey.

ABSTRACT: The Permian salt basin in the western interior of the United States is defined as that region comprising a series of sedimentary basins in which halite and associated salts accumulated during Permian time. The region includes the western parts of Kansas, Oklahoma, and Texas, and eastern parts of Colorado and New Mexico.

Following a long period of general tectonic stability throughout the region during most of early Paleozoic time, there was much tectonic activity in the area of the Permian salt basin during Late Pennsylvanian and Early Permian time just before bedded salt was deposited. The Early Permian tectonism was followed by stabilization of the basins in which the salt was deposited. These salt basins were neither contemporaneous nor continuous throughout the region so that many salt beds are also discontinuous. In general, beds in the northern part of the basin (Kansas and northern Oklahoma) are older, and the salt is progressively younger towards the south.

Since Permian time, the Permian salt basin has been relatively stable tectonically. Regionally, the area of the salt basin has been tilted and warped, has undergone periods of erosion, and has been subject to a major incursion of the sea; but deep-seated faults or igneous intrusions that postdate Permian salt are rare. In areas of the salt basin where salt is near the surface, such as southeastern New Mexico and central Kansas, there are no indications of younger deep-seated faulting and only a few isolated igneous intrusives of post-Permian age.

On the other hand, subsidence or collapse of the land surface resulting from dissolution has been commonplace in the Permian salt basin. Some dissolution of salt deposits has probably been taking place ever since deposition of the salt more than 230 million years ago. Nevertheless, the subsurface dissolution fronts of the thick bedded-salt deposits of the Permian basin have retreated at a very slow average rate during that 230 million years.

The preservation of bedded salt from subsurface dissolution depends chiefly on the isolation of the salt from moving groundwater that is not completely saturated with salt. Karst topography is a major criterion for recognizing areas where subsurface dissolution has been active in the past; therefore, the age of the karst development is needed to provide the most accurate estimate of the dissolution rate. The Ogallala Formation of Pliocene age is probably the most widespread deposit in the Permian salt basin that can be used as a point of reference for dating the development of recent topography. It is estimated that salt has been dissolved laterally in the vicinity of Carlsbad, NM, at an average rate of about 6-8 mi per million years.

Estimates of future rates of salt dissolution and the resulting lateral retreat of the underground dissolution front can be projected with reasonable confidence for southeastern New Mexico on the assumption that the climatic changes there in the past 4 million years are representative of climatic changes that may be expected in the near future of geologic time.

Large amounts of salt are carried by present-day rivers in the Permian salt basin; some of the salt is derived from subsurface salt beds, but dissolution is relatively slow. Groundwater movement through the Permian salt basin is also relatively slow.

ANNOTATION: The studies by the US Geological Survey (USGS) reported by Bachman and coworkers were fundamental for selecting the present Waste Isolation Pilot Plant (WIPP) Site and as a beginning assessment of the issue of halite dissolution.

The USGS cooperated with Oak Ridge National Laboratory (ORNL) to find an alternate site for radioactive waste disposal in salt beds after the Lyons, KS, site was abandoned in 1972. Bachman and Johnson (1973) examined the larger Permian Basin for geological stability as a criterion for site selection. They found that the area is generally tectonically stable, but they also recognized that salt has been dissolved in the basin since salt was deposited during the Permian.

Bachman and Johnson (1973) estimated for the first time that salt in the basin near Carlsbad, NM, was dissolved with an average lateral rate of about 6 to 8 mi/million years. To estimate this rate, Bachman and coworkers extrapolated or projected the position of the Ogallala Formation and underlying older rocks into areas affected by dissolution and assumed that salt extended to the western margin of the basin. Swenson examined dissolved salt load within several subbasins in the Permian Basin.

Bachman and Johnson (1973) briefly examined paleoclimate information, and concluded that the climatic range for the last 4 million years represents the probable extremes for the foreseeable future. Salt is being dissolved slowly, and the rate is not likely to change greatly in the near future because of climatic changes.

Bachman and Johnson (1973) recommended two areas for consideration as possible sites. In central Kansas, one area was recommended west of the solution front. In southeastern New Mexico, they recommended an area between Nash Draw and San Simon Sink. This area was later intensively examined, and both the first site of investigation and the current WIPP Site are within the recommended area.

Balazs, E.I. [Undated]. *Report on First-Order Leveling Survey for Sandia Laboratories Waste Isolation Pilot Plant (WIPP) Project.* [Rockville, MD: National Geodetic Survey]. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: "The National Geodetic Survey (NGS) of the National Ocean Survey (NOS) completed 516 km of first-order, class I leveling in New Mexico and Texas in the fall of 1977." A segment 202 km long was releveled from Carlsbad toward El Paso, showing about 10 cm of upward movement at the west end relative to Carlsbad and relative local subsidence over the Salt Basin. New lines (314 km) were established from Carlsbad across the Waste Isolation Pilot Plant (WIPP) Site, Nash Draw, San Simon Sink, and potash mine areas to second-order lines near Eunice and Hobbs, NM. Releveling will provide information about vertical movement. DWP

Balazs, E.I. 1982. *Vertical Movement in the Los Medaños and Nash Draw Areas, New Mexico, As Indicated by 1977 and 1981 Leveling Surveys.* NOAA Technical Memorandum NOS NGS 37. Rockville, MD: National Geodetic Survey. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Free-adjusted heights of two survey epochs were compared for the Los Medaños and Nash Draw areas. The changes in heights of common bench marks were tabulated and plotted. The apparent movement for the area documented in this report is relative to bench mark 1 BOR, set in a bridge in Carlsbad, NM. A total of 122 of the 147 common bench marks indicates consistent subsidence averaging approximately 18 mm between 1977 and 1981 (4.6 mm/year). At two bench marks, located over potash mines in the area, the subsidence is much larger.

Balestri, R.J., B.W. Torres, S.B. Pahwa, and J.P. Brannen. 1979. "Preliminary Safety Assessment of the WIPP Facility," *Scientific Basis for Nuclear Waste Management, Proceedings of the Symposium on Science Underlying Radioactive Waste Management, Materials Research Society Annual Meeting, Boston, MA, November 28-December 1, 1978*. Ed. G.J. McCarthy. New York, NY: Plenum Press. Vol. 1, 513-520.

ABSTRACT: A limited safety assessment for the Waste Isolation Pilot Plant (WIPP) has been based on the consequences to an individual maximally exposed "as a result of introducing the radionuclides into the biosphere." The consequences have not been extended for population or weighted by probability of release events. Ecological, hydrological, and geological parameters were assumed to be static, and the transfer coefficients for the pathway was assumed to be independent of soil and chemistry. Wastes were not assumed safe at any time, and the consequences were modeled as a function of time until a maximum was reached after the release event. "The consequence parameter is the 50-year dose commitment from one year of exposure." Five breaching scenarios were selected as representations of worst case events assumed to occur 1000 years after decommissioning. Four events transfer waste through liquid up to and through the overlying Rustler Formation aquifers; a fifth event represents drilling that brings waste directly to the surface. Contact handled transuranic (CH TRU) waste, based on assay data from Idaho National Engineering Laboratory (INEL), was assumed present. Various computer codes from INTERA Technologies, governmental agencies, and laboratories were used to model the transport functions through a computer code (CAPER: Consequence Assessment Program for Exposure to Radioaction) developed to control the data, output, and interactions of the codes.

For the four 'natural' breaching events, ". . . if a breach of WIPP does occur for which the modeling assumptions remain valid, the consequences are several orders of magnitude less than those associated with [the] current environment." The drilling scenario has substantially higher doses to drilling crew because the time delay introduced by geologic storage does not occur. Inhalation is the primary exposure mode. No conclusions are made about the safety of the WIPP based on these analyses.

While mathematical models have been constructed and used to represent elements of the repository, geological system, and biosphere, there is no established method to identify the appropriateness of models and response of the entire system. Such a method must be established before models and results can be used in making decisions. DWP

Bard, S.T. 1982. *Estimated Radiation Doses Resulting if an Exploratory Borehole Penetrates a Pressurized Brine Reservoir Assumed to Exist Below the WIPP Repository Horizon - A Single Hole Scenario*. EEG-15. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The consequences of a radiation dose have been analyzed for a scenario in which an exploratory gas or oil well is postulated to penetrate the repository and intercept a brine reservoir in the Castile Formation. Brine, corings, and drilling mud are contained in a one-acre holding pond on the surface. The dried holding pond area is reclaimed with a bulldozer to original topography after drilling. The estimated radiation bone dose commitments to a

bulldozer operator and a member of a farm family 500 m downwind from the pond area are summarized for penetration time 100, 400, and 1000 years after closure of the repository. The bone dose commitments are based on 40 hours' exposure for the bulldozer operator and as a fifty-year dose commitment following one-year intake of radionuclides by a member of the farm family. "The highest estimated 50-year bone dose commitment to an individual reclaiming the contaminated holding pond area was determined to be 590 millirem (mrem) from the inhalation of contact handled transuranic (CH TRU) wastes resuspended into the atmosphere at an event time of 100 years post-closure." It is conservatively assumed that both active and passive control of the site has been lost by 100 years after closure. A second dose model for this individual, using a specific activity approach, results in a 50-year dose commitment of 450 mrem. "Both . . . estimates may be compared to the 5800 mrem to bone surfaces that may be expected from natural background radiation to an individual in the United States over a fifty-year period. . . ." DWP

Barr, G.E., and D.D. Gonzalez. 1980. "Current Status of the Hydrogeology for the WIPP," *Proceedings of Workshop on Thermomechanical-Hydrochemical Modeling for a Hardrock Waste Repository, Berkeley, CA, July 29-31, 1980*. Ed. W.J. Schwarz. LBL-11204; ONWI-164; SAND80-1539C. Berkeley, CA: Lawrence Berkeley Laboratory. 89-94.

ABSTRACT: The current efforts to define the hydraulic system at the proposed Waste Isolation Pilot Plant (WIPP) Site are described. These efforts are directed toward further refining the field data and conducting specific tests to determine the isotropy of the media and the appropriateness of their representation as porous or as fractured systems.

Barr, G.E., F.W. Bingham, and M.S. Tierney. 1981. "The Use and Misuse of Scenarios in Waste-Disposal Studies," *Proceedings of the Workshop on Radionuclide Release Scenarios for Geologic Repositories, Paris, France, September 8-12, 1980*. SAND80-1537A. Paris, France: Organisation for Economic Co-Operation and Development. 79-90.

ABSTRACT: A scenario is an assumed sequence of physically possible events that describes a failure of a waste-disposal system. Six examples of the use of scenarios in analyzing the safety of a waste repository provide evidence for the following assertions. Scenarios are most effective when they are used to analyze specific sites, and the most productive use of scenarios requires a multidisciplinary team effort and feedback between the conceptual and analytical phases of the safety study.

Barr, G.E., S.J. Lambert, and J.A. Carter. 1979. "Uranium Isotope Disequilibrium in Groundwaters of Southeastern New Mexico and Implications Regarding Age-Dating of Waters," *Isotope Hydrology 1978, Proceedings of an International Symposium on Isotope Hydrology, Neuherberg, June 19-23, 1978*. STI/PUB/493; IAEA-SM-228/32; SAND77-1779. Vienna, Austria: International Atomic Energy Agency. Vol. 2, 645-660.

ABSTRACT: Regional exploration of bedded salt for a radioactive waste repository in the Delaware Basin (Permian, New Mexico, USA) included boreholes into the evaporites and associated rocks. One such hole, ERDA No. 6, encountered an accumulation of saturated NaCl-Na₂SO₄ brine accompanied by H₂S-rich gas. This fluid and fluids from other boreholes elsewhere in the area have been characterized geochemically according to solute content, ¹⁸O/¹⁶O and D/H ratios and natural actinide content. Deviations from the equilibrium ²³⁴U/²³⁸U activity ratio (α) of 1.0 were found in all water samples. These deviations are used to affirm the isolation of ERDA No. 6 and to establish bounds on the age of the ERDA No. 6 fluid.

A mathematical model for the age of ERDA No. 6 water intrusion was formulated in terms of the following variables: initial α -value (α_0) of the brine precursor waters, zero-order kinetic rate constants of leaching of ^{234}Th and ^{238}U from the rocks, and degree of leaching of ^{234}Th from the rocks. The model allows calculation of α -values of brines as a function of time, leach rate α_0 . Various combinations of α_0 's, leach fractions and leach rates indicate that the leach rate must be low. If no leaching is assumed and the α_0 is the highest known α from the nearby Capitan Reef ($\alpha_0=5.2$ at present), the fluid is older than 880,000 years. ERDA No. 6 brine has undergone more profound rock/fluid interactions, reflected in its solutes and stable isotopes, compared with younger meteoric Capitan waters.

Barr, G.E., W.B. Miller, and D.D. Gonzalez. 1983. *Interim Report on the Modeling of the Regional Hydraulics of the Rustler Formation*. SAND83-0391. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The finite-element code ISOQUAD was used to simulate the head distribution within the two major water-bearing units of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP), the Magenta and Culebra Dolomites. The derived surfaces correlate well with those generated manually by the US Geological Survey (USGS) and Sandia National Laboratories (SNL). Calculated migration of a continuously injected contaminant from an assumed smeared point source at the center of the site was observed in terms of concentration relative to the initial input. Migration rates of specific concentration fronts decreased with increasing time. The average rate of movement of the 10^{-3} relative concentration contour was less than 10 m/year for the first 800 years in the Culebra Dolomite. By 800 years, the migration of this concentration front has essentially ceased. In the case of the Magenta Dolomite, the average rate of movement of the 10^{-3} relative concentration contour was 0.44 m/year for the first 676 years of continuous contaminant injection; the contaminant plume in the Magenta shows little movement thereafter. For reasons of scale, the plumes calculation overestimates the actual rate of movement of contaminants. Particle velocities for selected streamlines, more characteristic of containment movement, are calculated for comparison with the results of the *Final Environmental Impact Statement (FEIS)*. These particle velocities indicate groundwater travel times of ~130,000 years from the center of the WIPP Site to a distance of 12.9 km (8 mi).

The validity of the porous-medium approximation of the Rustler aquifers was examined by the evaluation of the drawdown portion of the aquifer pump tests. Drawdown curves were successfully duplicated as a function of hydraulic conductivity, storativity, and well radius. Estimation of the effective radius examined in each well test indicates that there are no significant fluid-bearing fractures or channels within 60 m of tested wells. Because of variable test duration and in situ hydraulic properties, effective radii tested range from 37 to 1500 m.

Barrows, L.J. 1980. "Geophysical Studies of Evaporites in the Northern Delaware Basin," *Abstracts, Annual Meeting of the Southwest Section, American Association of Petroleum Geologists*. SAND80-0027A. 16. (Abstract Only).

ABSTRACT: Geophysics has been an integral part of the Waste Isolation Pilot Plant (WIPP) since its inception. Previous activities have included electrical resistivity surveys, review of petroleum exploration seismic lines, purchase of aeromagnetic and gravity surveys, installation of an earthquake seismometer, a seismic refraction survey, and five seismic reflection surveys. Ongoing or planned activities include installation of a multistation seismometer array, subsurface radar, vertical-gradient aeromagnetics, and high-resolution seismics.

The seismic reflection and gravity data indicate complex structure in the northern part of the site. The seismic lines show a deterioration in reflector quality, character, and continuity within this "disturbed zone." Events within the Castile Formation have a blocky nature with abrupt offsets and angular discontinuities between blocks. The lower members of the Castile Formation are thinner than normal. Both the underlying Delaware Mountain Group and overlying Salado Formation are less deformed than the Castile Formation. The present well control is consistent with the seismic interpretation. An interesting feature is an "expandable scale" contraction of the lower Salado in two wells in which the individual beds are present but have been reduced 10-50% in thickness.

Barrows, L.[J.], and J.D. Fett. 1985. "A High-Precision Gravity Survey in the Delaware Basin of Southeastern New Mexico," *Geophysics*. Vol. 50, no. 5, 825-833.

ABSTRACT: Since 1974, the Department of Energy (DOE) has been studying bedded salt deposits in southeastern New Mexico as a possible location for disposing of defense-generated transuranic and low-level radioactive wastes. The program, known as the Waste Isolation Pilot Plant (WIPP), includes intensive geologic characterization of about 40 km² and construction of an underground test facility. The gravity survey reported here is part of the geologic site characterization.

The gravity survey was conducted to delineate structural features near and at the proposed site. However, during the survey the gravity field was found to be dominated by effects of lateral density variations within relatively flat-lying strata. Particularly distinctive is a pattern of elongate negative anomalies about one-half milligal in amplitude. Bore holes in the anomalies encountered normal stratigraphy and no unusual geologic structures. However, bore hole densilogs showed lower densities and uphole velocity surveys showed lower acoustic velocities than are measured outside of the anomalies. The low densities adequately account for the observed gravity anomalies.

The regional stratigraphy contains water-soluble minerals (halite, polyhalite, anhydrite-gypsum, carbonates). Much of this material has dissolved, and the region has been identified as a karstland. At the site, dissolution is slowly affecting the Rustler Formation overlying the main salt-bearing units. The low rock densities, associated with the negative gravity anomalies, are interpreted as caused by alteration in the vicinity of solution conduits within the Rustler Formation. This interpretation is supported by partial coincidence between the negative gravity anomalies and closed topographic depressions (alluvial dolines), greater anhydrite-to-gypsum conversion detected in boreholes within the anomalies, and solution conduits encountered in one of the boreholes.

Barrows, L.J., D.D. Gonzalez, and W.D. Weart. 1982. "Geotechnical Field Measurements for Evaluation of the WIPP Site," *IEEE Transactions on Nuclear Science, Nuclear Science Symposium, San Francisco, CA, October 21-23, 1981*. SAND81-2383C. Vol. NS-29, no. 1, 239-241.

ABSTRACT: Direct and indirect field measurements of site features have been useful in evaluating the site for the Waste Isolation Pilot Plant (WIPP). Geophysical and hydrological investigations have been applied with a formal program of quality assurance to obtain reliable, well documented data and analytical techniques.

Geophysical techniques applied to resolving the deformation of deeper evaporites along the northern edge of the WIPP Site provide a case history. A wide range of surface seismic reflection, gravity, and electrical methods were designed to provide information about these relatively shallow units. Bore-hole logs have revealed additional velocity and density variation. Additional geophysical studies and drilling will help evaluate these features.

Hydrologic tests at the WIPP Site include 3-well pump tests, multi-well tracer tests, and long-term pump tests under unusual conditions. Transmissivities range from 10^{-1} to 10^{-4} ft²/day. In addition to low transmissivities, low pump rates, water quality, depth, power sources, and weather are serious obstacles. Tests may run for a year.

Data acquired by these programs and methods are part of the basis for consequence assessments for the WIPP. DWP

Barrows, L.J., W.D. Weart, and J.L. Hern. 1980. "Geophysical Studies of the Waste Isolation Pilot Plant," *Program with Abstracts, 109th Society of Mining Engineers of AIME Annual Meeting, Las Vegas, NV, February 24-28, 1980*. SAND80-0048A. Littleton, CO: Society of Mining Engineers of AIME. 446. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a planned repository for defense-generated nuclear wastes. The repository will be at a depth of 650 m in the evaporite formations of the Delaware Basin in southeastern New Mexico. Geophysical studies have included electrical resistivity, review of petroleum company seismic lines, purchase of a speculative aeromagnetic survey, operation of an earthquake seismometer station, five reflection seismic surveys, and a well logging program. Present or planned activities include adapting high resolution seismic techniques to the site conditions, a high-resolution vertical-gradient aeromagnetic survey, and installation of a digital seismometer array.

Barrows, L.J., S-E. Shaffer, W.B. Miller, and J.D. Fett. 1983. *Waste Isolation Pilot Plant (WIPP) Site Gravity Survey and Interpretation*. SAND82-2922. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A portion of the Waste Isolation Pilot Plant (WIPP) Site has been extensively surveyed with high-precision gravity. The main survey (in T22S, R31E) covered a rectangular area 2 by 4-1/3 mi encompassing all of WIPP Site Zone II and part of the disturbed zone to the north of the site. Stations were at 293-ft intervals along 13 north-south lines 880 ft apart. The data are considered accurate to within a few hundredths of a milligal.

Long-wavelength gravity anomalies correlate well with seismic time structures on horizons below the Castile Formation. Both the gravity anomalies and the seismic time structures are interpreted as resulting from related density and velocity variations within the Ochoan series. Shorter wavelength negative gravity anomalies are interpreted as resulting from bulk density alteration in the vicinity of karst conduits.

The WIPP gravity survey was unable to resolve low-amplitude, long-wavelength anomalies that should result from the geologic structures within the disturbed zone. It did indicate the degree and character of karst development within the surveyed area.

Bartel, L.C. 1989. *Results from Electromagnetic Surface Surveys to Characterize the Culebra Aquifer at the WIPP Site*. SAND87-1246. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The hydrologic character of the aquifer contained within the Culebra Dolomite Member of the Rustler Formation is being studied. The hydrology studies suggest that permeable portions of this aquifer may be in the form of a strip (or strips) that cannot be described by a uniform (horizontal or radial) flow model. Electromagnetic surface geophysical surveys were conducted over an area south of the Waste Isolation Pilot Plant (WIPP) facility to provide information on aquifer boundaries, zones of high transmissivity, etc. for the two-dimensional (2-D) and three-dimensional (3-D) fluid flow modeling. Approximately 20 line km of controlled-source audiofrequency magnetotelluric (CSAMT) data were acquired covering an area of approximately 12.6 km². A new, time-slice data analysis scheme, described briefly in this report, was applied to the data. From the time-slice analysis of the data, interpreted resistivities at various depth intervals are determined. The interpreted resistivities at a depth interval appropriate for the aquifer under study, calibrated using measured transmissivities at various well locations within the area, are used to determine an inferred transmissivity of the Culebra aquifer over the 12.6 km². From the analysis of the inferred-transmissivity results, the aquifer shows a north-south trending high-transmissivity zone connecting wells DOE-1 and H-11 in agreement with the hydrology tests. In general the high-transmissivity zone trends northeast between wells DOE-1 and H-15, trends north-south between well DOE-1 and a point east of P-17, encompassing well H-11, and trends to the southwest between wells P-17 and H-12. The analysis of the inferred-transmissivity results also shows wells H-3, H-15, and P-17 to be in an area of lower transmissivity, and wells H-4, H-12, H-14, Cabin Baby, WIPP-21, and ERDA-9 appear to be in an area of low transmissivity. There does not appear to be a high-transmissivity zone that trends from DOE-1 toward the northwest and the WIPP Facility. Combining the CSAMT resistivity data and the measured transmissivities at the various well locations gives a good overall picture of the transmissivity in areas where no well data exist.

Basler, J.A. 1983. *Instrumentation Used for Hydraulic Testing of Potential Water-Bearing Formations at the Waste Isolation Pilot Plant Site in Southeastern New Mexico*. Open-File Report 83-144. Albuquerque, NM: US Geological Survey.

ABSTRACT: Requirements for testing hydrologic test wells at the proposed Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM, necessitated the use of inflatable formation packers and pressure transducers. Observations during drilling and initial development indicated small formation yields that would require considerable test times by conventional open-casing methods. A pressure-monitoring system was assembled for performance evaluation utilizing commercially available components. Formation pressures were monitored with a 1/4-in.-diameter steel tube extending through the inflation element, which permitted sensing formation pressures in isolated test zones. Surface components of the monitoring system provided AC transducer excitation, signal conditioning for recording directly in engineering units, and both analog and digital recording. Continuous surface monitoring of formation pressures provided a means of determining test status and projecting completion times during any phase of testing. Maximum portability was afforded by battery operation with all surface components mounted in a small self-contained trailer.

The transducer system was successfully used for monitoring recovery from bailing, slug-injection tests, displacement tests, pressure-pulse tests, and pumping tests. Modification of the transducer assembly for use with the feed-through packer enabled monitoring of shut-in tests, slug tests, and pressure-pulse tests. The monitoring system permitted formation testing to determine transmissivities ranging from 1×10^{-6} ft²/day to 100 ft²/day.

BDM Corporation. 1978. *Consequence Assessment of Radionuclide Release from the WIPP Repository to the Environment*. BDM-TAC-78497-TR. Albuquerque, NM: BDM Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A computer program (CAPER: the Consequence Assessment Program for Exposure to Radionuclides) is being designed to combine pathway and dosimetry models to follow radionuclides from their release into the biosphere through the environment to uptake by, and dose to, man. An interim set of programs and routines to provide interfaces between pathway and dosimetry models has been used to produce consequence results for the Waste Isolation Pilot Plant (WIPP) until CAPER is operational. The programs and routines are generally explained, and tables of variables and sample output have been provided. Release mechanisms used for the examples were breach of the repository by water with transport through water-bearing units to the Pecos River at Malaga Bend and exploratory drilling into the repository. DWP

Beane, R.E., and C.J. Popp. 1975. *Chemical, Mineralogical, and Thermogravimetric Analyses of Selected Core Samples from Carlsbad, New Mexico*. Socorro, NM: New Mexico Institute of Mining and Technology. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Core samples from boreholes AEC-7 and AEC-8, located east of Carlsbad, NM, were analyzed for major elements, water insoluble fractions, and weight loss from heating at temperatures to 500°C. Water soluble minerals and sulfates form the bulk of the rock. Most of the insolubles fall chemically within the field defined by magnesium chlorite - potassium feldspar - talc, an assemblage recognized in evaporites that have undergone mild diagenesis. Other phases calculated to occur are mixed-layer illite-montmorillonite, quartz, and iron oxide. Differential thermal analysis and thermogravimetric analysis were used to analyze weight loss on heating. More than half of the samples showed weight losses less than 0.5%; a few samples ranged from 2 to 7 weight % fluid loss. There is little or no trend to weight loss with depth. Some zones show very little weight loss on heating and show good potential for radioactive waste disposal horizons. DWP

Beauheim, R.L. 1986. *Hydraulic-Test Interpretations for Well DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site*. SAND86-1364. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Eleven different zones were tested in Well DOE-2 in five phases of testing between 1984 and 1986. Testing techniques included a constant-head, borehole-infiltration test, drill-stem tests, slug tests, pressure-pulse tests, and multiwell pumping tests. Four of the zones tested—the lower Dewey Lake Red Beds, the Tamarisk Member of the Rustler Formation, the lower unnamed member of the Rustler Formation and Rustler/Salado contact, and the entire Salado Formation—had permeabilities too low to measure with the equipment and test techniques used. The other zones had permeabilities ranging over six orders of magnitude. No saturated strata were encountered above the Rustler Formation, although parts of the middle Dewey Lake Red Beds appear to have appreciable permeability.

In the Rustler Formation, the Culebra Dolomite Member is the most permeable unit, having a transmissivity of ~90 ft²/day. The Culebra behaves hydraulically as a double-porosity system, with the major permeability provided by fractures and the major storage provided by matrix porosity. The Culebra at DOE-2 is well connected hydraulically to the Culebra at Wells H-6b and WIPP-13 to the west, probably by interconnected fractures. Response times between these wells are very short (<1 day/10,000 ft). The Culebra does not appear to be as fractured to the south at Wells WIPP-12 and -18, or to the east at Well H-5b, as indicated by delayed, low-magnitude (or nonexistent) responses to DOE-2 pumping, and by low permeabilities interpreted from other tests conducted at those wells. The other Rustler members at DOE-2, which are not known to be fractured and do not display hydraulic responses typical of fractured (or double-porosity) media, have permeabilities three to four orders of magnitude lower than that of the Culebra. Hydraulic heads decrease through the Rustler with increasing

depth. This implies that the Tamarisk, and indirectly the Magenta and Forty-niner, could act as a source of recharge for the Culebra.

In the Salado Formation, the interval including Marker Beds 138 and 139 and the Waste Isolation Pilot Plant (WIPP) Facility horizon has an extremely low average permeability ($<0.3 \mu\text{d}$), and showed no evidence over about 2 days of testing of containing high-pressure sources of either brine or gas.

In the Bell Canyon Formation, the Hays sandstone was the most permeable unit tested, having an average permeability of about 2.4 millidarcies (0.55 ft/day). The Olds and Ramsey sandstones, overlying the Hays, have permeabilities almost two orders of magnitude lower. Hydraulic heads in the Bell Canyon sandstones could not be quantified precisely enough to define vertical gradients within the Bell Canyon.

In freshwater terms, the observed Bell Canyon head is higher than the hydraulic head of the Culebra Dolomite. If the Bell Canyon and Culebra were connected by an open borehole, however, salt dissolution in the Salado section would increase the specific gravity of the Bell Canyon fluid so that, at the elevation of the Culebra, the Culebra head would be higher than that of the Bell Canyon. In this event, the flow direction would be downwards from the Culebra into the Bell Canyon.

Beauheim, R.L. 1987a. *Analysis of Pumping Tests of the Culebra Dolomite Conducted At the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site*. SAND86-2311. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Two pumping tests were conducted in the Culebra Dolomite Member of the Rustler Formation at the H-3 hydropad at the Waste Isolation Pilot Plant (WIPP) Site. The first test was in 1984, with well H-3b3 pumped for 14 days at an average rate of 4 gal/min. The second test, the H-3 multipad test, was in late 1985 and early 1986, with well H-3b2 pumped for 62 days at an average rate of 4.8 gal/min. Both tests provided information on the hydraulic properties of the Culebra at the H-3 hydropad. The second test provided information on average Culebra hydraulic properties on a much larger scale; responses were observed up to 8000 ft from the pumping well.

The interpretation of these tests had three principal objectives. The first was to determine the most appropriate conceptualization of the nature of the Culebra flow system around the H-3 hydropad. The pumping well responses during the H-3 tests appear to be those of wells completed in a double-porosity medium with unrestricted interporosity flow. In such a system, fractures provide the bulk of the permeability, while matrix pores provide the majority of the storage capacity. The importance of fracture flow is indicated by the speed with which the observation wells on the H-3 hydropad respond to pumping and the nearly identical behaviors of these wells and the pumping well. The similarity between pumping- and observation-well behavior on the H-3 hydropad is so pronounced that the responses of all three wells on the hydropad can be interpreted only by using pumping-well analytical techniques, not observation-well analytical techniques. H-3b1 and H-3b3, in particular, appear to be very well connected by fractures.

The second objective was to quantify the hydraulic properties of the Culebra in the vicinity of the H-3 hydropad. The total-system (fractures plus matrix) transmissivity of the Culebra derived from the first test is $2.9 \text{ ft}^2/\text{day}$; that from the second test is $1.7 \text{ ft}^2/\text{day}$. The lower value derived from the second test probably represents lower transmissivity (lower fracture connectivity) at H-3b2 than at H-3b3, and/or lower average transmissivity of the volume of Culebra stressed in the multipad test as opposed to the smaller volume stressed in the first test. The fracture-to-total-system storativity ratios derived from the various analyses range from 0.03 to 0.25, indicating a relatively high degree of storage within the fractures. The highest

storativity ratios were consistently found at H-3b1. Wellbore skin values are highly negative, indicating direct wellbore connection with fractures.

The third objective was to quantify the average hydraulic properties of the Culebra between the H-3 hydropad and more-distant observation wells. Meeting this objective was complicated by the effects of an apparent increase in groundwater leakage from the Culebra into the Waste Handling Shaft on the data from wells near that shaft, and by water level/pressure trends already existing at many of the observation wells when the multipad test began. Between H-3 and wells DOE-1 and H-11 to the southeast, the average apparent Culebra transmissivity is between 5.5 and 13 ft²/day, and the apparent storativity is between 6.6×10^{-6} and 1.0×10^{-6} . The rapid responses observed at DOE-1 and H-11 during the multipad test, and the associated relatively high transmissivities, indicate a preferential hydraulic connection, probably related to fractures, between H-3 and the southeast portion of the WIPP Site.

Between H-3 and wells H-1 and H-2 to the north-northwest, the apparent transmissivity is between 0.46 and 2.5 ft²/day, and the apparent storativity is between 2.7×10^{-6} and 4.5×10^{-6} . If the possible shaft-leakage effects are ignored, the apparent transmissivity between H-3 and wells WIPP-19, -21, and -22 to the north is between 1.1 and 2.9 ft²/day, and the apparent storativity is between 9.0×10^{-6} and 2.9×10^{-6} . If shaft leakage did, as is thought, affect the responses observed at WIPP-19, -21, and -22, then the transmissivity values listed above are not representative. The wells to the north of H-3 are not so well connected hydraulically to H-3 as are DOE-1 and H-11; they provide no indications that groundwater flow occurs primarily through fractures.

The interpretations presented in this report represent an analytical approach to the understanding of large-scale tests. In an aquifer with considerable areal heterogeneity, an analytical approach has significant limitations. Calculated transmissivities and storativities are only "apparent" values, representing the average response of large volumes of aquifer to a stress imposed at a certain location. These interpretations are most useful in qualitatively defining areas of "higher" and "lower" transmissivity. Quantitative evaluation/simulation of heterogeneous systems on a large scale is best attempted with numerical models, an effort now under way.

Beauheim, R.L. 1987b. *Interpretations of Single-Well Hydraulic Tests Conducted At and Near the Waste Isolation Pilot Plant (WIPP) Site, 1983-1987*. SAND87-0039. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Both single-well and multiple-well hydraulic tests have been performed in wells at and near the WIPP site as part of the site hydrogeologic-characterization program. The single-well tests conducted from 1983 to 1987 in 23 wells are the subject of this report. The stratigraphic horizons tested include the upper Castile Formation; the Salado Formation; the unnamed, Culebra, Tamarisk, Magenta, and Forty-niner Members of the Rustler Formation; the Dewey Lake Red Beds; and Cenozoic alluvium. Tests were also performed to assess the integrity of a borehole plug isolating a pressurized brine reservoir in the Anhydrite III unit of the Castile Formation. The types of tests performed included drillstem tests (DSTs), rising-head slug tests, falling-head slug tests, pulse tests, and pumping tests.

The Castile and Salado testing was performed at well WIPP-12 to try to define the source of high pressures measured at the WIPP-12 wellhead between 1980 and 1985. The tests of the plug above the Castile brine reservoir indicated that the plug may transmit pressure, but if so, the apparent surface pressure from the underlying brine reservoir is significantly lower than the pressure measured at the wellhead. The remainder of the upper Castile did not show a pressure response differentiable from that of the plug. All attempts at testing the Salado in WIPP-12 using a straddle-packer DST tool failed because of an inability to locate good packer seats. Four attempts to test large sections of the Salado using a single-packer DST tool and a

bridge plug were successful. All zones tested showed pressure buildups, but none showed a clear trend to positive surface pressures. The results of the WIPP-12 testing indicate that the source of the observed high pressures is within the Salado Formation rather than within the upper Castile Formation and that this source must have a very low flow capacity and can only create high pressures in a well shut in over a period of days to weeks.

DSTs performed on the lower siltstone portion of the unnamed lower member of the Rustler Formation at H-16 indicated a transmissivity for the siltstone of about 2.4×10^{-4} ft²/day. The formation pressure of the siltstone is higher than that of the overlying Culebra at H-16 (compensated for the elevation difference), indicating the potential for vertical leakage upward into the Culebra. However, the top of the tested interval is separated from the Culebra by over 50 ft of claystone, halite, and gypsum.

The Culebra Dolomite Member of the Rustler Formation was tested in 22 wells. In 12 of these wells (H-4c, H-12, WIPP-12, WIPP-18, WIPP-19, WIPP-21, WIPP-22, WIPP-30, P-15, P-17, ERDA-9, and Cabin Baby-1), falling-head slug tests were the only tests performed. Both falling-head and rising-head slug tests were performed in H-1, and only a rising-head slug test was performed in P-18. DSTs were performed in conjunction with rising-head slug tests in wells H-14, H-15, H-16, H-17, and H-18. At all of these wells except H-18, the indicated transmissivities were 1 ft²/day or less and single-porosity models fit the data well. At H-18, the Culebra has a transmissivity of about 2 ft²/day. The apparent single-porosity behavior of the Culebra at H-18 may be due to the small spatial scale of the tests rather than to the intrinsic nature of the Culebra at that location. Pumping tests were performed in the other 3 Culebra wells. The Culebra appears to behave hydraulically like a double-porosity medium at wells H-8b and DOE-1, where transmissivities are 8.2 and 11 ft²/day, respectively. The Culebra transmissivity is highest, 43 ft²/day, at the Engle well. No double-porosity behavior was apparent in the Engle drawdown data, but the observed single-porosity behavior may be related more to wellbore and near-wellbore conditions than to the true nature of the Culebra at that location.

The claystone portion of the Tamarisk Member of the Rustler Formation was tested in wells H-14 and H-16. At H-14, the pressure in the claystone failed to stabilize in three days of shut-in testing, leading to the conclusion that the transmissivity of the claystone is too low to measure in tests performed on the time scale of days. Similar behavior at H-16 led to the abandonment of testing at that location as well.

The Magenta Dolomite Member of the Rustler Formation was tested in wells H-14 and H-16. At H-14, examination of the pressure response during DSTs revealed that the Magenta had taken on a significant overpressure skin during drilling and Tamarisk-testing activities. Overpressure-skin effects were less pronounced during the drillstem and rising-head slug tests performed on the Magenta at H-16. The transmissivity of the Magenta at H-14 is about 5.5×10^{-3} ft²/day, while at H-16 it is about 2.7×10^{-2} ft²/day. The static formation pressures calculated for the Magenta at H-14 and H-16 are higher than those of the other Rustler members.

The Forty-niner Member of the Rustler Formation was tested in wells H-14 and H-16. Two portions of the Forty-niner were tested at H-14: the medial claystone and the upper anhydrite. DSTs and a rising-head slug test were performed on the claystone, indicating a transmissivity of about 7×10^{-2} ft²/day. A buildup test of the Forty-niner anhydrite revealed a transmissivity too low to measure on a time scale of days. A pulse test, DSTs, and a rising-head slug test of the Forty-niner clay at H-16 indicated a transmissivity of about 5.3×10^{-3} ft²/day. Formation pressures estimated for the Forty-niner at H-14 and H-16 are lower than those calculated for the Magenta (compensated for the elevation differences), indicating that water cannot be moving downwards from the Forty-niner to the Magenta at these locations.

The lower portion of the Dewey Lake Red Beds, tested only at well H-14, has a transmissivity lower than could be measured in a few days' time. No information was obtained pertaining to the presence or absence of a water table in the Dewey Lake Red Beds at H-14.

The hydraulic properties of Cenozoic alluvium were investigated in a pumping test performed at the Carper well. The alluvium appears to be under water-table conditions at that location. An estimated 120 ft of alluvium were tested, with an estimated transmissivity of 55 ft²/day.

The database on the transmissivity of the Culebra dolomite has increased considerably since 1983. At that time, values of Culebra transmissivity were reported from 20 locations. This report and other recent reports have added values from 18 new locations, and have significantly revised the estimated transmissivities reported for several of the original 20 locations. In general, locations where the Culebra is fractured, exhibits double-porosity hydraulic behavior, and has a transmissivity greater than 1 ft²/day are usually, but not always, correlated with the absence of halite in the unnamed member beneath the Culebra. This observation has led to a hypothesis that the dissolution of halite from the unnamed member causes subsidence and fracturing of the Culebra. This hypothesis is incomplete, however, because relatively high transmissivities have been measured at DOE-1 and H-11 where halite is still present beneath the Culebra, and low transmissivity has been measured at WIPP-30 where halite is absent beneath the Culebra.

Recent measurements of the hydraulic heads of the Rustler members confirm earlier observations that over most of the WIPP site, vertical hydraulic gradients within the Rustler are upward from the unnamed lower member to the Culebra, and downward from the Magenta to the Culebra. New data on hydraulic heads of the Forty-niner claystone show that present hydraulic gradients, are upwards from the Magenta to the Forty-niner, effectively preventing precipitation at the surface at the WIPP site from recharging the Magenta or deeper Rustler members.

Beauhelm, R.L. 1987c. *Interpretation of the WIPP-13 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site.* SAND87-2456. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A large-scale pumping test of the Culebra Dolomite Member of the Rustler Formation was performed in early 1987 at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. This test (the WIPP-13 or northern) multipad test, complemented the H-3 (or southern) multipad test (conducted in late 1985 and early 1986) by creating a hydraulic stress that could be measured over the northern portion of the WIPP Site. The test consisted of pumping well WIPP-13 at a rate of 30 gpm for 36 days and monitoring drawdown and recovery responses in 17 observation wells and one WIPP shaft. Responses were observed in 14 of these wells, including one well 20,550 ft from WIPP-13 and in the WIPP Exhaust Shaft. Several of these wells had also responded during the H-3 multipad test.

Individual well tests at locations around the WIPP Site have demonstrated that the Culebra is a heterogeneous, water-bearing unit. The responses measured at observation wells to pumping tests in heterogeneous systems cannot be rigorously interpreted using standard analytical (as opposed to numerical) techniques developed for tests in homogeneous, porous media. Application of analytical techniques to data from heterogeneous media results in evaluations of average hydraulic properties between pumping and observation wells that are nonunique in the sense that they are representative only of the responses observed when a hydraulic stress is imposed at a certain location. These "apparent" hydraulic properties do, however, provide a qualitative understanding of the nature and distribution of both hydraulic properties and heterogeneities or boundaries within the tested area.

The interpretations of the responses at the pumping and observation wells are consistent with the following conceptualization: The Culebra is a fractured, double-porosity system around WIPP-13, H-6, and DOE-2, with relatively high transmissivity ($\sim 70 \text{ ft}^2/\text{day}$) and relatively low storativity (5×10^{-6} to 8×10^{-6}). This system appears to extend further to the north toward WIPP-30, although WIPP-30 itself lies in a lower transmissivity zone. The apparent transmissivity between WIPP-13 and observation wells toward the center of the WIPP Site to the south and east, where fracturing in the Culebra decreases, decreases to 16 to $28 \text{ ft}^2/\text{day}$, and apparent storativity increases to 3.6×10^{-5} to 5.5×10^{-5} . To the west toward Nash Draw, the apparent transmissivity increases to 265 to $650 \text{ ft}^2/\text{day}$, reflecting increased fracturing in that direction, while the apparent storativity increases to 5.2×10^{-5} to 6.4×10^{-5} .

The analyses of the responses measured at observation wells to the WIPP-13 multipad pumping test provide a qualitative conceptualization of three distinct domains within a heterogeneous portion of the Culebra north of the center of the WIPP Site. This conceptualization is being refined by using numerical-modeling techniques to simulate the WIPP-13 multipad test and other tests at the WIPP Site in an attempt to define the distribution of hydraulic properties that will reproduce the responses observed.

Beauhelm, R.L. 1988a. "Scale Effects in Well Testing in Fractured Media," *Fourth Canadian/American Conference on Hydrogeology, Fluid Flow, Heat Transfer and Mass Transport in Fractured Rocks, Banff, Canada, June 21-24, 1988*. Eds. B. Hitchon and S. Bachu. SAND87-1955C. Dublin, OH: National Water Well Association. Vol. 4, 152-159.

ABSTRACT: The hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico has centered on the Culebra Dolomite, a locally fractured unit exhibiting double-porosity behavior. Extensive well testing has been performed in the Culebra at a number of scales: single-well drillstem and slug tests, single-well pumping tests, short-term (1-10 days) pumping tests involving observation wells up to 140 ft away, and long-term (30-60 days) pumping tests involving observation wells at distances of up to 4 mi. Each scale of tests provides different and complementary types of information on the interactions between the fractures and the porous matrix and on the degree and continuity of fracturing. Case histories of tests performed at different scales provide examples of the concepts involved and the quantitative and qualitative results obtainable.

Small-scale (drillstem and slug) tests are most sensitive to the fractures in direct connection with the wellbore and provide the least opportunity for observable pressure equilibrium between fractures and matrix. These tests may indicate a transmissivity different from that obtained from larger scale tests. As the scale of the tests increases, the matrix participates more fully in the hydraulic response observed. Single-well pumping tests provide a good estimation of the double-porosity parameters affecting pressure responses on a local scale and may reveal the existence of fracture discontinuities. Short-term pumping tests with relatively close observation wells provide information on the spatial scale over which double-porosity behavior remains distinguishable from single-porosity behavior, as well as information on fracture discontinuities. Finally, long-term pumping tests with distant observation wells illustrate the regional-scale heterogeneous, single-porosity behavior of the system.

Beauhelm, R.L. 1988b. "The Role of Pumping Tests in Characterizing Fracture Properties and Distribution in the Culebra Dolomite at the WIPP Site," *EOS Transactions, American Geophysical Union*. SAND88-2443A. Vol. 69, no. 44, 1177. (Abstract Only).

ABSTRACT: For the past ten years, the hydrogeologic characterization of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico has centered on the Culebra Dolomite, the most transmissive water-bearing unit above the repository horizon. The Culebra is locally

fractured and is a potential radionuclide transport path to the accessible environment in the event of a repository breach. A variety of hydraulic and conservative-tracer tests has been performed in the Culebra to determine the extent to which fractures control flow and transport on different scales and to characterize the properties and distribution of fractures. This paper discusses the application of pumping tests to the characterization of the Culebra, while the accompanying paper by Pickens et al. discusses the application of tracer tests.

Pumping tests in fractured systems can provide a variety of types of information depending on the distribution of observation wells and the scale of testing. Thirty pumping tests have been performed at twenty locations in the Culebra. Single-well pumping tests provide good estimates of the degree of fracturing and resulting double-porosity parameters affecting pressure responses on a local scale, and often reveal the existence of discontinuities in the extent of fracturing, which appear as hydraulic boundaries. Short-term pumping tests with relatively close observation wells (within 43 m) provide information on the spatial scale over which double-porosity behavior remains distinguishable from single-porosity behavior, which relates to fracture density (or matrix-block size). Qualitatively different behaviors of observation wells in different directions from the pumping wells indicate preferential directions of fracturing. A series of spatially overlapping long-term pumping tests with distant observation wells (up to 6 km away) has illustrated the regional-scale heterogeneous, single-porosity behavior of the Culebra. Qualitatively different behaviors of observation wells with different orientations relative to the pumping wells provide information on regional fracture distributions.

Integration of the interpretations of the pumping-test data with the information on fracture characteristics derived from tracer tests has shown that fractures are highly significant in controlling flow and transport on the local scale. Although both fractured and unfractured portions of the Culebra are present within the WIPP land-withdrawal area, numerical modeling has shown that flow and transport behavior on a regional scale approaches that of a porous medium.

ANNOTATION: The paper referred to by Beauheim is included in the bibliography under Pickens et al. (1988).

Beauheim, R.L. 1989. *Interpretation of H-11B4 Hydraulic Tests and the H-11 Multipad Pumping Test of the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site.* SAND89-0536. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Drillstem tests, slug tests, a small-scale pumping test, and a large-scale pumping test of the Culebra Dolomite Member of the Rustler Formation were performed in 1988 at the H-11 hydropad at the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The drillstem, slug, and small-scale pumping tests were conducted in well H-11b4 to evaluate well and aquifer properties in preparation for a tracer test. The large-scale pumping test, known as the H-11 multipad test, was performed by pumping well H-11b1 in the southern part of the WIPP site at a rate of six gpm for 63 days and monitoring drawdown and recovery responses in three other wells on the H-11 hydropad and at 11 observation wells within a three-mile radius. Responses were observed in 10 of these distant wells. The H-11 multipad pumping test complemented the H-3 and WIPP-13 multipad pumping tests conducted in the central and northern portions of the WIPP site in late 1985 and early 1987, respectively.

Individual well tests at various locations around the WIPP site have demonstrated that the Culebra is a laterally heterogeneous water-bearing unit. The responses measured at observation wells to pumping tests in heterogeneous systems cannot be rigorously interpreted using standard analytical (as opposed to numerical) techniques developed for tests in homogeneous porous media. Application of analytical techniques to data from tests of heterogeneous media

results in evaluations of average hydraulic properties between pumping and observation wells that are nonunique in the sense that they are representative only of the responses observed when a hydraulic stress is imposed at a certain location. These "apparent" hydraulic properties do, however, provide a qualitative understanding of the nature and distribution of both hydraulic properties and heterogeneities or hydraulic boundaries within the tested area.

The interpretations of the responses at the test and observation wells provided the following information: The Culebra is a fractured, double-porosity system at H-11 with a transmissivity between 27 and 43 ft²/day and a storativity between 3.4×10^{-5} and 1.5×10^{-4} . Drawdown during the multipad test appeared to be largely concentrated to the north and south of H-11; wells to the east and west showed relatively low-magnitude responses. The rapid and high-magnitude responses observed at DOE-1, H-3b2, and H-15 during the multipad test are believed to reflect the presence of a fracture network extending to the north from H-11. Numerical simulations indicate that the fracture network also extends south of H-11, but no wells are currently situated within it.

Double-porosity hydraulic behavior was observed at DOE-1 during the multipad test, and at both DOE-1 and H-3b2 during other pumping tests performed at those locations. The fractures appear to continue past DOE-1 to the north toward H-15, although H-15 itself lies in a lower transmissivity, apparently single-porosity zone. Apparent transmissivities in the region north of H-11 range from 7.1 to 9.0 ft²/day and apparent storativities range from 2.4×10^{-6} to 8.4×10^{-6} . Apparent transmissivities between H-11 and observation wells to the west, southwest, and southeast, where fracturing in the Culebra decreases and single-porosity hydraulic behavior is observed, range from 6.0 to 21.0 ft²/day and apparent storativities range from 1.8×10^{-5} to 6.5×10^{-5} . Interpretation of the responses to the multipad test observed at the western and southern wells was complicated by an anomalous and widespread rise in water levels of unknown origin.

Thus, the analyses of the responses measured at observation wells to the H-11 multipad pumping test are consistent with a conceptualization of two distinct domains within a heterogeneous portion of the Culebra south of the center of the WIPP site: a fractured region having low storativity extending to the north and south from H-11, and a relatively unfractured region west, southwest, and southeast of H-11 having higher storativity. This conceptualization is being refined using numerical-modeling techniques to simulate the H-11 multipad test and other tests at the WIPP site in an attempt to define a distribution of hydraulic properties that will reproduce the responses observed.

Beauheim, R.L., and A.M. LaVenue. 1991. "Use of Large-Scale Transient Stresses and a Coupled Adjoint-Sensitivity/Kriging Approach to Calibrate a Groundwater-Flow Model at the WIPP Site," *GEOTAL 90, Stockholm, Sweden, May 14-17, 1990*. SAND89-2373C. Paris, France: Organisation for Economic Co-Operation and Development. 369-376.

ABSTRACT: Performance assessment calculations for the Waste Isolation Pilot Plant (WIPP) require a reliable groundwater-flow model for the Culebra Dolomite, the most transmissive water-bearing unit overlying the repository horizon. Since 1976, 58 wells have been completed to the Culebra Dolomite to provide data on hydraulic head, transmissivity, and storativity. Testing at these wells has indicated that the Culebra is a locally fractured medium exhibiting double-porosity hydraulic behavior. Variations in the degree of fracturing of the Culebra in the vicinity of the WIPP Site have resulted in a range of transmissivities spanning six orders of magnitude. This high degree of heterogeneity has complicated flow-model calibration by increasing the uncertainty in transmissivity estimates between measurement points. Initial modeling efforts concentrated on obtaining a flow model calibrated to estimated steady-state conditions. When that model was used to try to simulate transient hydraulic stresses, however, the calibration was found to be inadequate. Manual efforts to try to improve the transient calibration had limited success.

A coupled adjoint-sensitivity/kriging methodology was developed to facilitate transient calibration. Kriging is used to define an initial transmissivity distribution for the model. Adjoint-sensitivity techniques are then used to identify regions within the model where transmissivity changes will reduce a cumulative least-squares performance measure consisting of the difference between model-calculated and observed hydraulic heads. "Pilot points" with specified transmissivities are then located in the most sensitive regions. The pilot-point transmissivities are included in the transmissivity data base for kriging to generate a revised transmissivity field. This process is repeated until a satisfactory calibration is obtained. The approach allows for the specification of both steady-state and transient performance measures to permit simultaneous calibration to steady-state and transient head data.

This approach has been successfully applied to the calibration of the Culebra groundwater flow model. The Culebra model consists of a single layer of 28 x 48 grid blocks representing an area extending 21.3 x 30.6 km, roughly centered on the 41.5 km² WIPP Site. A key factor permitting the delineation of hydraulically significant fracturing using the coupled adjoint-sensitivity/kriging calibration approach was the existence and documentation of large-scale transient hydraulic stresses on the Culebra. These stresses were caused by construction of four shafts at the WIPP Site and by three large-scale pumping tests lasting one to two months each. The pumping tests were performed at different locations around the WIPP Site, and were designed to have spatially overlapping fields of influence. Each test produced observable hydraulic responses over an area of 10 to 20 km². Calibration to these tests provided information on the distribution of fracturing that would never have been obtained from steady-state calibration alone and significantly changed the transmissivity field used for solute-transport modeling.

This study has shown that coupling adjoint-sensitivity techniques with kriging results in a highly efficient approach to combined steady-state and transient model calibration and that calibration of a regional-scale model requires calibration to regional-scale transient stresses. Steady-state calibration or transient calibration to non-overlapping local-scale stresses cannot provide a reliable regional-scale model for performance-assessment calculations.

Beauheim, R.L., and J.F. Pickens. 1985. "Effects of Borehole History on Well-Test Analysis," *EOS Transactions, American Geophysical Union*, SAND85-2008A. Vol. 66, no. 46, 890. (Abstract Only).

ABSTRACT: The behavior of water-bearing units during hydraulic tests may be strongly influenced by the pressure and thermal history imparted to the borehole prior to testing. Drilling and well-completion activities typically create disequilibrium between pressure and thermal conditions in the bore hole and those in the surrounding formations. As the overall system moves towards equilibrium, transient recovery conditions develop that can be mistaken for a formation's natural hydraulic response to a given test. The misperception of these transient conditions can lead to erroneous estimates of formation hydraulic properties and static pressures. These problems can be most severe when testing low-permeability media under shut-in conditions. The effects of bore hole history may affect test data to varying degrees, depending on factors including the duration and magnitude of the disequilibrium, the length of time the system has been moving back towards equilibrium, and the hydraulic properties of the rock.

Tests performed in bore hole DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico illustrate the effects of bore hole history. Apparently anomalous pressure rises have been explained through consideration of the bore-hole thermal history. Reversals in pressure trends can be explained through a consideration of the pressure history of the bore hole.

Beauheim, R.L., and J.F. Pickens. 1986. "Applicability of the Pressure Derivative to Hydraulic-Test Analysis," *EOS Transactions, American Geophysical Union*, SAND86-0437A, Vol. 67, no. 16, 276. (Abstract Only).

ABSTRACT: Use of the pressure derivative in well-test interpretation has recently flourished in the petroleum industry. Pressure-derivative data (i.e., rate of pressure change with time) can provide significant information on the nature of the hydrogeologic system being tested. This contribution can be particularly important in single-well testing. The addition of pressure-derivative analysis can allow conclusive differentiation between single-porosity, double-porosity, and fractured systems, as well as determination of such parameters as distances to hydraulic boundaries. It can be particularly useful in identifying causes for data deviations from type curves or other pressure-response idealizations.

The utility of the pressure derivative is strongly dependent on the quality of the test data. Because pressure-derivative analysis is entirely dependent on the rate of pressure change, a high signal-to-noise ratio in the data is imperative. Pressure-derivative analysis is virtually impossible with data collected using hand-held devices, and many of the pressure-transducer systems marketed today also lack the necessary precision. Currently, the best data-acquisition systems use quartz-crystal transducers.

Beauheim, R.L., and G.J. Saulnier, Jr. 1989a. "Evaluation of Excavation Effects on Rock-Mass Permeability Around the Waste-Handling Shaft at the WIPP Site," *Proceedings of an NEA Workshop on Excavation Response in Geological Repositories for Radioactive Waste, Winnipeg, Manitoba, Canada, April 26-28, 1988*, SAND88-1092C. Paris, France: Organisation for Economic Co-Operation and Development. 427-439.

ABSTRACT: Pulse-injection permeability tests were performed in six subhorizontal boreholes drilled at four horizons in the Waste Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site to evaluate potential changes in permeability caused by stress relief around the shaft. The tests were performed using a triple-packer test tool capable of simultaneous isolation and pressure and temperature monitoring of three intervals within a borehole. The tests were designed to provide a "profile" of permeability with increasing distance from the shaft wall. All lithologies tested had very low hydraulic conductivities, with values ranging from 6×10^{-16} to 1×10^{-13} m/sec. No significant changes in permeability as a function of distance from the shaft wall were observed. Thus, if a zone of enhanced permeability caused by stress relief exists around the shaft, it is probably within the first 1-2 m of rock around the shaft that could not be tested using the available test-tool configuration. The testing revealed the presence of a depressurization zone around the shaft, apparently caused by drainage of fluid from the formations into the shaft.

Beauheim, R.L., and G.J. Saulnier, Jr. 1989b. "In-Situ Hydraulic Testing of Evaporites at the Waste Isolation Pilot Plant Site," *28th International Geological Congress, Abstracts, Washington, DC, July 9-19, 1989*, SAND88-2708A, Vol. 28, no. 1-107. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a research and development facility of the US Department of Energy (DOE) designed to demonstrate the safe disposal of transuranic wastes resulting from the United States' defense programs. The WIPP repository horizon lies 650 m below land surface in the bedded halite of the Permian Salado Formation in the Delaware Basin in southeastern New Mexico. Questions have arisen recently as to what amount of porosity in the backfilled waste-emplacement rooms might become saturated with brine before creep deformation of the surrounding halite host rock consolidates the backfill and closes off the remaining unsaturated porosity. To evaluate the potential for brine in the

Salado Formation to migrate into the repository and shafts during the backfill-consolidation process, which is expected to last 100 years or more, a program of hydraulic testing of the primarily evaporitic rock around the repository and shafts was initiated. Testing was performed in the WIPP Waste Handling Shaft in the summer of 1987, testing from the repository workings (the "underground") began in August 1988, and testing is planned to begin in the Air Intake Shaft in mid-1989.

The objectives of the testing program are to determine the extent of the hydrologic disturbed rock zone (DRZ) around the repository and shafts; evaluate the permeability of halite, anhydrite, and clay units of the Salado that could contribute brine to the underground openings; define the fluid-pressure distribution within the Salado near the WIPP Facility and shafts; define the continuity of saturation within the Salado; and determine whether the low-permeability evaporites beyond the DRZ behave hydraulically as saturated porous media subject to Darcy's law. In addition, tests in selected bore-hole intervals will be repeated after 2 and 5 years to evaluate time dependence in the evolution of the hydrologic DRZ and depressurized zones around the underground openings.

Tests are being conducted in 0.1-m diameter holes drilled or cored to depths of as much 10 m. In the shafts, one to three subhorizontal holes are drilled radially at each testing horizon. In the underground, as many as five holes are drilled at each testing location: vertically upward and downward, subhorizontal, and diagonally upward and downward. The holes are filled with brine as soon after they are drilled as possible. Guarded-packer systems are then installed to isolate different sections of the boreholes for testing. Each isolated interval is monitored with a pressure transducer and a thermocouple. Borehole-closure gages are included in the bottom-hole test intervals in the testing performed in the underground to allow discrimination between pressure rises caused by hole closure and those caused by fluid inflow. Data-acquisition systems controlled by microcomputers record all test data, and allow real-time data plotting and printing.

The pore pressure in the rock in the immediate vicinity of a borehole tends to decrease during and after drilling because of fluid drainage into the newly opened hole. Because of the extremely low hydraulic conductivities of the horizons tested to date ($K = 10^{-12}$ to 10^{-15} m/sec), recovery from this depressurization to predrilling pressures is slow. To accelerate the pressure recovery, the test tools are constructed to minimize the fluid volumes within the borehole test intervals. Small volumes of fluid are also injected under pressure to help increase the lowered fluid pressures in and around the boreholes to near the estimated predrilling pressure. Pulse injection and/or pulse-withdrawal tests are initiated after pressures have stabilized or have at least defined a consistent trend. Test analyses are performed using a well-test simulator that incorporates drilling and pretest pressure histories and provides estimates of transmissivity, storativity, and formation pressure.

Results to date from testing of the Salado in the Waste Handling Shaft indicate that the DRZ around the shaft is currently restricted to the first 1.6 m or less from the excavation. From 1.6 m to 12.7 m, hydraulic conductivities of 2×10^{-14} to 3×10^{-14} m/sec have been interpreted for halite, anhydrite, and polyhalite beds. Fluid pressures increase with distance from the shaft, reflecting drainage into the shaft since its construction in 1982.

In the WIPP underground, the DRZ also appears to be restricted at present (up to 5 years after construction) to the first few meters surrounding the excavation. Outside the DRZ, no indication of unsaturated conditions has been found. Test behaviors are consistent with those predicted from Darcy's law and other basic principles of flow through porous media, although significant heterogeneity has been observed. More detailed and recent findings will be presented at the Congress.

The results of this test program are being used to develop a detailed characterization of the hydraulic behavior of the evaporites surrounding the underground repository workings and shafts under both undisturbed and disturbed (by excavation) conditions. Data from this

program will be used in numerical modeling to assess the volume of brine likely to flow into the repository and shafts during backfill consolidation. The data will also be used in performance assessment modeling of the long-term behavior of the repository system.

Beauhelm, R.L., B.W. Hassinger, and J.A. Klalber. 1983. *Basic Data Report for Borehole Cabin Baby-1 Deepening and Hydrologic Testing, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico.* WTSD-TME-020. [Albuquerque, NM]: D'Appolonia Consulting Engineers, Inc. for Westinghouse Electric Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Borehole Cabin Baby-1 was originally drilled to a depth of 4159.0 ft below kelly bushing (8.0 ft above ground surface) in 1974 and 1975 as a "wildcat" hydrocarbon exploratory well. Control of the bore hole was given to the US Department of Energy (DOE) after it was found to be a "dry hole." Cabin Baby-1 was reentered, deepened, and hydrologically tested in August and September 1983. The well is located in Section 5, T23S, R31E, just outside the limit of WIPP Zone III, approximately 2.5 mi south of the Waste Isolation Pilot Plant (WIPP) exploratory shaft.

The deepening and testing of Cabin Baby-1 was undertaken to provide data on the hydrologic properties, including hydrostatic head potential of selected permeable zones in the Bell Canyon Formation; to provide representative fluid samples from selected permeable zones in the Bell Canyon Formation for determination of fluid composition and density; and to define further the stratigraphy of the upper Bell Canyon Formation at the Cabin Baby-1 location.

The bore hole was deepened from the previous total depth to a new depth of 4298.6 ft below kelly bushing by continuous coring. Field operations related to deepening and logging of the borehole began August 12, 1983 and were completed August 30, 1983. Hydrologic testing activities began August 30, 1983 and were completed September 29, 1983. Drill-stem tests were conducted in four zones in the Bell Canyon Formation, and one test of the Salado Formation was performed. Fluid samples were collected from the Hays and Olds sandstones of the Bell Canyon Formation.

Bechtel National, Inc. 1979a. *Soils Design Report - Volume I, Plant Site Near Surface Structures.* Document No. DR-22-V-01. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The soils design report presents the results of foundation studies for the surface structures at the Waste Isolation Pilot Plant (WIPP) located in southern New Mexico about 26 mi east of Carlsbad in eastern Eddy County. The results of studies for the access roads and railroad will be presented in Volume II of the soils design report.

To develop information for this report, a field exploration program, laboratory testing, and engineering analyses were performed during November 1978 through May 1979.

The logs of all borings and test pits, together with the results of all field and laboratory tests, are contained in the series of reports by Sergeant, Hauskins, and Beckwith. The soil test results are summarized in this report. DWP

ANNOTATION: The reports by Sergeant, Hauskins, and Beckwith are included in this bibliography.

Bechtel National, Inc. 1979b. *Soils Design Report - Volume II. Access Roads and Railroad.* Document No. DR-22-V-02. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Soil and foundation studies in the field and laboratory for access roads and an access railroad to the WIPP Site were conducted by Sergeant, Hauskins, and Beckwith; this report summarizes the results of the work. The access roads total about 17 mi of construction, 13 from the north and 4 from the south. The access railroad is about 6 mi long, extending from the existing spur to the west. The fieldwork was conducted in two phases: 9 shallow borings were drilled and sampled, and 48 test pits were excavated, sampled, and tested. Surface soils consist mostly of sand and silty sand with some outcrops of caliche. The shallow subsurface deposits consist of sand, caliche, and underlying Gatuña, Santa Rosa, or Dewey Lake Formations. No groundwater was encountered.

Laboratory work included classification tests, California Bearing Ratio (CBR), chemical tests, and triaxial tests. Fill will need to be compacted, but local materials meet requirements for fill, road subbase, and subballast for railroad. DWP

ANNOTATION: The work by Sergeant, Hauskins, and Beckwith, which is the background for this summary, is reported in this bibliography.

Bechtel National, Inc. 1979c. *Geologic Data and Hole History for Borehole WIPP-12.* Document No. 22-V-510-01. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: WIPP-12, located in the southeastern quarter of section 17, T22S, R31E, encountered the upper Castile Formation at a depth of 2778 ft below the surface. The drillhole encountered 3 ft of Mescalero caliche, 5 ft of Gatuña Formation, 142 ft of Santa Rosa Formation, 474 ft of Dewey Lake Red Beds, 326 ft of Rustler Formation, 1774 ft of Salado Formation, and 50 ft of Castile Formation. About 1042 ft of core were recovered. A suite of geophysical logs was run in the hole.

WIPP-12 was drilled to confirm a suspected anticlinal structure indicated by a seismic reflector anomaly; confirm continuity and attitude of bedding; determine lithology, stratigraphy, and structure to correlate with other drill holes; acquire core for laboratory testing; and examine hydrologic properties of core from suspected water-bearing zones. Core properties are reported in data tables. No conclusions are reported for structure or correlation. DWP

Bechtel National, Inc. 1979d. *Geologic Data for Borehole B-25.* Document No. 22-V-510-02. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: B-25, located in the southeast quarter of section 20, T22S, R31E, was drilled to determine the lithology and stratigraphy for geologic correlation and shaft design, to determine in situ permeability of selected horizons, and to acquire core for rock testing. The hole was continuously cored from 22.4 to 901.3 ft depth, and it was then reamed to a diameter of 6 1/4 in.

B-25 encountered 14 ft of overburden and Mescalero caliche, 20.7 ft of Gatuña Formation, 10.1 ft of Santa Rosa Formation, 488.2 ft of Dewey Lake Red Beds, 309.9 ft of Rustler Formation, and 58.9 ft of Salado Formation.

The Rustler/Salado contact, Culebra Dolomite, and Magenta Dolomite intervals were prepared and then tested for hydrologic characteristics. Units were isolated by packers and then swabbed until no more fluid was recovered. An electric tape was lowered into the hole to monitor fluid level recovery for an hour. A second, timed swab run was used to calculate transmissivity. The transmissivities calculated for these three zones, respectively, are 5×10^{-3} ft²/day, 1×10^{-2} ft²/day, and 7×10^{-4} ft²/day. These calculations indicate the relative transmissivities, but they may not accurately represent site conditions. DWP

Bechtel National, Inc. 1979e. *Geology Laboratory Results of Rock Testing*. Document No. 22-V-510-04. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Forty-two core samples and five hand samples from bore holes and test pits B-1, B-5, B-9, B-12, B-15, B-25, B-32, B-28, B-29, WIPP-12, and TP-4 were tested for various physical properties and mineralogy. The samples represented the Gatuña, Santa Rosa, Dewey Lake, Rustler, and Salado Formations. The tests included bulk specific gravity, porosity, absorption, unconfined compressive strength, modulus of elasticity and Poisson's ratio, sonic velocity, petrography, X-ray diffraction, spectrography, and wet-dry cycles. These data are reported without further analysis. DWP

Bell, D.R. 1984. *WIPP Hydropad Satellite Survey. Final Report*. Tucson, AZ: Hydro Geo Chem, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Wellheads in the vicinity of the Waste Isolation Pilot Plant (WIPP) and of hydrologic interest were surveyed in 1984 using satellite positioning and differential leveling. Two first order-class I horizontal reference points (BURRO, near Tucson, AZ; BETTIE, near Hobbs, NM) were used to provide corrections to satellite data for receivers located at survey points. Elevations determined by processed satellite positioning data resulted in a standard deviation from 0.14 to 0.29 m with an average of 0.216 m. Common points with the 1981 level survey by the National Geodetic Survey (NGS) yield apparently significant differences that cannot be resolved because of the differences in the basis of elevation and geoidal height corrections used by the two surveys. The standard deviation of elevation differences between the two types of surveys is similar to the average standard deviation for elevations determined by satellite positioning. The relative elevations of wellheads determined by satellite positioning appear to be accurate and within required parameters. DWP

Bell & Murphy and Associates. 1979. *Geophysical Investigation of the Waste Isolation Pilot Plant Eddy County, New Mexico*. Dallas, TX: Bell & Murphy and Associates. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: About 74 line mi of seismic reflection data were collected in 1978 within the sixteen square mi centered on the Waste Isolation Pilot Plant (WIPP) Site. Grant Geophysical Corporation recorded and processed the data; Bell and Murphy Associates provided quality assurance and interpreted the data. Milton Dobrin consulted on all phases.

The data were collected to prepare seismic structure contour maps of the Salado and Castile Formations, in particular, to ascertain geologic structures(s) affecting these horizons. The Cherry Canyon Formation was also mapped.

Vibrator patterns and geophone arrays were spaced at 110-ft intervals for data acquisition. Two short experimental lines, totalling about 2.2 mi, used 55 ft spacings. Geophone arrays consisted of a 6-arm fan of 36 geophones. The sweep frequency was from 100-25 Hz for 12 sec. A 12-fold stack was created.

Data quality varied due to equipment and field conditions. Refractions arrived at about the same time as reflections, complicating the process of muting and compositing shallow data. The data are generally considered fair. The Salado, Castile, and Cherry Canyon Formations, and the Cowden anhydrite member of the Salado Formation, are characterized by homoclinal dips to the east of about 100 to 125 ft/mi. The Castile reflectors could not be identified in the north-central four square mi of the survey area. Well logs indicate 200 to 500 ft of anhydrite is missing "... and was apparently replaced by salt. This lithologic change may be indicative of the cause of Castile reflection deterioration in this area." The geophysical data and well data available do not indicate faulting on the Castile Formation between ERDA-9 and WIPP-12.

DWP

Bentley, H.W. 1983. "Development and Testing of Groundwater Tracers at the Waste Isolation Pilot Plant (WIPP Site), New Mexico," *EOS Transactions, American Geophysical Union*, Vol. 64, no. 45, 714. (Abstract Only).

ABSTRACT: Thiocyanate and five fluorinated derivatives of benzoic acid have been used as groundwater tracers at selected locations in the Culebra Dolomite Member of the Permian Rustler Formation. The tracers, which are analyzed by high performance liquid chromatography at a sensitivity of about 10 $\mu\text{g/L}$, were selected because they were unlikely to exhibit sorption or biodegradation and because of their ease of handling and analysis.

Results indicate that perfluorobenzoate and trifluoromethylbenzoate are neither sorbed nor degraded. These results include a tracer test lasting more than a year, field tests designed to demonstrate non-sorptive behavior, and laboratory verification of non-biodegradation. Thiocyanate and o-, m-, and p-fluorobenzoate do show aerobic bacterial degradation, but have proved useful in the low-oxygen waters of the Culebra.

Beraun, R., and M.A. Molecke. 1987a. "Numerical Thermal Modeling of the WIPP In Situ Room A1 Simulated DIIW Experiments," *Waste Management 87, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 1-5, 1987*. Ed. R.G. Post. SAND87-0467C. Tucson, AZ: University of Arizona. Vol. 2, 245-253.

ABSTRACT: The intent of this paper is to present the results of transient thermal analyses performed to determine temperatures in the near- and far-field, in the vicinity of a defense high-level waste container and an emplacement drift. Three different drift/canister configurations were modeled: one containing nitrogen gas, another crushed salt, and the last bentonite/sand as a backfill material between the container and the bore-hole wall. The test containers are a nonreference overpack design, consisting of a 2.5-cm thick mild steel container either with or without a thin overwrap of TiCode-12. The thermal conductivity of the salt formation was assumed to be temperature dependent, while both the density and specific heat were assumed to be constant. The analyses were undertaken using a four node, bilinear, quadrilateral finite-element nonlinear heat transfer program, COYOTE, and a finite-difference thermal analyzer code, SINDA. Results presented include typical temporal and

spatial distributions of temperature. The near-field temperature results obtained from the numerical modeling compare well with measured experimental data.

Beraun, R., and M.A. Molecke. 1987b. *Thermal Analysis of the WIPP In Situ Room At DHLW Package Experiments*. SAND86-0681. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents the results of transient thermal analyses performed to determine temperatures in the near- and far-field vicinity of a defense high-level waste container and an emplacement drift. Three different drift/waste package configurations were modeled: one containing nitrogen gas, another crushed salt, and the last bentonite/sand as the backfill material between the container and the bore-hole wall. The thermal conductivity of the salt formation was assumed to be temperature dependent while both the density and specific heat were assumed to be constant. Analyses were undertaken using a four node, bilinear, quadrilateral finite-element nonlinear heat transfer program, COYOTE, and a finite-difference thermal analyzer code, SINDA. Typical temporal and spatial distributions of temperature are presented for each case. The temperature profiles and histories of the backfill material and host rock salt are used to assess their thermal behaviors and to guide future material test analyses. The near-field temperatures obtained from these thermal analyses are compared with measured experimental data.

Berry, H.A. 1989. *An Aerial Radiological Survey of the Waste Isolation Pilot Plant and Surrounding Area, Carlsbad, New Mexico*. AMO-8809; EGG-10617-1189. Las Vegas, NV: EG&G Energy Measurements, Inc.

ABSTRACT: An aerial radiological survey was conducted during the period 8 April to 19 April 1988 over a 404-square-km (156-square-mi) area covering the Waste Isolation Pilot Plant (WIPP) located near Carlsbad, NM, and the surrounding area. The survey was conducted at a nominal altitude of 91 m (300 ft) with a line spacing of 152 m (500 ft). A contour map of the terrestrial exposure rates plus the cosmic exposure rate extrapolated to 1 m above ground level was prepared and overlaid on an aerial photograph of the area. The average terrestrial exposure rates ranged from approximately 6.0 to 9.0 microrentgens per hour ($\mu\text{R/hr}$). Two areas of increased exposure rate were evident. Both areas indicated higher than normal concentrations of naturally occurring radionuclides. A machine-aided search of data for man-made sources of radiation indicated the presence of Cs-137 at the Gnome site, which was expected from previous survey work done in the area. No other sources of man-made radiation were found.

Bertram-Howery, S.G., and R.L. Hunter. 1989a. *Plans for Evaluation of the Waste Isolation Pilot Plant's Compliance with EPA Standards for Radioactive Waste Management and Disposal*. SAND88-2871. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Department of Energy (DOE) is actively pursuing the disposal of transuranic (TRU) waste in a geologic environment at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. The Waste Isolation Pilot Plant (WIPP) Project will assess compliance with the Environmental Protection Agency's (EPA's) *Environmental Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191)*. The Standard is divided into two subparts. Subpart A limits annual radiation doses to members of the public from waste management and storage operations at disposal facilities, and Subpart B limits cumulative releases of radioactive materials for 10,000 years, radiation doses to members of the public for 1000 years, and radioactive contamination of certain sources of groundwater for 1000 years, as a result of disposal of wastes. The WIPP Project

will assess compliance with Subpart A primarily by means of an extensive monitoring program. The Project will assess compliance with Subpart B primarily using the performance assessment techniques developed for the evaluation of the performance of high-level waste repositories. Compliance with the Assurance Requirements and the Ground Water Protection Requirements will be assessed using other techniques. The WIPP Project will be the first to evaluate the compliance of a mined geologic repository with the EPA Standard. Although Subpart B of the Standard was remanded to EPA by the United States Court of Appeals for the First Circuit, this paper discusses the Standard as first promulgated. Compliance plans for the WIPP will be revised as necessary in response to any changes in the Standard.

Bertram-Howery, S.G., and R.L. Hunter, eds. 1989b. *Preliminary Plan for Disposal-System Characterization and Long-Term Performance Evaluation of the Waste Isolation Pilot Plant*. SAND89-0178. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The US Department of Energy (DOE) is planning to dispose of transuranic wastes at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. Sandia National Laboratories (SNL) is responsible for evaluating the compliance of the WIPP with the Environmental Protection Agency's (EPA's) *Environmental Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191, Subpart B)*. This plan has been developed to present the issues that will be addressed before compliance can be evaluated. These issues examine the procedural requirements for evaluating compliance, which follow from the procedural nature of the Standard, and the technical requirements for further characterizing the behavior of the disposal system, including uncertainties, to support the compliance assessment. The plan briefly describes the activities that will be conducted prior to 1993 by SNL to characterize the WIPP disposal system's behavior and predict its performance.

Bertram-Howery, S.G., and P.N. Swift. 1990. *Status Report: Potential for Long-Term Isolation by the Waste Isolation Pilot Plant Disposal System*. SAND90-0616. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) must comply with Environmental Protection Agency (EPA) Regulation *40 CFR Part 191, Subpart B*, which sets environmental standards for radioactive waste disposal. The regulation, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes* (hereafter referred to as the Standard), was vacated in 1987 by a Federal Court of Appeals and is undergoing revision. By agreement with the State of New Mexico, the WIPP Project is evaluating compliance with the Standard as promulgated in 1985 until a new regulation is available.

This report summarizes the early-1990 status of Sandia National Laboratories' (SNL's) understanding of the Project's ability to achieve compliance. The report reviews the qualitative and quantitative requirements for compliance, and identifies unknowns complicating performance assessment. It discusses in relatively nontechnical terms the approaches to resolving those unknowns, and concludes that SNL has reasonable confidence that compliance is achievable with the Standard as first promulgated. This report is not a formal evaluation of compliance; available data and models are insufficient for a full-scale assessment, and *40 CFR Part 191* has not been reissued following remand. The first preliminary performance assessment report for the WIPP will be completed in December 1990.

Bertram-Howery, S.G., M.G. Marietta, D.R. Anderson, K.F. Brinster, L.S. Gomez, R.V. Guzowski, and R.P. Rechard. 1989. *Draft Forecast of the Final Report for the Comparison to 40 CFR Part 191, Subpart B, for the Waste Isolation Pilot Plant*. SAND88-1452. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The US Department of Energy (DOE) is planning to dispose of transuranic (TRU) wastes that have been generated by defense programs at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. The WIPP Project will assess compliance with the requirements of the United States Environmental Protection Agency's (EPA's) Standard, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191)*. Assessing compliance with the long-term performance criteria of Subpart B of the Standard is a cornerstone of successful implementation of a DOE TRU waste disposal system.

This report forecasts the planned 1992 document, *Comparison to 40 CFR, Part 191, Subpart B, for the Waste Isolation Pilot Plant (WIPP)*. It has the same format, with the same table of contents. The text is, where available, a preview for 1992. Where not yet available, the text is either preliminary or incomplete. DOE, as the implementing agency for the WIPP under the Standard, is responsible for determining whether the WIPP complies with the four requirements of Subpart B. The 1992 document, which will describe the compliance evaluation process and compare the WIPP's performance with Subpart B of the Standard, will be the quantitative basis for DOE's determination. That report will evolve from this forecast.

Bertram-Howery, S.G., M.G. Marietta, R.P. Rechard, P.N. Swift, D.R. Anderson, B.L. Baker, J.E. Bean, Jr., W. Beyeler, K.F. Brinster, R.V. Guzowski, J.C. Helton, R.D. McCurley, D.K. Rudeen, J.D. Schreiber, and P. Vaughn. 1990. *Preliminary Comparison with 40 CFR Part 191, Subpart B for the Waste Isolation Pilot Plant, December 1990.* SAND90-2347. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is planned as the first mined geologic repository for transuranic (TRU) wastes generated by defense programs of the US Department of Energy (DOE). Before disposing of waste at the WIPP, the DOE must evaluate compliance with the United States Environmental Protection Agency's (EPA's) Standard, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR Part 191)*. Sandia National Laboratories (SNL) is evaluating long-term performance against criteria in Subpart B of the Standard. "Performance assessment" as used in this report includes analyses for the Containment Requirements (191.13(a)) and the Individual Protection Requirements (191.15). Because proving predictions about future human actions or natural events is not possible, the EPA expects compliance to be determined on the basis of specified quantitative analyses and informed, qualitative judgment. The goal of the WIPP performance assessment team at SNL is to provide as detailed and thorough a basis as practical for the quantitative aspect of that decision.

This report summarizes SNL's late-1990 understanding of the WIPP Project's ability to evaluate compliance with Subpart B. This preliminary assessment cannot be defensibly compared to the requirements of the Standard to interpret whether the WIPP disposal system complies with Subpart B. Defensibility of the compliance evaluation ultimately will be determined primarily by qualitative judgment regarding "reasonable expectations of compliance," assuming that concept is retained by the EPA in repromulgating the vacated Subpart B. Other considerations such as completeness and adequacy of the numerical simulations will also be factors in determining defensibility. Performance assessment must determine the events that can occur, the likelihood of these events, and the consequences of these events. The impacts of uncertainties must be characterized and displayed; however, no single summary measure can adequately display all the information produced in a performance assessment. Adequate documentation is an essential part of a performance assessment.

In lieu of results suitable for comparison with the Standard, this report presents results of sensitivity analyses that address specific uncertainties in the modeling system. All results are preliminary and are conditional on assumed conceptual models and parameter value distributions. The results show the degree to which some uncertainties in the conceptual models that describe aspects of disposal-system behavior may affect predicted performance.

The results also demonstrate the methodology used to assess performance. The reported complementary cumulative distribution functions (CCDFs) are statistical means of families of CCDFs. The modeling system is sensitive to changes in scenario probabilities, and reductions in the probability of intrusion significantly reduce predicted probabilistic cumulative releases. Comparison of clay-lined-fracture and dual porosity transport models for the dominant water-bearing unit above the repository indicate a significant increase in radionuclide retardation and a consequent reduction in predicted releases with the dual-porosity model. Simulations of a variable number of intrusions show that, for the selected probability model, multiple intrusions do not increase the largest cumulative releases. Simulations of a hypothetical waste modification suggest that for modifications to be effective, waste permeability must be reduced more than four orders of magnitude below the estimated unmodified value to restrict brine flow to an intruding bore hole. Simulations of gas generation and the effects gas will have on brine flow and radionuclide transport are not sufficiently advanced to be incorporated in this year's CCDF curves, but preliminary results of one-dimensional simulations are included. Preliminary analyses for the Individual Protection Requirements suggest that no releases will occur; therefore, dose predictions are not likely to be required.

Although disposal-system characterization work has been under way for about 15 years and much is known about the WIPP, all work necessary to support the performance assessment has not been completed. Most work currently in progress to support the performance assessment is not advanced enough to support a defensible comparison to the Standard because many important modules are in preliminary or intermediate stages of understanding or readiness. The compliance assessment system can be used for sensitivity and uncertainty analyses and is adequate for preliminary performance studies.

Biffle, J.H. 1981. *Second Benchmark Problem for WIPP Structural Computation with the JAC Computer Program*. SAND81-0767. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report describes calculations using the JAC computer program for the second benchmark problem for Waste Isolation Pilot Plant (WIPP) structural computations. The problem considers 27 distinct geological layers, including 10 clay layers—4 of which are to be modeled with sliding interface conditions. Heated and unheated drifts at a depth of 650 m are considered. The results are described in accordance with the instructions in the description of the benchmark problem. A discussion is included of the applicability of using JAC for this type of problem.

Bingham, F.W., and G.E. Barr. 1979. *Scenarios for Long-Term Release of Radionuclides from a Nuclear-Waste Repository in the Los Medanos Region of New Mexico*. SAND78-1730. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report discusses hypothetical sequences of events that could conceivably release radionuclides from radioactive waste buried in the proposed Waste Isolation Pilot Plant (WIPP) repository. All the scenarios are described in terms specific to the WIPP Site; they include only events whose occurrence is physically possible there. The report estimates the relative probabilities of the scenarios at times ranging from 1000 to 1 million years after the repository is sealed. Although none of the scenarios is judged likely, the report recommends several for detailed computer modeling and consequence analysis.

Bingham, F.W., and G.E. Barr. 1980. "Development of Scenarios for the Long-Term Release of Radionuclides from the Proposed Waste Isolation Pilot Plant in Southeastern New Mexico," *Scientific Basis for Nuclear Waste Management. Proceedings of the International Symposium, Boston, MA, November 27-30, 1979*. Ed. C.J.M. Northrup, Jr. SAND79-0955C. New York, NY: Plenum Press. Vol. 2, 771-778.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a project for the disposal of radioactive waste, from US defense programs, which contains long-lived transuranic elements. Radioactive safety analyses for WIPP require descriptions of mechanisms that can be assumed to release waste. Scenarios are developed to decide which processes are possible, to decide which processes need further study, and which processes can be eliminated, to recommend processes for early study, and to group processes for computer modeling.

Preliminary fault trace analysis was too uncertain and too unwieldy to guide experimental programs and plant design. As an alternative, event trees were constructed that began with an event assumed to breach the repository and move waste. Nineteen breach events were developed based on processes known to be possible in the Delaware Basin. Subsequent events specify how waste is moved and contacts people.

Event trees were ranked by estimating relative probabilities of events. Safety analysis actually assumes unit probability for events, and the consequences appear acceptable. Relative probabilities are helpful in deciding which scenarios are most likely and should continue to be examined.

Scenarios were grouped into three classes for modeling based on radionuclide transport mechanisms. Bounds to the consequences of each class of scenarios were calculated, eliminating the need to calculate the consequences of each scenario or assume worst-case scenarios. The scenario classes are direct exposure to the biosphere, water flow between two aquifers, and water flow from only one aquifer. Based on relative probabilities, drilling scenarios dominate the first 1000 years. Cracking, seal failure, and drilling begin to be important in scenarios at 10,000 years. Cracking and dissolution dominate at 100,000 and 1 million years. Four basic models are recommended for computer modeling: 1) direct drilling into waste, 2) hydraulic connection of upper and lower aquifers, 3) hydraulic connection allowing only radionuclide diffusion to the upper aquifer, and 4) hydraulic connection allowing flow from an upper aquifer through the repository and back to the upper aquifer. The last model bounds radionuclide transport for a single aquifer.

These methods may not be appropriate elsewhere. Site-specific information made possible many important assumptions. DWP

Bingham, F.W., M.L. Merritt, and M.S. Tierney. 1980. "Supplements to the Release Scenario Analyses for the Waste Isolation Pilot Plant," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980*. ONWI-212. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 138-141.

ABSTRACT: Three supplementary waste release scenarios for the Waste Isolation Pilot Plant (WIPP) have been analyzed since the publication of the *Draft Environmental Impact Statement (DEIS)*. Some reference repository specifications have been changed from those in the DEIS, and radionuclide solubility limits are included. The scenarios represent rupture of a pressurized brine pocket under a repository, domestic use of groundwater near the WIPP, and agricultural use of water from the Pecos River. Ra-226 is the most significant contributor to doses calculated from these scenarios. Ra-226 concentrations from pumped well water is about 5 times the limit for nonoccupational exposure, but the water is too salty to be potable. The Ra-226 ingestion rate from agricultural use of Pecos River water is less than 10^{-4} of the average natural dietary intake. DWP

Black, S.R. 1982. *Basic Data Report Borehole WIPP-12 Deepening Waste Isolation Pilot Plant (WIPP) Project Southeastern New Mexico*. TME 3148. Albuquerque, NM: D'Appolonia Consulting Engineers, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Borehole WIPP-12 was originally drilled in 1978 as an exploratory borehole to characterize the geology of the Waste Isolation Pilot Plant (WIPP) Site in Eddy County, NM. A report describing the original field work and geology of the borehole was recently released. WIPP-12 was reentered and deepened in late 1981. WIPP-12 is located in Section 17, T22S, R31E, just outside the limit of Zone II, approximately one mi north of the exploratory shaft site. The deepening of WIPP-12 was undertaken to investigate the presence of an anticlinal or domal structure and thickening of halite indicated by surface seismic reflection surveys conducted in the area; to determine the nature and extent of deformation in the Castile Formation, in a location adjacent to the zone of anomalous seismic reflections found north of the well location ("Disturbed Zone"); and to characterize any fluid-bearing zones encountered in the Castile Formation while drilling.

Field operations related to deepening of the borehole began November 16, 1981, and were completed January 1, 1982. The borehole was deepened through the Castile Formation to a total depth of 3927.5 ft by coring. Pressurized brine was encountered on November 22, 1981 at a depth of about 3016 ft. The brine reservoir is apparently related to a system of near-vertical fractures of unknown extent observed in Anhydrite III. The Halite I member is about 200 ft thicker than observed in undisturbed areas in the vicinity of WIPP (for example, Borehole DOE-1). Small-scale lithologic features such as folding of anhydrite stringers in halite and halite lineation appear to confirm the presence of a structural disturbance at this location.

This Basic Data Report includes geologic information gathered during WIPP-12 deepening. All information relating to characterization of the brine reservoir is contained in other reports. With minor exceptions, no analytical or interpretive work was performed on the data for inclusion in this report. Slight adjustments were made to coring depths reported by the driller to achieve correlation with geophysical logs.

Black, S.R., R.L. Beauheim, and J.K. Register. 1984. "Hydrogeology of a Brine Occurrence in Bedded Evaporites, Delaware Basin, New Mexico," *Abstracts with Programs, Geological Society of America, 97th Annual Meeting, Reno, NV, November 5-8, 1984*. Vol. 16, no. 6, 446. (Abstract Only).

ABSTRACT: While investigating the subsurface geology near the Waste Isolation Pilot Plant (WIPP) Site, a bore hole (designated WIPP-12) intercepted a pressurized brine reservoir in an anhydrite unit in the Permian evaporite sequence. Brine flowed at the surface at rates up to 15,000 barrels/day. Extensive investigation, including core analysis, drillstem testing, flow testing, and fluid sampling revealed that the brine reservoir consists of a system of fractures in anhydrite on the flank of a gentle anticline formed by halo-tectonism; an estimated volume of 17 million barrels of brine is contained within a heterogeneous system of large near-vertical fractures with relatively high permeability and low storage capacity, and tiny microfractures with relatively low permeability and high storage capacity; the brine is connate Permian seawater that migrated to the fractures from surrounding rock. The brine reservoir is isolated from other similar occurrences in the Delaware Basin and from regional meteoric groundwater systems by intact evaporites with extremely low permeabilities.

Boa, J.A., Jr. 1977. *Borehole Plugging Program (Waste Disposal)*. Report No. 1; Miscellaneous Paper C-77-14. Vicksburg, MS: US Army Engineer Waterways Experiment Station. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This study was initiated to try and find competent grouts to be used in stemming boreholes associated with radioactive waste disposal. The grouts need to have a life of several thousand years and be essentially impermeable. In addition, the grouts should be

pumpable up to depths of several thousand ft into environments of high temperature. Grouts for use in both salt and nonsalt formations are to be studied.

Boa, J.A., Jr. 1978. *Borehole Plugging Program (Waste Disposal). Report 1. Initial Investigations and Preliminary Data.* Miscellaneous Paper C-78-1. Vicksburg, MS: US Army Engineer Waterways Experiment Station. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report covers efforts during the first year of the program. A study was initiated to find competent grouts to be used in stemming bore holes associated with radioactive waste disposal. The grouts must be durable for several thousand years and be essentially impermeable. In addition, the grouts should be pumpable to depths of several thousand ft into environments of high temperature. Grouts for use in both salt and nonsalt formations are to be studied. This program is still under way.

Bodine, M.W., Jr. 1978. "Clay-Mineral Assemblages from Drill Core of Ochoan Evaporites, Eddy County, New Mexico," *Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, Carlsbad, NM, May 4, 1977.* Ed. G.S. Austin. New Mexico Bureau of Mines and Mineral Resources Circular 159. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 21-30.

ABSTRACT: The ERDA-9 drill hole, Eddy County, NM, was cored for 1,987 ft, from 230 ft below the top of the Salado Formation through the upper 41 ft of the Castile Formation. Clay minerals in 47 insoluble residues include corrensite, random to partially ordered clinochlore-saponite mixed-layer clays, illite, clinochlore, saponite, a tentatively identified talc-saponite mixed-layer clay, serpentine, and talc. Serpentine is restricted to the Castile and lowermost Salado Formations; (?)talc-saponite is confined to some polyhalite beds in and overlying the McNutt potash zone. The salztions (thin argillaceous seams) consist of corrensite, illite, and clinochlore, while the adjacent evaporite strata often contain abundant random mixed-layer clinochlore-saponite, mixed-layer (?)talc-saponite, or saponite. Chemical compositions of the residues have high Mg-Al atom ratios reflecting abundance of the trioctahedral clays. Mineralogy and chemistry of the assemblages strongly indicate that severe alteration and Mg-enrichment of normal clay detritus occurred in the evaporite environment through brine-sediment interaction. It is further suggested that the relatively immature clays—saponite, mixed-layer (?)talc-saponite, and randomly interstratified clinochlore-saponite—formed later through recrystallization of preexisting trioctahedral clays in response to transient pore fluids; the salztions, impermeable to such fluids, developed a more mature clay assemblage in a static pore fluid environment. The serpentine-saponite residues with their high Mg-Al and Si-Al atom ratios in Castile and lowermost Salado evaporites are indicative of a silica-rich detrital source; the more aluminous clay assemblages with decreased Mg-Al and Si-Al atom ratios in the overlying evaporite strata suggest a substantially more argillaceous detrital source.

Bodine, M.W., Jr., and C.A. Loehr. 1978. *Selected Investigations of Igneous Dikes Intruding Ochoan Sediments in the Carlsbad Region. Interim Report (Jan. 6, 1978).* Socorro, NM: New Mexico Institute of Mining and Technology, Geoscience Department. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Dike exposures in evaporites at two widely separated localities appear to be part of a single intrusive episode along a lineament up to 75 mi long. Trends and geophysical evidence from Yeso Hills, south of Whites City, and underground workings of Kerr-McGee mine between Carlsbad and Hobbs, suggest a single lineament. Both dike and evaporite lithologies are altered; halite at the mine is more altered than gypsum/carbonate outcrops at

Yeso Hills. Salt in the mine is altered up to 12 meters from the dike; clays are altered to about 5 m. A new trioctahedral mica clay, named trioctillite, is the major mineral replacing talc-illite-trioctahedral clays. Textural effects of the intrusion are minimal. DWP

Bodine, M.W., Jr., and J.R. MacMillan. 1978. *Investigation of Petrology, Mineralogy and Geochemistry of a Permian Basin Core. Interim Report (Jan. 6, 1978).* Socorro, NM: New Mexico Institute of Mining and Technology, Geoscience Department. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Core samples from ERDA-9 were selected to study the genesis of the evaporites and extent of post-depositional alteration. Silicates were separated for size analysis, x-ray diffraction, and scanning electron microscopy. Whole rock, water soluble, acid insoluble, and clay size insoluble fractions were chemically analyzed. Cores and thin sections were described for lithology, textures, mineral associations, and petrography. Samples represented major lithologies, a depositional cycle, polyhalite-anhydrite occurrences, possible disposal horizons, and postdepositional solution and recrystallization.

Minerals and textures indicate post-depositional alteration attributed to fluids migrating through the sediments. Polyhalite and atypical mineral assemblages (e.g., sylvite - langbeinite), along with low bromine and variable age dates, suggest drastic recrystallization. The mineralogy and chemistry of acid insoluble silicates preclude detrital origin.

K-bearing minerals and units should be evaluated basin-wide to determine the mechanisms and extent of alteration. Dynamic models should be developed to help evaluate post-depositional fluid flow. DWP

Borns, D.J. 1982. "Deformation of a Layered Evaporite Sequence and the Role of Pressure Solution, Northern Delaware Basin, Waste Isolation Pilot Plant (WIPP) Site, SE New Mexico," *Abstracts with Programs 1982, Geological Society of America, 95th Annual Meeting, New Orleans, LA, October 18-21, 1982.* SAND82-1204A. Vol. 14, no. 7, 448. (Abstract Only).

ABSTRACT: The Delaware Basin of southeastern New Mexico contains approximately 1000 m of layered evaporites. Areas in the northern Delaware Basin, bordering the Capitan Reef, have anomalous seismic reflection data, such as loss in reflector continuity. Core from holes within this zone exhibit complex mesoscopic folds and extension structures. On a larger scale, anticlines and synclines are indicated by structure contours based on boreholes. The deformation is probably gravity driven, either vertical (halokinesis) or subhorizontal (gravity slide). The age of deformation is equivocal, Permian to recent.

Small-scale structures suggest that deformation is episodic with an early, syndepositional stage of isoclinal folding. Later, tight to open asymmetric folding is more penetrative and exhibits an opposite sense of asymmetry than the earlier isoclinal folding. The younger folds are associated with development of zonal crenulation cleavage and microboudinage of more competent carbonate layers. At the same time, halite beds developed a dimensional fabric and ptygmatic folds in anhydrite stringers. Late-stage, near vertical fractures formed in competent anhydrites. Microscopic textures exhibit rotated anhydrite porphyroblasts, stress shadow growth and microboudinage. Except during late-stage deformation, anhydrite and halite recrystallized synkinematically. Drastic strength reduction in anhydrites through dynamic recrystallization occurs experimentally near 200°C. However, evaporites of the Waste Isolation Pilot Plant (WIPP) Site never experienced temperatures above 40°C. Microscopic fabrics and pressure, temperature history of the evaporites suggest that pressure solution was the active mechanism during deformation. This mechanism stresses the importance of fluid in facilitating deformation in low temperature evaporite sequences.

Borns, D.J. 1983a. *Petrographic Study of Evaporite Deformation Near the Waste Isolation Pilot Plant (WIPP)*. SAND83-0166. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Delaware Basin of southeastern New Mexico contains ~1000 m of layered evaporites. Areas in the northern Delaware Basin, bordering the Capitan Reef, have anomalous seismic reflection characteristics such as loss in reflector continuity. Core from holes within this zone exhibits complex mesoscopic folds and extension structures. On a larger scale, anticlines and synclines are indicated by structure contours based on bore holes. The deformation is probably gravity-driven. Such a process is initiated by basin tilting during either a Mesozoic or Cenozoic period of uplift. The age of deformation is equivocal, ranging from Permian to recent.

Small-scale structures suggest that deformation was episodic with an early, syndepositional stage of isoclinal folding. Later, open-to-tight asymmetric folding is more penetrative and exhibits a sense of asymmetry opposite to that of the earlier isoclinal folding. The younger folds are associated with development of zonal crenulation cleavage and microboudinage of more competent carbonate layers. At the same time, halite beds developed dimensional fabrics and convolute folds in anhydrite stringers. Late-stage, near-vertical fractures formed in competent anhydrite layers. Microscopic textures exhibit rotated anhydrite porphyroblasts, stress shadow growth, and microboudinage. Except during late-stage deformation, anhydrite and halite recrystallized synkinematically. Drastic strength reduction in anhydrites through dynamic recrystallization occurs experimentally near 200°C. However, evaporites of the Waste Isolation Pilot Plant (WIPP) Site never experienced temperatures >40°C. Microscopic fabrics and pressure, temperature history of the evaporites suggest that pressure solution was the active mechanism during deformation of evaporites at the WIPP Site. This conclusion stresses the importance of fluid in facilitating deformation in low-temperature evaporite sequences. The formation of pressurized brine pockets is empirically associated with deformation. The development of high-angle fractures in the uppermost anhydrite unit of the Castile in response to folding provides the reservoir for the brines. Brine fluids may have emanated from deforming halite and anhydrite units through pressure-solution-induced reduction of porosity.

Borns, D.J. 1983b. "Kinetics of Evaporite Deformation," *Abstracts with Programs, Geological Society of America, 96th Annual Meeting, Indianapolis, IN, October 31 - November 3, 1983*. Vol. 15, no. 6, 530. (Abstract Only).

ABSTRACT: Evaporite sequences have been studied at Sandia and elsewhere as sites proposed for hazardous waste disposal and hydrocarbon development and storage. Rates of deformation are important in evaluating the geological performance of different evaporites. Reported naturally occurring strain rates ($\dot{\epsilon}$) are such: 5×10^{-11} /sec for a salt glacier; 10^{-11} for mine closure; 3×10^{-14} , 10^{-15} , and 10^{-16} for salt domes; and 3×10^{-16} for bedded salt deformation near the Waste Isolation Pilot Plant (WIPP) Site. Rates are controlled by the temperature, stress and active mechanism of deformation for each specific case.

Strain rates are estimated through in situ measurements and the integration of geometric strain analysis and stratigraphic arguments for time duration. An inherent problem in the estimates is the large extrapolation of rates through time. Another approach to estimate rates is to calculate $\dot{\epsilon}$ directly using the constitutive models for different dominant deformation mechanisms. Specific relative mechanisms can be determined from petrofabric study. Such calculations, however, suffer from the relatively poor data on diffusion in intergranular fluids and the variety of grain boundary diffusion models.

Specifically for deformation near the WIPP Site, southeastern New Mexico, geometric-stratigraphic integration predicts a $\dot{\epsilon}$ of 10^{-14} /sec to 10^{-16} /sec. Also, strain rates of 10^{-15} to 10^{-16} /sec are calculated by constitutive models for dislocation creep and pressure-solution. The rates using two approaches are basically in agreement. These rates are generally lower than those in salt domes because gravity-driven flow structures near WIPP result from a lower

T and σ and, therefore, pressure solution is the dominant mechanism rather than dislocation creep.

Borns, D.J. 1985. *Marker Bed 139: A Study of Drillcore From a Systematic Array.* SAND85-0023. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In southeastern New Mexico, Marker Bed 139 (MB139) is one of 45 numbered siliceous or sulfatic units within the Salado Formation of the northern Delaware Basin. MB139 is divided into five zones. Zones I and V are the upper and lower contact zones, respectively. Zone II is a syndepositionally deformed subunit of polyhalitic anhydrite. Zone III is mixed anhydrite and polyhalitic anhydrite, a distinctive pale-green and pink, with subhorizontal fractures. Zone IV consists of interlayered halite and anhydrite without the overprint of polyhalite.

This sequence was transitional between submarine and subaerial. The anhydritic units of MB139 formed in salt-pan or mudflat environments or both. Undulations observed along the upper contact of MB139 are interpreted to result from traction deposits or from reworking of the upper portion of the marker bed during the transition from anhydrite to halite deposition. Zones II and III exhibit soft-sediment deformation and later traces of dewatering, e.g., formation of stylolites. Such deformation is not observed in the halite above MB139 or in Zone V and the halite units below MB139.

A distinctive set of subhorizontal fractures occurs in MB139 in mid-zone III and, to some extent, in Zone IV. These fractures are partially infilled with halite and polyhalite. Brine occurrences at the mined facility horizon at the Waste Isolation Pilot Plant (WIPP) may be related to these fractures. The fractures formed either in response to stress cycles that were functions of sedimentation and erosion or in response to deformation in the underlying Castile Formation. The subhorizontal orientation, dominant in the sampling data, is more consistent with the interplay between stress and sedimentation cycles.

Borns, D.J. 1987a. "Structural Development of Evaporites in the Northern Delaware Basin," *Geology of the Western Delaware Basin, West Texas and Southeastern New Mexico.* Eds. D.W. Powers and W.C. James. El Paso Geological Society Guidebook 18. SAND87-0825J. El Paso, TX: El Paso Geological Society. 80-97.

ABSTRACT: Within the evaporites of the northern Delaware Basin, deformation has been observed on mega- to microscopic scales. Sequences of anticlines and synclines are delineated by correlation of well logs. Drillcores exhibit fold structures within the anhydrites and halites. Textures from these cores suggest that the deformation was the result of several events. Such events are a depositional-diagenetic stage and a later penetrative event.

Three processes have been proposed for the origin of these structures: dissolution, gravity-driven deformation, and syndepositional processes. The several stages of structural development may represent in part all three of these processes and can confuse discussion of the dominant mechanisms. Overall, the gravity-driven deformation (gravity inversion of halite and anhydrite units) appears to have produced the basin-scale anticlines and synclines. Dissolution appears to have produced some large-scale troughs along the western side of the basin. The timing of the deformation other than the syndepositional stage is difficult to fix. Recent work suggests that the gravity-driven deformation commenced with the basin tilting that began 30 Ma. Such uplift and tilting occurred during the Mesozoic, at the Cretaceous-Tertiary boundary and during an ongoing stage that commenced 30 Ma ago. This youngest period of tilting may be the dominant period of deformation.

Borns, D.J. 1987b. *The Geologic Structures Observed in Drillhole DOE-2 and Their Possible Origins: Waste Isolation Pilot Plant.* SAND86-1495. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) for underground storage of transuranic waste produced by defense-related programs. The WIPP underground storage facility will be located approximately 650 m below the surface within a sequence of evaporites over 1000-m thick. This evaporite sequence is divided into three major units (in descending order): the 100-m thick Rustler Formation; the 600-m thick Salado Formation in which the underground facility is placed; the 300-m thick Castile Formation. After 10 years of geological site characterization, the major effort of this task is drawing to a close. Still, such questions remain as the origins of evaporite deformation within the Salado and Castile Formations. Two mi north of the WIPP Site, a stacked sequence of depressions, defined by marker beds in the Salado, was indicated by shallow bore holes. Such structures raise questions regarding the role of dissolution and gravity tectonics at the WIPP Site. To investigate these structures, DOE decided to drill hole DOE-2 north of the WIPP Site.

At DOE-2, the downward displacement of stratigraphic markers in the Salado confirmed the presence of stacked depressions, which were the primary target of the drilling program. The halitic units between the marker beds were thickened compared to the average section determined from basin-wide drilling. Halitic units in the lower Salado show evidence of recrystallization during deformation and parasitic fold structures. Such deformation structures and thickened halitic units are inconsistent with dissolution within the Salado as the cause of deformation in the basal units of the Salado. The remaining question is whether dissolution occurred in the underlying Castile and resulted in the deformation of the Salado. At drill hole DOE-2 and in nearby deep bore holes, complex structures in the Castile Formation are found. One hundred m or more of halite is expected in an average section of the Castile Formation; however, the only Castile halite section penetrated by DOE-2 is less than 3 m thick. In contrast, markers in the anhydrite units indicate recumbent structures and thickening of the anhydrite units by folding. As a consequence, the Castile Formation is nearly its average thickness, with the folded thickness of anhydrite compensating for the missing halite. The nearby thickening of halite within the Castile, the absence of relic anhydrite laminae in the attenuated halite units, and the high strain fabric of the remaining halite suggest that dissolution was not the dominant process in the Castile. The favored hypothesis for the Castile structures is salt flow in response to gravity inversion of the anhydrite and halite units of the Castile.

Borns, D.J. 1987c. *Rates of Evaporite Deformation: The Role of Pressure Solution.* SAND85-1599. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Evaporite sequences have been intensely studied for hazardous waste disposal and hydrocarbon development and storage. Rates of deformation are important in evaluating the long-term performance of different evaporites. Reported naturally occurring strain rates ($\dot{\epsilon}$) are $5 \times 10^{-11} \text{ s}^{-1}$ for a salt glacier; 10^{-11} for mine closure; 3×10^{-14} , 10^{-15} , and 10^{-16} for salt domes; 3×10^{-16} for bedded salt. Rates are controlled by temperature, differential stress, and active mechanism of deformation for each specific type of evaporite and setting.

Strain rates are estimated through in-situ measurements and the integration of geometric strain analysis and stratigraphic arguments for the time required for the observed deformation to occur. An inherent problem in such calculations is the large extrapolation of rates through time. Another approach for rate estimation is to calculate $\dot{\epsilon}$ directly, using the constitutive models for different deformation mechanisms that may be dominant. Specific mechanisms can be determined from petrofabric study, as at the Waste Isolation Pilot Plant (WIPP) Site, southeastern New Mexico, where textures indicating that pressure solution was active are observed. Calculations based on experimental data are limited by the relatively poor data on diffusion in intergranular fluids. A variety of grain boundary diffusion models has been used.

Some models (e.g., cubic approximation of the grain shape) leave gradients undefined at the grain edge.

For gravity-driven deformation near the WIPP Site, geometric-stratigraphic integration predicts a $\dot{\epsilon}$ of 10^{-14} s^{-1} to 10^{-16} s^{-1} . Strain rates of 10^{-15} to 10^{-16} s^{-1} are predicted using models for dislocation creep and pressure solution. The rates using two approaches, geometric-stratigraphic and constitutive, are basically in agreement. These rates for the gravity-driven flow structures near WIPP reflect lower temperatures and stresses than salt domes. At the temperatures and stresses estimated for the WIPP flow structures, pressure solution is probably the dominant mechanism, rather than dislocation creep. It remains to be determined where in the transition from transient to steady-state response to an underground excavation in rock salt pressure solution becomes a major mechanism.

Borns, D.J., and S-E. Shaffer. 1985. *Regional Well-Log Correlation in the New Mexico Portion of the Delaware Basin*. SAND83-1798. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Although well logs provide the most complete record of stratigraphy and structure in the northern Delaware Basin, regional interpretations of these logs generate problems of ambiguous lithologic signatures and one-hole anomalies. Interpretation must therefore be based on log-to-log correlation rather than on inferences from single logs. In this report, logs from 276 wells were used to make stratigraphic picks of Ochoan horizons (the Rustler, Salado, and Castile Formations) in the New Mexico portion of the Delaware Basin. Current log correlation suggests that the Castile is characterized by lateral thickening and thinning; some Castile thinnings are of Permian age; irregular topography in the Guadalupian Bell Canyon Formation may produce apparent structures in the overlying Ochoan units; extensive dissolution of the Salado is not apparent in the area of the Waste Isolation Pilot Plant (WIPP) Site.

Borns, D.J., and J.C. Stormont. 1987. "Delineation of the Disturbed Rock Zone Around Excavations in Salt, Waste Isolation Pilot Plant (WIPP), SE New Mexico," *Abstracts with Programs, Geological Society of America, 1987 Annual Meeting and Exposition, Phoenix, AZ, October 26-29, 1987*. Vol. 19, no. 7, 595. (Abstract Only).

ABSTRACT: For nuclear waste repositories with both long operational periods (≤ 50 yr) and long performance assessment periods ($\leq 10,000$ yr), the Disturbed Rock Zone (DRZ), the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation, is important to both operational (e.g., slab or fracture failure of the excavation) and long-term performance (e.g., seal system performance and fluid transport). At the Waste Isolation Pilot Plant (WIPP), the DRZ has been characterized with three approaches: visual observation; permeability measurements; geophysical methods. Visual observations in drill holes indicate that fluids and fractures (preexisting and excavation induced) are common in the host rock of the underground facility. Numerous gas permeability measurements indicate that beyond 2 m from an excavation halite and interbeds (anhydrite and clay) allow very low gas flow (calculated permeabilities < 1 microdarcy). Within 2 m of the excavation, very high flow rates were measured. Geophysical studies have utilized radar, transient electromagnetic method (TEM) and direct current (DC) electromagnetic methods. Radar has been useful, but the penetration of radar is limited by the water content and bedded nature of the host rock. The TEM was able to detect a fourfold increase in resistivity from 1 to 5 m into the rock. This trend may reflect a variation in the moisture content from 1% by weight near the excavation to 4% in the host rock. The DC method has been able to detect zones of moisture around the excavation. All three approaches have defined a DRZ at WIPP extending laterally throughout the excavation and varying in depth from 1 to 5 m, according to the size and age of the opening. Electromagnetic and seismic imaging studies are under way in addition to gas flow measurements and crosshole ultrasonics to develop more detailed three-dimensional definitions of the DRZ.

Borns, D.J., and J.C. Stormont. 1989a. "An Interim Report on Excavation Effect Studies at the Waste Isolation Pilot Plant: The Delineation of the Disturbed Rock Zone," *Proceedings of an NEA Workshop on Excavation Response in Geological Repositories for Radioactive Waste, Winnipeg, Canada, April 26-28, 1988*, SAND87-1375. Paris, France: Organisation for Economic Co-Operation and Development. 413-425. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: For nuclear waste repositories with both long operational periods (50 year) and long performance assessment periods (10,000 years), the Disturbed Rock Zone (DRZ), the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation, is important to both operational (e.g., slab or fracture failure of the excavation) and long-term performance (e.g., seal system performance and fluid transport). At the Waste Isolation Pilot Plant (WIPP), the DRZ has been characterized with three approaches: visual observation, geophysical methods, and permeability measurements. Visual observations in drill holes indicate that fluids and fractures are common in the host rock of the underground facility. Geophysical studies have utilized radar, electromagnetic (EM), and direct current (DC) electromagnetic methods. Radar has been useful, but the penetration is limited by the water content and bedded nature of the host rock. The EM method was able to detect a fourfold increase in resistivity from 1 to 5 m into the rock. This trend reflects a fourfold increase in the moisture content from near the excavation (0.5 to 1% by weight) to 5 m into the host rock (2 to 3% by weight). The DC method has been able to detect zones of moisture around the excavation. Numerous gas permeability measurements indicate that beyond 2 m from an excavation halite and interbeds (anhydrite and clay) allow very low gas flow (calculated permeabilities <1 microdarcy for gas flow tests and <0.01 microdarcy for brine-based permeability tests). Within 2 m of the excavation, very high flow rates (10^4 SCCM [standard cm^3/min]) were measured. All three approaches have defined a DRZ at the WIPP extending laterally throughout the excavation and varying in depth from 1 to 5 m, according to the size and age of the opening.

Borns, D.J., and J.C. Stormont. 1989b. "The Delineation of the Disturbed Rock Zone Surrounding Excavations in Salt," *Rock Mechanics as a Guide for Efficient Utilization of Natural Resources: Proceedings of the 30th US Symposium, West Virginia University, Morgantown, WV, June 19-22, 1989*. Ed. A.W. Khair. SAND88-2230C. Brookfield, VT: A.A. Balkema. 353-360.

ABSTRACT: At the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico, the Disturbed Rock Zone (DRZ), the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation, has been characterized with visual observations, geophysical methods, and gas-flow measurements. The visual observations, geophysics, and gas-flow tests have defined a DRZ at the WIPP extending laterally throughout the excavation and varying in depth from 1 to 5 m. Desaturation and microfracturing has occurred to some degree within the zone. The dilation that results from the microfracturing in the DRZ provides a component of the observed closure.

Borns, D.J., L.J. Barrows, D.W. Powers, and R.P. Snyder. 1983. *Deformation of Evaporites Near the Waste Isolation Pilot Plant (WIPP) Site*. SAND82-1069. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Delaware Basin is a broad asymmetric sedimentary trough in southeastern New Mexico and west Texas. Basin subsidence occurred from the Pennsylvanian into the Triassic. The basin also underwent tilting since the early Cenozoic.

Layered evaporite units are 1000 m thick in the basin. These evaporites are divided into three stratigraphic units (listed in order of increasing age): the Rustler Formation, the Salado Formation, and the Castile Formation. These units, especially the Castile, are deformed along portions of the margin of the Delaware Basin and in some areas internal to the basin. In the northern Delaware Basin adjacent to the Waste Isolation Pilot Plant (WIPP) Site, the term "Disturbed Zone" (DZ) has been applied to an area in which deformation structures are found in bore holes and from which chaotic seismic reflection data were obtained. The origin and timing of this deformation is considered important for the determination of failure scenarios for the WIPP Site. However, the deformation does not present a major hazard to the construction and operational stages of the facility.

Geophysical studies (borehole logging, seismic reflection, and detailed gravity) have covered the DZ areas. Logs show vertical relief in the order of tens to hundreds of meters. Seismic profiles suggest a blocky structure with abrupt offsets and changes in dip between units. This chaotic structure occurs within the Castile Formation, but with little or no deformation exhibited by the overlying and underlying strata. Changes in seismic character, such as wiggle shapes, imply that unit thicknesses and/or acoustic properties vary. On the periphery of the DZ, seismic profiles indicate salt flowage flexures. Outside the DZ, the seismic time structures appear to be generated by lateral velocity variations. The gravity field is dominated by anomalies originating in lateral density variations within relatively flat-lying strata. Low-amplitude, long-wavelength effects of DZ structures cannot be resolved.

Through detailed core description, both meso- and microscopic, fold styles in the DZ units are separable into distinct stages and sequences of generation. An older sedimentary stage of folding is distinguished from later tectonic folding by microfabric development and opposite senses of asymmetry. The tectonic folding and deformation displays a progressive development of fabrics ending in late-stage fracturing of competent anhydrite units. Petrofabrics reveal synkinematic growth of rotated anhydrite porphyroblasts and stress shadow growth. Microboudinage is also common. Of the possible deformation mechanisms for anhydrite and halite, pressure solution appears the most applicable to the DZ. Therefore, an intergranular fluid plays an important role in facilitating deformation under the pressure, temperature, and stress histories of the region.

Gravity foundering, gravity sliding, gypsum dehydration, dissolution, and depositional variations (e.g., thickness) are all hypotheses of origin of deformation that have been considered. Of these, gravity foundering and sliding are considered the most probable causes of deformation. However, no hypothesis adequately answers why the deformation has a limited areal distribution. A possible explanation would be areal variations in rock strength caused by variations of intergranular water content. Age and timing of deformation are also crucial. Standard stratigraphic arguments based on superposition may not apply to such highly incompetent material as halite. Gravity foundering could have happened at any time since deposition, including the present; gravity sliding would probably have occurred since basin tilting began in the Cenozoic.

Deformation could be ongoing. However, the strain rates are such ($\approx 10^{-16} \text{ s}^{-1}$) that deformation would progress slowly, relative to the facility's time frame of 2.5×10^5 years. Deformation of Salado units would be minimal ($< 10 \text{ m}$) or nonexistent, but within this time frame, upper anhydrite units of the Castile could fracture and provide the volume for a brine reservoir. Such volumes would be small ($< 1\%$) and would require $\approx 10^4$ to 10^6 years to develop. At these strain rates, fractures that connect the fractured anhydrites of the Castile with the middle Salado could not develop. Deformation should not directly jeopardize the facility over the next 2.5×10^5 years.

Bradshaw, P.L., and E.T. Louderbough, 1987. *Compilation of Historical Radiological Data Collected in the Vicinity of the WIPP Site*. DOE/WIPP-87-004. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The Radiological Baseline Program (RBP) at the Waste Isolation Pilot Plant (WIPP) has been implemented to characterize the radiological conditions at the site prior to receipt of radioactive wastes. Because southeastern New Mexico was the site of an underground nuclear test in 1961, various sampling programs have intermittently monitored background and elevated radiation levels in the vicinity of the WIPP. In addition, the site region was radiologically characterized during the 1970s in support of the WIPP *Environmental Impact Statement (EIS)*.

The historical data are drawn primarily from monitoring activities of the US Public Health Service (PHS), the US Environmental Protection Agency (EPA), the US Geological Survey (USGS), and Sandia National Laboratories (SNL), Albuquerque. Information on air and water quality, meat, milk, biota, and vegetation is included in the report.

Two wells at the Gnome site show slight contamination from the Gnome detonation, while two other wells at Gnome were intentionally contaminated as part of a tracer test. USGS well 1, within 330 m of the Gnome shaft, has shown no contamination from the detonation.

This survey is intended to provide a source of reference for historical data on radiological conditions in the vicinity of the WIPP Site prior to establishing a systematic RBP. DWP

Brandshaug, T. 1979. *Thermal and Thermo-viscoelastic Analysis of the Lower Horizon Area in the WIPP.* Technical Memorandum Report RSI-0080. Rapid City, SD: RF/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM)

ABSTRACT: A finite element thermal and thermo-viscoelastic analysis of conditions considered typical of an underground demonstration of spent fuel disposal at the Waste Isolation Pilot Plant (WIPP) revealed that most of the room closure is caused by viscous salt response to overburden. For an unventilated room, temperatures rise for about 30 years with an average rise of 28°C in the vicinity of the room after 25 years. Salt temperatures peak after 7 years for a ventilated room, with average rises of about 5°C. The maximum temperature rise can be reduced 80% by ventilation. For an unventilated room, 35% of room closure after 25 years is caused by thermal effects, while the ventilated room shows 14% of total closure caused by thermal effects. The creep law used has limitations, and the question remains whether the coupled effect of total stress, differential stress, and temperature on the creep behavior of salt rock is significant enough to alter the creep results as obtained. DWP

Brandshaug, T. 1986. *A Thermomechanical Analysis of the WIPP High Level Waste Container Borehole Interaction.* SAND-86-110. RSI-0078. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The 14-cm-dia. container borehole problem design proposed for the new High Level Waste (HLW) container borehole has been analyzed. The 14-cm-dia. container is cylindrical in shape and is placed in a borehole drilled into the salt rock. The container integrity of the dome-shaped top of the 14-cm-dia. container during the waste isolation period

This report investigates the normal stresses that may be induced on the dome-shaped top of the HLW container, as well as the radial stresses on the cylindrical portion of the container during the waste isolation period. The end-of-isolation initial heat power density (APD) of 18 W/m² using 1,000 W containers and 90 W/m² using 1,000 W containers. At the time of emplacement of the 14-cm-dia. container in a potential repository, the container is lowered into a vertical borehole in the floor of the disposal room. There will be an open space (annulus) between the container and the wall of the drilled bore hole. In one study, the annulus was considered open as well as filled with "flushed" salt material and also "in

blend of bentonite and silica sand" material. Several different annuli sizes were also considered in this study.

Results show that the normal stresses on the dome of the TiCode-12 container are spatially nonuniform and time dependent. The maximum normal stresses predicted are similar for the two APDs considered; however, the time of occurrence of the maxima is significantly different. For the two backfill materials considered, the predicted normal stresses on the dome are approximately 11% lower when the "bentonite/sand" is used, compared to the "crushed salt." The "crushed salt" was taken to be "stiffer" than the "bentonite/sand." Results also show that a larger backfilled annulus in the range from 0.05 m to 0.30 m will have the effect of decreasing the normal stresses on the container dome, as well as the radial stresses on the cylindrical portion of the container, only during early times. Ultimately, the use of larger backfilled annuli results in stresses of greater magnitude than smaller annuli. When backfill material is used for the conditions studied, it appears that an optimum annulus size is approximately 0.05 m. There are indications that an open annulus (no backfill) provides an opportunity to reduce the maximum normal stresses on the dome of the TiCode-12 container, as well as the radial stresses on the cylindrical portion of the container, to magnitudes lower than those predicted when backfill material is present.

Brandshaug, T., J.L. Ratigan, and L.L. Van Sambeek. 1979. *Preliminary Design of an Experiment for Determination of the Load Bearing Capacity of a Heated Pillar in the PRE-WIPP Designated Area.* Technical Memorandum Report RSI-0088. Rapid City, SD: RE/SPEC, Inc.

ABSTRACT: The heated pillar experiment has been proposed to evaluate the load-bearing capacity of a salt pillar subject to stresses from excavation and thermal loads. The preliminary experimental design concerns geometry, electrical power, and time limits. Drift width around the heated pillar is considered to be at least 4 m, and drift or pillar height is to be less than 5 m. The experimental area is assumed to be at a depth of 305 m. Electrical heater loading should be about 2 kW/m of pillar length. This will result in temperatures less than 100°C during the first year. Elevated temperatures in the pillar will drop by 50% within two weeks and 75% within five weeks after ending heating. Based on non-linear analyses, load bearing capacity should begin to decrease after four to six months, assuming unconfined compressive strength of about 15-20 MPa. Further detailed analyses can more accurately assess transient displacements both before and after strength failure. DWP

Branstetter, L.J. 1983. *Pretest Parametric Calculations for the Heated Pillar Experiment in the WIPP In Situ Experimental Area.* SAND82-2781. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Results are presented for a pretest parametric study of several configurations and heat loads for the heated pillar experiment (Room II) in the Waste Isolation Pilot Plant (WIPP) In Situ Experimental Area. The purpose of this study is to serve as a basis for selection of a final experiment geometry and heat load. The experiment consists of a pillar of undisturbed rock salt surrounded by an excavated annular room. The pillar surface is covered by a blanket heat source that is externally insulated. A total of five thermal and ten structural calculations is described in a four-to-five year experimental time frame. Results are presented that include relevant temperature/time histories, deformations, rock salt stress component and effective stress profiles, and maximum stresses in anhydrite layers that are in close proximity to the room. Also included are predicted contours of a conservative post-processed measure of potential salt failure. Observed displacement histories are seen to be highly dependent on pillar and room height, but insensitive to other geometrical variations. The use of a tensile cutoff across slidelines is seen to produce more accurate predictions of anhydrite maximum stress, but to have little effect on rock-salt stresses. The potential for salt failure is seen to be

small in each case for the time frame of interest and is only seen at longer times in the center of the room floor.

Branstetter, L.J. 1985. *Second Reference Calculation for the WIPP.* SAND83-2461. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Results of the second reference calculation for the Waste Isolation Pilot Plant (WIPP) Project using the dynamic relaxation finite-element code SANCHO are presented. This reference calculation is intended to predict the response of a typical panel of excavated rooms designed for storage of nonheat-producing nuclear waste. Results are presented that include relevant deformations, relative clay seam displacements, and stress and strain profiles. This calculation is a particular solution obtained by a computer code that has proven analytic capabilities when compared with other structural finite-element codes. It is hoped that the results presented here will be useful in providing scoping values for defining experiments and for developing instrumentation. It is also hoped that the calculation will be useful as part of an exercise in developing a methodology for performing important design calculations by more than one analyst using more than one computer code and for defining internal Quality Assurance (QA) procedures for such calculations.

Branstetter, L.J., R.D. Krieg, and C.M. Stone. 1981. *A Method for Modeling Regional Scale Deformations and Stresses Around Radioactive Waste Depositories in Bedded Salt.* SAND81-0237; NUREG/CR-2339. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: When heat-producing nuclear waste is placed in mined drifts, the surrounding geology is disturbed to some extent. Primary concerns on a regional scale may include fracture of brittle stratigraphic layers bounding water-bearing strata, surface upheaval or subsidence, and disturbance of other nearby mining operations. This study presents a structural analysis method that may serve as a base for answering questions of this sort. The analysis method is presented with the use of a generic but very specific problem. A depository in bedded salt is chosen for analysis and a cylinder of earth 0.8 mi deep by 3.0 mi in diameter is modeled. Sandstone, shale, and bedrock are modeled as linear elastic media. The rock salt is modeled with an elastic, secondary creep model. Drifts that are backfilled with crushed salt are modeled with a simple volumetrically creeping model that accurately captures the subsidence caused by drift closure. Following a slight initial subsidence, the results show a maximum surface rise of 0.46 m at 90 years with eventual subsidence of 0.18 m after thousands of years at a point directly above the depository center.

Branstetter, L.J., R.D. Krieg, and C.M. Stone. 1982. *The Effect of a Random Variation of Rock Salt Creep on Calculations of Storage Room Closure for the WIPP Project.* SAND82-0024. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Heterogeneity is characteristic of many geologic media. In particular, naturally occurring rock salt in southeastern New Mexico shows a wide variation of secondary creep rates between tested samples. It is important to know how this scatter in properties affects room closure predictions. This report presents the results of a study designed to quantify this effect for a particular isothermal storage room model. A series of calculations of room closure is made with both homogeneous and randomly distributed creep properties. Calculations involving random property variations were divided into two sets: those in which variations occurred only in the vertical direction and those in which both horizontal and vertical variations were present. The introduction of randomly distributed creep properties is shown to yield room closure predictions that, when averaged among several calculations, are reduced from the single prediction of an analogous homogeneous calculation. The analysis finds an average creep property value that could be used to achieve the same closure result as the

average of several random calculations. Some statements concerning confidence intervals on room closure predictions are made.

Braustetter, L.J., C.M. Stone, and R.D. Krieg. 1981. *WIPP Benchmark II Results Using SANCHO*. SAND81-0853. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Results of the second benchmark problem in the Waste Isolation Pilot Plant (WIPP) code evaluation series using the finite-element dynamic relaxation code SANCHO are presented. A description of SANCHO and its model for sliding interfaces is given, along with a discussion of the various small routines used for generating stress plot data. Conclusions and a discussion of this benchmark problem, as well as recommendations for a possible third benchmark problem are presented.

Brausch, L.M., and D.M. Winters. 1979. *Assessment of Waste Isolation Periods Prior to Direct Access by Exploratory Drilling in Geologic Waste Repositories*. DOE/AL/05346-T5. Pittsburgh, PA: Westinghouse Electric Corporation.

ABSTRACT: The consequences of drilling into the Waste Isolation Pilot Plant (WIPP) at some future time are important because drilling represents the worst-case mode of direct introduction of radioactivity to the biosphere. Minimum reasonable periods for this hypothetical scenario have been investigated because the consequences depend on the length of time that passes before the intrusion is assumed to occur.

It was assumed that current drilling technology is maintained or improved, there is no control over the site, knowledge of the site is lost, and there is incentive to explore the site. Based on the probabilities assigned to events, it is estimated there is a 95% probability drilling would not occur at the site before 250 years have passed. It is estimated that the probability is 99% that drilling during this period would not intercept a waste canister because of institutional controls and the limited area of waste canisters. Facility design should include provision for site markers and record preservation. Incentives to drill the site do not appear overly significant during the 250-year period. DWP

Brausch, L.M., A.K. Kuhn, and J.K. Register. 1982. *Natural Resources Study Waste Isolation Pilot Plant (WIPP) Project Southeastern New Mexico*. TME 3156. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant.

ABSTRACT: The potential effects of developing resources within and outside of Zone III at the Waste Isolation Pilot Plant (WIPP) have been evaluated to assist the Department of Energy (DOE) in setting policy for resource recovery. The methods applied were to determine which technologies or activities are applicable, to evaluate the disturbance of rock strata near the WIPP by these activities, and to assess any effects on radiation dose consequences reported in the *Safety Analysis Report (SAR)*. It is concluded that activities related to potash and hydrocarbon resource extraction and solution mining from within (and outside of) Control Zone IV, using currently available and applicable technology, will not compromise the integrity of the WIPP or increase the likelihood of a breaching event.

Plausible waste-release events that could occur after loss of institutional controls "are fundamentally independent of former resource recovery restrictions at the site. . . . [P]otash exploration and conventional mining or solution mining in Control Zone IV are physically too far removed to affect the integrity of the WIPP facility." Typical "exploration and production of hydrocarbons from within control Zone IV likewise would not affect the waste emplaced in the WIPP facility. . . . The communication events analyzed in the WIPP SAR . . . are

applicable to current resource extraction technology in Control Zone IV and beneath Control Zones I, II, and III (for hydrocarbons)."

The DOE could prudently allow resource recovery in Control Zone III. "... many resource recovery operations will be reviewed by the BLM ... and the Minerals Management Service ... planned activities will be evaluated on a case-by-case basis to insure that the integrity of the WIPP facility will not be jeopardized." DWP

Brausch, L.M., J.S. Hart, K.R. Porter, and J.K. Register. 1980. *Technical and Environmental Analyses Development of the Site and Preliminary Design Validation Program Los Medanos Site, Southeastern New Mexico.* TME 3058. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Office. (Copy on file at the US Department of Energy Public Reading Room, National Atomic Museum, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Program is currently the authorized alternative for disposing of radioactive waste from defense programs; the preferred alternative is to dispose of these wastes in the first repository developed for radioactive waste from commercial sources. Additional site studies, under the site preliminary design validation (SPDV) program, include constructing two deep shafts and an underground experimental facility before a final decision is made about the suitability of the WIPP Site. This report evaluates the environmental impacts of constructing the shafts and underground facility, but it is not the document for making decisions.

The most significant impacts of the program are on noise levels and archeological resources. The effects on archeology can be mitigated by an approved plan. Moderately significant impacts are on terrain (subsidence), soils, air quality, vegetation, wildlife, and housing. Mitigating measures are proposed for effects on soils, vegetation, and wildlife. The least significant impacts are on terrain (salt storage pile), population, employment, economy, land use and recreation, and transportation. Mitigating measures are proposed for salt storage, land use, and recreation. DWP

Brodsky, N.S. 1990. *Crack Closure and Healing Studies in WIPP Salt Using Compressional Wave Velocity and Attenuation Measurements: Test Methods and Results.* SAND90-7076. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Compressional wave ultrasonic data were used to qualitatively assess the extent of crack closure during hydrostatic compression of damaged specimens of Waste Isolation Pilot Plant (WIPP) salt. Cracks were introduced during constant strain-rate triaxial tests at low confining pressure (0.5 MPa) as specimens were taken to either 0.5, 1.0, or 1.5% axial strain. For three specimens taken to 1.0% axial strain, the pressure was increased to 5, 10, or 15 MPa. For the remaining specimens, pressure was raised to 15 MPa. Waveforms for compressional waves traveling both parallel and perpendicular to the direction of maximum principal stress were measured in the undamaged state, during constant strain-rate tests and then monitored as functions of time while the specimens were held at pressure. Both wave velocities and amplitudes increased over time at pressure, indicating that cracks closed and perhaps healed. The recovery of ultrasonic wave characteristics depended upon both pressure and damage level. The higher the pressure, the greater the velocity recovery; however, amplitude recovery showed no clear correlation with pressure. For both amplitudes and velocities, recoveries were greatest in the specimens with the least damage.

Two different data interpretations are presented for the inverse correlation between velocity and amplitude recoveries and damage level. The first explanation is based entirely upon brittle deformation processes. For cracks to close relatively quickly, crack walls must remain close to their original geometries. For higher levels of damage, crack surfaces are offset and may not reclose immediately upon pressurization. The second explanation involves plastic deformation

mechanisms. During constant-strain-rate triaxial testing, the hardness of the microstructure increases as cracks are introduced. The increased hardness causes the creep rate for crack closure to be lower in specimens taken to higher levels of damage. For both data interpretations, complete crack closure and healing are expected if hydrostatic stress is maintained for an extended time period.

Brokaw, A.L., C.L. Jones, M.E. Cooley, and W.H. Hays. 1972. *Geology and Hydrology of the Carlsbad Potash Area, Eddy and Lea Counties, New Mexico.* USGS-4339-1. Denver, CO: US Geological Survey.

ABSTRACT: The potash mines of southeastern New Mexico are in a sparsely populated area 15-30 mi east of Carlsbad. Topographic relief is low, surface drainage poor, and collapse features common. The climate is semiarid.

Sedimentary rocks attain thicknesses of more than 20,000 ft and range in age from Ordovician to Quaternary. The area includes the northern end of the Delaware Basin and the largely buried Capitan Reef. The basin contains as much as 13,000 ft of Permian strata. The oldest exposed rocks are of Late Permian age, but drilling has provided much data on the buried older rocks. The principal structures are broad gentle features related to late Paleozoic sedimentation: the northern Delaware Basin, a shelf north and west of the basin, and a central basin platform to the east. These structures were tilted eastward before Pliocene time, have been inactive since, and now show a general eastward dip of less than 2 degrees.

The salt deposits are in the Late Permian Ochoan Series composed of a thick salt-bearing evaporite lower part (Castile, Salado, and Rustler Formations) and a thin nonsalt-bearing upper part (Dewey Lake Red Beds).

The Castile Formation consists largely of interlaminated gray anhydrite and brownish-gray limestone, but includes much rock salt. It is about 1,500-1,600 ft thick along the southern edge of the potash area; it thins northward to about 1,000 ft near the margin of the Delaware Basin and tongues out in the southernmost parts of the northwest shelf. All the salt is concentrated in a thick middle member that lies 200-300 ft above the base of the formation.

The Salado Formation, the main salt-bearing unit of the potash area, ranges in thickness from about 1,900 ft in the south to about 1,000 ft in the north. The formation is characterized by thick persistent units of rock salt alternating with thinner units of anhydrite and polyhalite. Thin seams of claystone underlie the anhydrite and polyhalite unit, and there are a few beds of sandstone and siltstone at large intervals. The Salado Formation is divided into three informal units: a lower and an upper salt member, generally free of sylvite and other potassium and magnesium evaporite minerals, and the McNutt potash zone, generally rich in these minerals.

The Rustler Formation, mostly anhydrite and rock salt, thins from 300 to 400 ft in the southern part of the area to about 200-250 ft in the northern part. Some dolomite is present in the upper and lower parts of the formation, and thin to thick units of sandstone and shale are interbedded at long to short intervals.

The Dewey Lake Red Beds at the top of the Ochoan series consist of reddish-brown siltstone and fine-grained sandstone. The formation is 250-550 ft thick in the potash area.

Three main hydrologic units control the groundwater hydrology of the Carlsbad potash mining area: the Pecos River, the water-bearing strata overlying the Salado Formation, and the Capitan Limestone and other water-bearing strata underlying the Salado. The distribution and development of large dissolution features, particularly in the Nash Draw and Clayton Basin areas, exert a major effect on the occurrence and movement of the groundwater. The Pecos River receives nearly all of the groundwater outflow from the area. Most of that outflow reaches the Pecos near Malaga Bend.

The main water-yielding units overlying the Salado Formation are the basal solution breccia zone and the Culebra Dolomite Member of the Rustler Formation, the Santa Rosa Sandstone, and the alluvium. The basal solution breccia zone is the hydrologic unit most significant in the solution of halite from the upper part of the Salado Formation. The easternmost extent of evaporite solution in the potash mining area is roughly at the common boundary between Ranges 30 and 31 E. The formations above the Salado Formation seem to be connected hydrologically and can be considered a single multiple aquifer system. Solution activity and associated collapse, subsidence, and fracturing have increased the overall permeability of the rocks and the interformational movement of water in the aquifer system.

Groundwater in the formations above the Salado moves generally southward and southwestward across the potash mining area toward the Pecos River. Although the total amount of groundwater discharging to the Pecos River is not known, it has been estimated that 200 gals per minute enter the river from the basal solution breccia zone.

The potentiometric and water-table contours outline a series of groundwater ridges and troughs imposed on the regional southward to southwestward pattern of groundwater movement. A large southwestward-plunging groundwater trough extends from Malaga Bend northeastward roughly through Nash Draw to beyond the mining area in the vicinity of Laguna Plata. Another much smaller trough is east and southeast of the Project Gnome site.

The Salado Formation has an intergranular porosity and permeability that ranges from low to virtually none. Locally, fractures and solution openings impart a spotty formational permeability. In the potash mining area, the Salado Formation is dry except for water in the leached zone at the top of the formation and small pockets of water or water and gas encountered occasionally during mining.

The Cambrian to Permian sedimentary rocks underlying the Salado Formation contain water of brine composition and are under high artesian pressure. These rocks are not exposed in the potash mining area but lie deeply buried throughout much of southeastern New Mexico and western Texas. In the potash mining area the elevations of the potentiometric surfaces of different zones of these rocks range from a few ft to a few hundred ft above or below the land surface.

Brookins, D.G. 1980a. "Polyhalite K-Ar Radiometric Ages from Southeastern New Mexico," *Isochron/West*. No. 29, 29-30.

ABSTRACT: Four new radiometric K-Ar ages for polyhalites from southeastern New Mexico are compared to seven previous ages. The new samples are mixed with halite and sylvite. The exact halide content could not be determined from x-ray diffractometry, nor can it be stated with certainty that other halides and/or other evaporite minerals are present or not. Earlier studies of langbeinite and langbeinite-sylvite mixtures noted a distinct lowering of K-Ar ages with increasing sylvite content. The K-Ar analyses and age calculations were carried out by Geochron Laboratories, Inc., to see if similar effects are noted for polyhalites.

Of eleven samples, four polyhalites considered pure average 11.98% K, and these samples range from 200 to $216 \pm$ million years. Six less pure samples average 12.39% K and range in age from 209 ± 7 million years to 154 ± 15 million years. Samples with observed sylvite yield more recent ages. One sample, mixed with halite and sylvite, was adjacent to a Tertiary age igneous dike; the evaporite sample yielded an age of 21.4 ± 0.8 million years. DWP

ANNOTATION: The seven previous ages for polyhalitic samples are reported in Brookins, Register and Krueger (1980), which is included in this bibliography. An earlier study by Schilling (1973) which showed the lower ages related to sylvite content, is not referred to in this bibliography.

Brookins, D.G. 1980b. "Use of Evaporite Minerals for K-Ar and Rb-Sr Geochronology: Evidence from Bedded Permian Evaporites, Southeastern New Mexico, USA," *Naturwissenschaften*. Vol. 67, 604.

ABSTRACT: Potassium-rich evaporites of the Delaware Basin (USA) are known to be Permian in age; they have not been subjected to tectonism except mild folding. A Tertiary igneous dike intrudes the evaporites, and Pleistocene rubble chimneys are known. The K-Ar and Rb-Sr systematics of these rocks have been evaluated for the effects of post-formation events such as dissolution, deformation, and nonepisodic events. Sylvite samples have been dated by Rb-Sr methods, and polyhalite was studied with K-Ar. Sylvite isochrons from Rb-Sr methods yield an age of 214 ± 15 Ma for 36 samples. K-Ar methods yielded ages of 198 ± 7 Ma to 216 ± 7 Ma for pure polyhalite and 154 ± 15 Ma to 187 ± 7 Ma for impure polyhalite. The lowered ages apparently are proportional to Na content as halite in impure samples. Diapirism or pronounced events will perturb these systems, but K-Ar and Rb-Sr should be useful tools to examine chemical-isotopic integrity of the beds. DWP

Brookins, D.G. 1980c. "Clay Minerals Suitable for Overpack in Waste Repositories: Evidence From Uranium Deposits," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, MA, November 27-30, 1979*. Ed. C.J.M. Northrup, Jr. New York, NY: Plenum Press. Vol. 2, 427-435.

ABSTRACT: Studies of clay minerals as overpack material around radioactive waste canisters have resulted in some disagreement over migration of radionuclides through the overpack. Data on clay minerals from uranium deposits of the Grants, NM, mineral belt are useful because these deposits are old, some have been remobilized and reprecipitated, some have had uranium disseminated by groundwater, and deposits have characteristic clay mineral and elemental suites.

Rb-Sr studies suggest that most of these clay mineral assemblages have remained closed systems since deposition or diagenetic events. Barren zones are typically more montmorillonite-rock, while uranium ore zones include more chlorite or illite; the data suggest chlorite forms during mineralization and fixes a number of elements. It is argued that sand-poor shales from the Morrison Formation be used as canister overpack materials. In the event of canister failure, reactions should promote chlorite formation and sorption of radionuclides. The clay would also retard fluid flow around canisters. DWP

Brookins, D.G. 1981a. "Geochemical Study of a Lamprophyre Dike Near the WIPP Site," *Scientific Basis for Nuclear Waste Management, Proceedings of the Third International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, MA, November 17-20, 1980*. Ed. J.G. Moore. New York, NY: Plenum Press. Vol. 3, 307-313.

ABSTRACT: A Tertiary-age igneous dike intrudes the evaporite rocks of the Delaware Basin over a length of about 125 km. The contact effects can, with caution, be used as an analog to emplacing a radioactive waste canister in the Salado Formation. Contact effects include recrystallization and alteration of typical Salado silicate assemblages (corrensite + illite + talc + chlorite) to 1M-d phlogophtic clay $\pm$ saponite $\pm$ mixed layer saponite-chlorite $\pm$ a talc silicate mixture. Fluid inclusions show maximum homogenization temperatures of 150°C at the contact zone. Fluid movement was probably restricted to very close to the dike edge. Chemistry of the rocks is relatively homogeneous. Rare earth element (REE) analyses from the dike rock are typical of these rocks with pronounced enrichment of light REE relative to heavy REE. Ce and Eu do not show loss or negative anomaly. There appears to have been little chemical exchange between dike and host evaporite; the host evaporites were more altered

although not extensively and with little modification of original structures. This indicates canister and overpack "should remain relatively stable in the evaporites." DWP

Brookins, D.G. 1981b. "Geochronologic Studies Near the WIPP Site, Southeastern New Mexico," *Environmental Geology and Hydrology in New Mexico*. Eds. S.G. Wells, W. Lambert, and J.F. Callender. New Mexico Geological Society Special Publication No. 10. [Roswell, NM]: New Mexico Geological Society. 147-152.

ABSTRACT: The US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) Site is currently being investigated for pilot storage of defense-generated radioactive waste. A critical facet of the overall study is the question whether the rocks have remained closed systems with respect to their bulk chemistry and isotopic composition since formation in the Late Permian or whether they have been subjected to episodic or more-or-less continuous recrystallization during the post-Late Permian. Early attempts at K-Ar dating of sylvites mixed with other salts yielded inconclusive results, primarily because sylvite is not well suited for K-Ar study because of loss of radiogenic ^{40}Ar . Rb-Sr study of sylvites yields a 214 ± 15 million years before present (MYBP) isochron indicating closed system conditions to Rb and Sr since latest Permian or earliest Triassic. Pre-200 MYBP K-Ar dates have also been determined for pure langbeinites and polyhalites. When mixed with sylvite, age lowering results. The Rb-Sr systematics of eolian clay minerals known to have interacted with the evaporite brine yield a poorly defined isochron of 390 ± 77 MYBP, but the apparent date does indicate that the clay mineral-brine interactions were not so severe as to completely rehomogenize Sr isotopes despite the clay mineral alteration. A 34 ± 1.5 MYBP lamprophyre dike intrudes the evaporite sequence some 70 km north of the WIPP Site. Contact effects, including recrystallization of polyhalite, are restricted to within 10 m of the dike. Finally, polyhalite inclusions in one rubble chimney yield a pre-200 MYBP age indicating no major recrystallization effects caused by this disturbance of the evaporite sequence. Collectively, the geochronologic studies argue for pre-200 MYBP formation of the evaporite minerals and stability of the rocks since that time.

ANNOTATION: The sylvite studies reported here are derived from Register and Brookins (1980), while the polyhalite dates were reported by Brookins, Register, Krueger (1980). Both of these references are included in this bibliography.

Brookins, D.G. 1982. "Study of Polyhalite from the WIPP Site, New Mexico," *Scientific Basis for Nuclear Waste Management, Proceedings of the Materials Research Society Annual Meeting, Boston, MA, November 1981*. Ed. S.V. Topp. New York, NY: North-Holland. Vol. 6, 257-264.

ABSTRACT: Polyhalite ($\text{K}_2\text{Ca}_2\text{Mg}(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$) is an important mineral present in the bedded evaporites of the Waste Isolation Pilot Plant (WIPP) Site, southeastern New Mexico. Polyhalite contains two structurally bonded water molecules, and it is thus important to know if this mineral formed at or close to the time of sedimentation or, as proposed by others, more or less continuously throughout the Mesozoic and Cenozoic. If formed much later than original evaporite formation, then this implies a new source of water in order for the polyhalite to form in turn raising questions about water abundance and mobility in the bedded evaporites. Polyhalite is not well suited for Rb-Sr geochronologic study because of the large amounts of common Sr, but it has been shown to be suitable for study by the K-Ar geochronologic methods. Pure polyhalites and those mixed with very small amounts of impurities yield K-Ar dates in the range of 200-220 MYBP and indicate little if any, loss of ^{40}Ar . Polyhalites mixed with sylvite, halite, and (Na,K)Cl yield lower ages due to loss of ^{40}Ar from the halides. Apparent age lowering is proportional to halide content, and an extrapolated age of formation of near 225 MYBP results. Collectively, the K-Ar data convincingly show that the polyhalites formed at the time of sedimentation (except for isolated occurrences near dike intrusions) in

Late Permian time. Finally, thermodynamic calculations, supported by petrographic study, show that polyhalite is often stable with respect to carnallite, sylvite, and other minerals formerly thought to be older than polyhalite.

Brookins, D.G. 1988. "Seawater $^{87}\text{Sr}/^{86}\text{Sr}$ for the Late Permian Delaware Basin Evaporites (New Mexico, USA)," *Chemical Geology*. Vol. 69, 209-214.

ABSTRACT: The Delaware Basin, southeastern New Mexico, USA, contains a thick section of marine evaporites. The three uppermost units of evaporites, all from the time of the Ochoan deposition, are (in ascending order) the Castile Formation, the Salado Formation, and the Rustler Formation. The Castile consists predominantly of bedded and massive anhydrites; the Salado of massive halite with numerous interbeds of anhydrite, sylvite, and minor other units; and the Rustler of impure anhydrites, gypsums, halites, silty and clayey units, dolomites and others.

The previously established seawater $^{87}\text{Sr}/^{86}\text{Sr}$ curve for the Late (Latest?) Permian is marked by a dramatic increase from ~ 0.7068 at ~ 250 Ma ago to >0.7072 by the Permian-Triassic boundary. Data are not shown for rocks of approximate Ochoan age.

The results of our study show the following average $^{87}\text{Sr}/^{86}\text{Sr}$ values for the rocks samples: Castile $0.706880 (\pm 0.000005)$; Salado $0.70688 (\pm 0.000004)$; and Rustler $0.706976 (\pm 0.000008)$. Thus, a systematic increase in $^{87}\text{Sr}/^{86}\text{Sr}$ is observed from Castile to Salado and especially to Rustler, consistent with a previous prediction. These data are submitted for the seawater curve for the Ochoan Group of upper evaporites of Late Permian age.

Brookins, D.G., and S.J. Lambert. 1987a. "K-Ar and Rb-Sr Age Determinations from Clay Minerals and Related Minerals from the WIPP (Waste Isolation Pilot Plant), Southeastern New Mexico," *Isochron/West*. SAND86-0223J. Vol. 49, 4-7.

ABSTRACT: Potassium-argon (K-Ar) and rubidium-strontium (Rb-Sr) dates on clay minerals in samples from the lower Salado Formation cluster between about 330-430 Ma. An isochron of 428 Ma signifies that samples have been little affected by diagenesis in the brines. The isochron and limited range of ages may be indicating a particular (though unidentified) source area.

Brookins, D.G., and S.J. Lambert. 1987b. "Radiometric Dating of Ochoan (Permian) Evaporites, Waste Isolation Pilot Plant Site, Delaware Basin, New Mexico, USA," *Scientific Basis for Nuclear Waste Management: A Materials Research Society Fall Meeting*, Boston, MA, December 1-4, 1986. Eds. C.K. Bates and W.B. Scott, Jr. SAND86-2190. Pittsburgh, PA: Materials Research Society. Vol. 84, 141-150.

ABSTRACT: We have attempted radiometric dating of halite, carnallite, and other minerals from the Delaware Basin. These systems are of major importance for understanding the stability of the evaporite sequence at the Waste Isolation Pilot Plant (WIPP) site, a U.S. Department of Energy (DOE) facility. We undertook this dating to determine (1) primary age of evaporite genesis, (2) timing of recrystallization, (3) age of bedded and bedded evaporite minerals (leontes, polyhalite, leucocite), gypsum, dolomite, and (4) the potential for some of these minerals to have been radiometrically reset at any time following their incorporation into the evaporite medium. We have shown earlier that polyhalite can indeed be successfully dated by the K-Ar method, and once corrections are applied for bedded anhydrite minerals, ages of 330 ± 10 Ma for the Delaware Basin are obtained. Polyhalite from non-bedded upper Salado polyhalite anhydrites yield 220 ± 10 Ma, even when corrected for bedded anhydrite, due to loss of ^{40}Ar from K-Ar dates on leontes and leucocite, and due to uptake of ^{87}Ar by Rb-Sr dates on

higher. Detrital clay minerals from the Delaware Basin collectively yield a highly scattered isochron (390 ± 77 Ma), but samples from a local area, such as the WIPP Site, give a much better age of 428 ± 7 Ma. These dates show that the interaction between the clay minerals and the evaporitic brines was insufficient to reset the clay minerals Rb-Sr systematics. In a related study, we note that a dike emplaced into the evaporite at 34 Ma had only very limited effect on the intruded rocks; contact phenomena were all within 2 m of the dike. All of our geochemical (radiometric and trace element) studies of the WIPP Site argue for preservation of the isotopic and chemical integrity of the major minerals for the past 200 Ma.

Brookins, D.G., and S.J. Lambert. 1988. "WIPP Site Studies: Secondary Selenite Veins in the Rustler Formation and Dewey Lake Red Beds," *Scientific Basis for Nuclear Waste Management XI*, Boston, MA, November 30-December 3, 1987. Eds. M.J. Apted and R.E. Westerman. SAND87-1610J. Pittsburgh, PA: Materials Research Society. Vol. 112, 233-241.

ABSTRACT: Defense-generated transuranic (TRU) waste will be stored at the Waste Isolation Pilot Plant (WIPP) in the bedded halite of the Salado Formation (Permian), which is overlain by the impure Permian evaporites of the Rustler Formation and the Dewey Lake Red Beds. Both the Rustler and Dewey Lake contain abundant to less common secondary selenite veins of uncertain origin, and dissolution zones occur in the Rustler. The Rustler Formation also contains two dolomite aquifers, the Magenta and Culebra Members. The purpose of this study is to determine whether vein selenite is locally derived or has been introduced in moving groundwater solutions. We have used Sr isotopic studies and rare earth elements (REE), U and other trace element data to address the problem. The Sr isotopic data show that neither the Salado nor Rustler anhydrites have exchanged with secondary sources of Sr, and this is supported by the REE and U data. Further, selenite veins from the Rustler possess Sr isotopic compositions identical to the Rustler, indicating local origin, and this is also supported by the U and REE data. Selenite veins from the Dewey Lake Red Beds possess Sr isotopic compositions closer to surface caliche deposits and may contain near-surface derived Sr. U and REE data show more scatter and evidence for extrinsic sources than the vein/host-rock pairs from the Rustler. Sr isotopic compositions of the Magenta and Culebra indicate that the Magenta has undergone less water/rock interaction than the Culebra. Collectively, the data argue for more possible surface or near-surface water/rock interactions in the Dewey Lake Red Beds than in the Rustler Formation; such interactions in the Salado Formation have been minimal.

Brookins, D.G., and J.K. Register. 1981. *Potassium-Argon and Neutron Activation Analysis Studies of Polyhalites near the WIPP Site*. SAND81-7071. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Polyhalite may indicate the stability of the evaporite section. If polyhalite is young, structurally bonded water could indicate water infiltration; old polyhalite indicates no infiltration as polyhalite is quite soluble. Five of eight samples agree with independent evidence of an Rb-Sr date of 213 ± 10 Ma. Ages 20-30 million years younger than the Permian suggest a final diagenetic recrystallization. Two samples included in the five come from a rubble chimney, indicating limited fluid involvement in forming the chimney. Samples with sylvite and halite yielded younger ages (suggesting that samples with halide impurities yield younger ages. An empirical correction factor for ages is suggested based on Na_2O content.) Samples associated with a Tertiary-age dike show ages younger than, but consistent with, the intrusion age. These samples are indirect evidence that the dike affected only contact zones and that continuous to episodic recrystallization of evaporites through the Mesozoic and into the Cenozoic is not supported.

Neutron activation analyses for Na content provide evidence of rare earth element (REE) and other trace element concentrations. Two samples of the intrusive (lamprophyre) are typical of

alkali basalts or lamprophyres, demonstrating little if any loss or exchange of REE to evaporites. DWP

Brookins, D.G., J.K. Register, Jr., and H.W. Krueger. 1980. "Potassium-Argon Dating of Polyhalite in Southeastern New Mexico," *Geochimica et Cosmochimica Acta*. Vol. 44, no. 5, 635-637.

ABSTRACT: Polyhalite, $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$, is an important mineral in many evaporites. Although its use for K-Ar dating has never been investigated, our results indicate that it is a very useful mineral for dating events ranging from the time of potash mineralization to any younger events that may have affected the evaporite. Five K-Ar dates on pure polyhalite, including two from included material and from beds distorted by the formation of a rubble chimney, yield dates between 198 and 216 Myr, in good agreement with Rb-Sr dates and the diagenetic age of the potash deposits from the same rocks. Two polyhalites mixed with sylvite gave lower dates (154 and 174 Myr) which is to be expected because of radiogenic ^{40}Ar loss from the sylvite phase. One polyhalite, formed after the intrusion of a 31 Myr lamprophyre dike, yielded 21 Myr. Collectively our results indicate that pure polyhalite is satisfactory for K-Ar dating and may provide critical age information in studies of the geologic history of the evaporite sequences.

Brookins, D.G., D.B. Ward, and S.J. Lambert. 1990. "Authigenic Clay Minerals in the Rustler Formation, WIPP Site Area, New Mexico," *Scientific Basis for Nuclear Waste Management 13, Boston, MA, November 27-December 2, 1989*. Eds. V.M. Oversby and P.W. Brown. SAND89-1405C. Pittsburgh, PA: Materials Research Society. 665-672.

ABSTRACT: Transuranic (TRU) waste is planned for disposal in the Late Permian evaporites of the Delaware Basin, southeastern New Mexico, at the Waste Isolation Pilot Plant (WIPP) Site. The disposal horizon is located in the bedded halite of the Salado Formation, which is overlain by the impure halite-anhydrite (gypsum)-siltstone-mudstone of the Rustler Formation. The Rustler Formation also contains two dolomite members, the Magenta and Culebra, which transmit water. The Culebra Member is suspected to have actively interacted with waters at times from the Late Permian to the present, and it is important to assess the reactivity of these waters in conjunction with WIPP stability.

We have investigated the Rb-Sr systematics of clay minerals from the Culebra Member and elsewhere in the Rustler Formation. By separating the less than 0.125-microdarcy size material we are able to deal with presumed true authigenic clay minerals. The authigenic fraction is especially sensitive to chemical and isotopic exchange with waters, and an episodic exposure to a large amount of water will reset the clay minerals to such a time. Our data yield 259 ± 22 Ma Rb-Sr isochron, which is consistent with the Late Permian age of the Rustler Formation. This age demonstrates that age-determining cations in these clay minerals have preserved their isotopic and chemical integrity since the Late Permian.

Brookins, D.G., J.K. Register, M.E. Register, and S.J. Lambert. 1978a. "Burying High Level Wastes," *Nature*. Vol. 273, no. 5665, 704.

ABSTRACT: K-Sr data have been improperly interpreted to argue against evaporites for burial of radioactive waste. K-Ca analyses of sylvite demonstrate solid species are retained, even though inert gas, such as ^{40}Ar , can be lost. Sylvite from New Mexico yields low K-Ar dates (18 ± 8 to 74 ± 8 my), though samples of langbeinite and langbeinite with sylvite yield ages from 245 ± 10 Ma to 137 ± 8 Ma, respectively, and argue against "recent" recrystallization. Rb-Sr studies of water-soluble evaporites and authigenic clays from New Mexico yield a date of 204 Ma. Polyhalite and sylvite are early diagenetic minerals. Argon is therefore not

representative of radiogenic daughter products; strontium has been retained for 200 Ma. Clays have also been observed to preferentially absorb actinides. DWP

Brookins, D.G., J.K. Register, M.E. Register, and S.J. Lambert. 1978b. "Rb-Sr Systematics and Related Studies of the Salado and Castile Formations, Southeastern New Mexico," *Abstracts with Programs, Geological Society of America, 1978 Joint Annual Meeting, Toronto, Ontario, Canada, October 23-26, 1978.* SAND78-1187A. Vol. 10, no. 7, 372. (Abstract Only).

ABSTRACT: Rb-Sr geochronologic study of the bedded salt deposits from the Castile and Salado Formations, southeastern New Mexico, has been undertaken to test their feasibility for alkali and alkaline earth retention in conjunction with the Waste Isolation Pilot Plant (WIPP) in that area.

Whole-rock samples (i.e., water soluble plus insoluble material) are typically unsuited for Rb-Sr isochron work; several of these samples do indicate the R_o (i.e., $Sr(87/86)$ at $T=0$) value to be about 0.708, thus indicating that large amounts of brine, typically enriched in ^{87}Sr , were not generated in the sample area since evaporite formation some 235 ± 10 Ma.

The water-soluble fraction of evaporite samples yields an apparent isochron date of 206 Ma with $R_o = 0.7084$ while clay minerals (minus-two micron size) yield 325 Ma with $R_o = 0.7123$. A composite of the water soluble fractions and clay minerals yields a date of 204 Ma with $R_o = 0.7137$. This 204 Ma date is interpreted as a minimum because of the high R_o value; but it does suffice to indicate that the evaporite-clay mineral systems apparently have remained closed to widespread alkali-alkaline earth migration since close to the age of evaporite formation. Strontium, which is an important mobile constituent of radioactive waste, has certainly been retained in the evaporites for 2×10^8 years. The impurities, such as trioctahedral clays in the rock salt, have also been found to preferentially absorb from aqueous solution actinides present in waste. The information gathered so far from New Mexico suggests that similar studies should be undertaken to assess the favorability of the extensive bedded salt deposits of Canada.

Brookins, D.G., J.K. Register, M.E. Register, and S.J. Lambert. 1980. "Long-Term Stability of Evaporite Minerals: Geochronological Evidence," *Scientific Basis for Nuclear Waste Management, Materials Research Society Annual Meeting, Boston, MA, November 27-30, 1979.* Ed. C.J.M. Northrup, Jr. SAND79-1283C. New York, NY: Plenum Press. Vol. 2, 479-486.

ABSTRACT: Evaporite samples from the Permian Salado Formation have been evaluated with K-Ar and Rb-Sr methods to determine the stability of evaporite minerals. K-Ar analyses of polyhalite samples showed ages from 198 ± 7 to 216 ± 7 Ma for pure specimens and ages of 174 ± 6 and 154 ± 6 Ma for mixtures with sylvite and halite. Rb-Sr dates of water-soluble components yielded an average of 199 ± 20 Ma for 41 samples; an isochron age after five anomalous samples was eliminated in 214 ± 15 Ma with and initial $^{87}Sr/^{86}Sr = 0.7093 \pm 0.0007$. Clay mineral samples yield an isochron age of 390 ± 77 Ma.

The minimum age for Salado-Castile sedimentation and the recommended isochron age for potash ore formation is 214 ± 15 Ma. The recommended isochron age for polyhalite is 208 ± 10 Ma. Ages include samples from rubble chimneys and indicate that large amounts of water did not pass through the chimneys. The system has remained closed for more than 200 million years. ^{40}Ar loss from sylvite gives ages less than 200 Ma. A K-Ar date of 21.4 ± 0.8 Ma on polyhalite with an igneous intrusion shows these minerals can date post-formation events. Initial strontium ratios from these rocks are within the limits for Permian sea water. Clay mineral dates indicate incomplete reaction with brines during deposition and diagenesis. Proposals for continuous to episodic alkali and alkaline earth migration in these sediments after

200 Ma is refuted, and the Waste Isolation Pilot Plant (WIPP) Site is favorable to retain radioactive waste. DWP

Brush, L.H. 1990. *Test Plan for Laboratory and Modeling Studies of Repository and Radionuclide Chemistry for the Waste Isolation Pilot Plant*. SAND90-0266. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This Test Plan describes laboratory and modeling studies of the chemistry of brines that could enter Waste Isolation Pilot Plant (WIPP) disposal rooms; the effects of anoxic corrosion of metals in steel containers and the waste on the gas and H_2O budgets of the repository; the effects of microbial activity, especially microbial degradation of celluloses in the waste, on the gas and H_2O budgets of the repository, the Eh and pH of any brine present, and the chemical behavior of radionuclides; the effects of radiolysis on the gas and H_2O budgets of the repository; the efficacy of backfill additives proposed to remove microbially produced CO_2 or prevent the formation of H_2 from anoxic corrosion, and their effects on repository chemistry; the chemical behavior of Pu, Am, Th, and U in WIPP brines; additional development of the EQ3/6 geochemical software package for use in predicting the behavior of silicates and radionuclides in brines.

This Test Plan describes studies of the chemical behavior of the repository as currently designed and the chemical behavior of radionuclides under these conditions. Addenda will discuss additional studies relevant to designing modifications, especially reprocessed waste, and chemically hazardous waste constituents.

Brush, L.H., D. Grbic-Galic, D.T. Reed, X. Tong, R.H. Vreeland, and R.E. Westerman. 1990. "Preliminary Predictions of Repository Chemistry for the Waste Isolation Pilot Plant," *Abstracts with Programs, Geological Society of America, 1990 Annual Meeting, Dallas, TX, October 29-November 1, 1990*. SAND90-1695A. Vol. 22, no. 7, A100. (Abstract Only).

ABSTRACT: The design-basis, defense-related, transuranic (TRU) waste to be emplaced in the Waste Isolation Pilot Plant (WIPP) could, if sufficient H_2O and nutrients were present, produce as much as 1,500 moles of gas per drum of waste. Gas production could pressurize the repository to 150 atm (lithostatic pressure) and perhaps higher.

Anoxic corrosion of Fe and Fe-based alloys and microbial degradation of celluloses are the gas-production processes of greatest concern, but radiolysis of brine could also be important. The proposed backfill additives $CaCO_3$, CaO , $CuSO_4$, KOH , and $NaOH$ may remove or prevent the production of some of the expected gases. We describe these processes, laboratory and modeling studies to quantify them for design-basis waste, and preliminary results of these studies.

Because of the heterogeneous nature of design-basis waste, the Eh and pH of any brine present in WIPP disposal rooms could vary significantly over short distances after reacting with the waste.

The WIPP Project is investigating the consequences of gas production and considering engineered alternatives, including reprocessing the waste, to reduce gas production rates or potentials. Reprocessing would also reduce the range of Eh and pH expected for the repository.

Buck, A.D. 1985. *Development of Two Candidate Concrete Mixtures (Salt, Nonsalt) for Repository Sealing Applications*. Miscellaneous Paper SL-85-8. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers.

ABSTRACT: Two concrete mixtures were developed in 1983 for possible use in repository sealing application. The salt concrete was basically an adaptation of BCT 1-F salt grout made by adding aggregate. The nonsalt mixture was a similar adaptation of nonsalt BCT 1-FF grout.

The basic requirement was continued workability after 2 hours of intermittent mixing. Tests of hardened specimens included strength, modulus of elasticity, permeability, coefficient of linear thermal expansion, thermal conductivity, expansion, creep, and examinations by x-ray diffraction for phase composition and by scanning electron microscopy for microstructure. Some of the physical tests were done on specimens that had been kept at $23 \pm 1.7^\circ\text{C}$ and on other specimens kept at $61 \pm 2^\circ\text{C}$. Tests for expansion and examinations for phase composition and microstructure are being continued at 6-month or yearly intervals.

It was concluded that each concrete mixture was a viable candidate for use in repository sealing applications.

Buck, A.D., and J.P. Burkes. 1979. *Examination of Grout and Rock from Duval Mine, New Mexico.* Miscellaneous Paper SL-79-16. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

ABSTRACT: Petrographic examination was made of a 17-year-old grout specimen that had been surrounded by rock salt. It was found that the contact between the grout and the rock salt was tight and that the composition and microstructure of the grout seemed normal for such material. The grout contained calcium silicate hydrate, calcium hydroxide, tetracalcium aluminate dichloride-10-hydrate, and some halite and sylvite.

Buck, A.D., and R.E. Reinhold. 1985. *Characterization of Four Class II High Sulfate-Resistant Portland Cements.* Miscellaneous Paper SL-85-9. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers.

ABSTRACT: As part of the materials selection process for underground repository sealing of nuclear wastes, all available Class II high sulfate-resistant (HSR) portland cements that were commercially available in the United States in 1981 were obtained for testing and evaluation. Four such cements were found. The Class II designation is that used by the American Petroleum Institute; the HSR type is similar to a Type V portland cement as described in ASTM C 150 in that it is intended to impart high sulfate resistance to the cement by the absence or near absence of calculated tricalcium aluminate (C_3A).

Each cement was characterized by a combination of chemical-physical testing and x-ray diffraction examination; it was concluded that all were generally similar and could be interchanged if such a need arose.

Buck, A.D., J.A. Boa, Jr., and D.M. Walley. 1985. *Development of a Sanded Expansive Salt Grout for Repository Sealing Application.* Miscellaneous Paper SL-85-11. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers.

ABSTRACT: A sanded version of the basic BCT 1-F expansive salt grout was developed by the US Army Engineer Waterways Experiment Station (WES) in early 1983 for use in a test by Terra Tek in the fall of 1983 in Salt Lake City, UT. This grout is known as TT83. Initial laboratory test showed this mixture had adequate workability, impermeability, strength, and positive volume change. There were problems with flow when this material was batched for the Terra Tek test. Later investigation indicated this was probably caused by use of different equipment with lower mixing capacity. Specimens made from this grout show over 0.1% expansion at an age between 56 and 90 days and about 0.3 to 0.4% at 1 year; expansion testing

is being continued at 6-month intervals. It was concluded that this mixture is probably satisfactory for use in repository sealing applications in a salt-rock horizon.

Buck, A.D., J.P. Burkes, and R.E. Reinhold. 1985. *Characterization of Several Plasters and One Retarder for Repository Sealing Mixtures*. Miscellaneous Paper SI-85-10. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers.

ABSTRACT: Samples of plasters (i.e., calcium sulfate hemihydrate, $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$) from six sources and one plaster retarder from a different source were obtained and characterized by a combination of chemical and physical testing and by petrographic examination. The petrographic examination included x-ray diffraction (XRD), optical microscopy, differential thermal analysis (DTA), and scanning electron microscopy (SEM) procedures.

The intent of this work was twofold. One purpose was to determine whether plaster per se could be used as an ingredient for cementitious mixtures intended for repository sealing applications. Previous experience had been with use of a proprietary admixture that contained plaster. The second purpose was to determine one or more methods of distinguishing between the alpha and beta forms of calcium sulfate hemihydrate.

It was concluded that commercially available plaster of paris rather than a proprietary admixture could be used as an ingredient for the proposed cementitious mixtures. The other finding was that, as expected, the beta form of $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ is finer and thus requires more water for mixing, so the coarser alpha form is preferable for the described use. While the two forms can be distinguished by physical tests, by DTA, by SEM, and by optical microscopy, the latter procedure is the simplest and the quickest. All that is required is examination of a plaster as an immersion mount with a polarizing microscope to determine particle size and shape.

Four of the six plasters were the alpha form while two were the beta form. The retarder contained both forms of plaster along with organic material (thought to be keratin).

Buck, A.D., J.P. Burkes, and J.E. Rhoderick. 1981. *Examination of ERDA-10 Grout Specimens at Different Ages*. Miscellaneous Paper SI-81-20. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

ABSTRACT: A bore hole designated ERDA-10 was filled with portland cement-based grout in October 1977. The bore hole is located in Eddy County, NM. The hole was filled with grout of four compositions, three of which were similar and made with salt water as mixing water; the upper portion of the hole was filled with a grout made using fresh water as mixing water. During the filling operation, test specimens were cast using these grouts. The deepest plug (plug 1) was cored 48 hours after placement. During the filling operation, test specimens were cast using all four grout compositions. The core from plug 1 and the test specimens were sent to the Structures Laboratory of the US Army Engineer Waterways Experiment Station (WES) for physical tests and petrographic examination. They were stored in the laboratory at temperatures ranging from about 23 to 54°C.

Tests and examinations were made at three ages: 23 ± 8 days, approximately 1 year, and approximately 3 years. This report presents the results of the petrographic examination that included use of x-ray diffraction (XRD) and scanning electron microscopy (SEM).

The grouts made with salt water formed tetracalcium aluminate dichloride-10-hydrate ($\text{C}_3\text{A}(\text{CaCl}_2)\text{H}_{10}$) at the expense of ettringite during continued hydration. The $\text{C}_3\text{A}(\text{CaCl}_2)\text{H}_{10}$ was already present when the grouts were examined at the early ages (23 ± 8 days).

The amount of calcium hydroxide in both the salt-water and the fresh-water grouts decreased with age. The calcium hydroxide presumably was reacting with the fly ash in the grout to produce calcium silicate hydrate.

The microstructures of the grouts showed progressive densification with age. This microstructure was always fairly open because of the high water-to-solids ratios; these were 0.64 to 0.74 by mass for the three salt-water grouts and 0.49 for the fresh-water grouts.

Phase composition and microstructure were considered normal for these materials; the range of temperature from about 23 to about 54°C did not seem to have any detectable effect on composition or microstructure.

It was found that carbonation had taken place during 3 years of immersion in salt water or fresh water. Carbonation was largely confined to surfaces of specimens.

Some cracking of specimens had taken place. This is ascribed to a combination of several factors that included shrinkage after heat of hydration expansion, possible short periods of drying during storage and during intermittent testing, and possible expansion caused by continued hydration after the initial cooling.

In spite of some carbonation and cracking of specimens, the earlier published and present data suggest that these grouts should be regarded as satisfactory compositions for their intended purpose.

Buck, A.D., J.E. Rhoderick, J.P. Burkes, K. Mather, R.E. Reinhold, and J.A. Boa, Jr. 1983. *Modification of Bell Canyon Test (BCT) 1-FF Grout*. Miscellaneous Paper SL-83-18; SAND83-7097. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

ABSTRACT: Bell Canyon Test (BCT) 1-FF grout was developed as a candidate material for use in repository sealing applications and was actually used in two field tests in New Mexico.

This grout and modifications of it were made in the laboratory and tested or examined for workability, compressive strength, restrained expansion, permeability, phase composition, and microstructure. Most of these were done to an age of 1 year. Compressive strength and expansion data were determined beyond this age (960 days). Modifications included use of three other cements, two other fly ashes, a silica fume, different water contents, and different amounts of expansive additive (plaster).

Each cement and mineral admixture was characterized by conventional chemical and physical tests as well as by x-ray-diffraction examination.

In general, the results indicated that the modifications to the basic BCT 1-FF grout produced other grouts that were as good as it. An exception to this was the grout mixture (M-8-C) made with shrinkage compensating expansive cement; it had an excessive flow time (>20 sec). Another grout mixture (M-9-C) also had excessive flow time and lower strength.

It was thought that these problems could be solved with more modification to these two mixtures.

Burkes, J.P., and J.E. Rhoderick. 1983. *Petrographic Examination of Bell Canyon Tests (BCT) 1-FF Field Grouts Over a Three-Year Period*. Miscellaneous Paper SL-83-12; [SAND83-7115.] Vicksburg, MS: US Army Engineer Waterways Experiment Station.

ABSTRACT: The Bell Canyon field test involving the placement of two grout plugs took place 26 September 1979 (Plug 1) and 14 February 1980 (Plug 2), respectively. Samples cast in the

field were brought to the US Army Engineer Waterways Experiment Station (WES) and cured in hole AEC-7 (lease) brine. Samples were examined periodically through 1 year and then at 2- and 3-years of age to obtain petrographic, physical, and some chemical data. This report deals solely with the petrographic data because the physical data have been presented in other reports. Cracking of specimens was observed; this was believed to be caused largely by moisture and temperature changes in the laboratory.

The two plugs were similar in composition; Plug 1 grout had more tetracalcium aluminate monosulfate-12-hydrate (C_4ASH_{12}) and more garnet-hydrogarnet solid solution series material (hydrogarnet) by x-ray diffraction (XRD) than Plug 2. Tetracalcium aluminate dichloride-10-hydrate ($C_3A(CaCl_2)H_{10}$) was present in both samples in varying amounts at different ages. The amount of ($C_3A(CaCl_2)H_{10}$) in the samples was probably controlled by the proximity of the surface examined by XRD to the brine the samples were stored in.

The Plug 2 grout contained more ettringite and calcium hydroxide; Plug 1 grout contained more detectable calcium silicate hydrate (C-S-H). The grout-to-host (anhydrite rock) bond appeared to be tight with no visible cracking in simulated-borehole samples that were examined immediately after fracturing. A white precipitate was found on samples of both events during storage and is believed to be a combination of some chemical reaction between the groundwater and grout as well as precipitate from the brine. It had no detectable detrimental effects.

The infiltration of the brine during placement of the grout in satellite Holes 3 and 4 weakened the grout and retarded some of the grout so that it did not harden.

The XRD examinations of both Plug 1 and Plug 2 grouts point out that chloride and carbonate ions from the brine are causing some alteration to the original phases at and near the contact of grout and brine. After 3 years of storage, this alteration has penetrated the grout to a depth of about 1 or 1.5 in. with the severity of alteration becoming less with increasing distance from contact surfaces.

The grout from the two placements at ages up to 3 years showed no significant overall deterioration or alteration from the original grout.

The Plug 1 and Plug 2 samples will continue to be examined by XRD and SEM at 1-year intervals for an indefinite time.

Butcher, B.M. 1980. *Creep Consolidation of Nuclear Depository Backfill Materials*. SAND79-2212. Albuquerque, NM: Santa National Laboratories.

ABSTRACT: Evaluation of the effects of backfilling nuclear-waste repository rooms is an important aspect of waste-repository design. Consolidation of the porous backfill takes place as the room closes with time, causing the supporting stress exerted by the backfill against the intact rock to increase. Estimation of the rate of backfill consolidation is required for closure-rate predictions and should be possible if the creep law for the solid constituent is known. A simple theory describing consolidation with a spherical void model is derived to illustrate this relationship. Although the present form of the theory assumes a homogeneous isotropic incompressible material atypical of most rocks, it may be applicable to rock salt, which exhibits considerable plasticity under confined pressure. Application of the theory is illustrated assuming a simple steady-state creep law to show that the consolidation rate depends on the externally applied stress, temperature, and porosity.

Butcher, B.M. 1981. "An Elastic-Plastic Mechanical Constitutive Description for Rock Salt Triaxial Compression," *EOS Transactions, American Geophysical Union*. SAND80-1935A. Vol. 62, no. 45, 1029. (Abstract Only).

ABSTRACT: A model for the time-independent part of the mechanical deformation of rock salt from the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico is presented. A recently published creep model was first used to correct conventional triaxial compression data for time-dependent deformation. The experimental data was from tests at a loading rate of approximately 11.9 N/s, 23°C and confining pressures from 0 to -20.7 MPa. The corrected time-independent curves were then used to determine material constants for the model. Generalization to a three-dimensional plasticity failure theory using a general constitutive relation was also performed.

Butcher, B.M. 1989. *Waste Isolation Pilot Plant Simulated Waste Compositions and Mechanical Properties*. SAND89-0372. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Analyses of the final state of collapse of various types of contact handled (CH) waste drums are required to assess the performance of the waste storage areas in the Waste Isolation Pilot Plant (WIPP). To provide data for calculations, tests must use simulated (instead of actual) waste. Data on the contents of the principal categories of contact handled transuranic (TRU) waste from the Idaho National Engineering Laboratory (INEL) were used to define standard compositions of simulated waste. Categories of baseline waste will be created by mixing appropriate amounts of the simulants together. Selection of materials is discussed. Methods for estimating the consolidation characteristics of simulated waste are also described. Theoretical solid densities, theoretical solid compressibilities, and initial void volumes of various waste components are estimated, and a method for estimating consolidation curves in the absence of experimental data is described.

Butcher, B.M. 1990. *Preliminary Evaluation of Potential Engineered Modifications for the Waste Isolation Pilot Plant (WIPP)*. SAND89-3095. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Analyses related to the *Supplemental Environmental Impact Statement (SEIS)* and preliminary performance assessment studies have suggested that alteration of the method of waste emplacement in the Waste Isolation Pilot Plant (WIPP) may be necessary to satisfy waste storage regulations. Good engineering practice also dictates consideration of changes that are useful for better containment of waste. This report presents a preliminary evaluation of various engineered modifications that might be considered. The report is based on work that has been ongoing at Sandia National Laboratories (SNL) since FY88, before formation of the present Engineered Alternatives Task Force (EATF) by the Department of Energy (DOE) WIPP Project Office.

The engineered modifications under consideration are described and characterized in the first part of the report according to the objective that would be addressed by their application; their level of complexity; and some of the presently understood limitations and uncertainties of their use. Results of studies conducted to date to examine the feasibility of some of the modification concepts are presented, with emphasis on the effects of waste "supercompaction."

The principal conclusion from these studies is that, while reprocessing or other treatment of combustible waste is desirable, some degree of processing of metallic wastes is necessary to meet desired waste-room storage requirements. The primary reasons for these conclusions are that the expected porosity and permeability of unprocessed metallic wastes, and to a lesser extent combustible waste, appear to be excessive, relative to permeabilities required to control brine flow in the event of human intrusion into the WIPP Facility; and processing, in combination with gas-generation prevention measures, can be used to reduce both total gas-generation quantities and rates.

For processing of the waste, either shredding of metallic wastes and mixing with one or more filler materials, or reducing the waste void volume in drums by in situ grouting, is being

considered on the basis of present information, to greatly reduce in situ permeabilities. In addition, such treatment may provide benefits in reducing the total gas-generation quantities in the WIPP repository environment; controlling brine chemistry, and hence effective radionuclide solubilities within the repository; and making predictions of both short- and long-term repository behaviors more reliable by making the room behavior and environment more uniform.

In addition to processing, the following engineering modification is considered necessary for emplacement of the waste. The modification utilizes a grout barrier around individual seven-packs of supercompacted or grouted waste to further reduce flow of fluids. With this design, the seven-packs and the grout are mechanically rigid and strong and will support expected overburden pressures without excessive deformation or cracking. In contrast, unprocessed waste in a similar configuration would be expected to undergo extensive compaction, causing the grout to fail. The present concept also includes the possibilities that gas-getters or preventers (such as copper sulfate $[CuSO_4]$) might be emplaced in or between individual drums in each seven-pack; and modified backfill such as salt/bentonite or bentonite screens might be emplaced outside the grouted waste units. Several critical studies that will address the validity of these modifications are under way and others are needed, as discussed in the report.

The modifications described in this report are proposed in the hope that they will serve as a focus for further definition and numerical evaluation. To further test their validity, they must also be incorporated into laboratory, bin-scale, and alcove testing as quickly as practicable.

Butcher, B.M., and J.P. Hill. 1984. *A Method for Defining the Distribution of Triaxial Stress States in Underground Structures*. SAND83-2506. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A method for defining the distribution of triaxial stress states in three-dimensional underground structures is described. The reason for interest in the degree of triaxiality is that one of the ways to evaluate how well a particular constitutive model correctly predicts stress states in the underground structure is by comparison with laboratory results, i.e., laboratory tests should be undertaken that simulate as closely as possible the dominant triaxial stress paths and end states the underground structure is likely to encounter during service. Thus, the dominant triaxial states of a particular application must be defined to permit constitutive model evaluation. The method is illustrated by examination of the solution from a preliminary stress analysis of a complex drift configuration at the bottom of a deep shaft in a proposed underground testing facility. In this example the dominant triaxial states depend very strongly on the assumed in situ stress state and are quite distinct from stress states normally considered in laboratory testing. A method of showing the distribution of stress states is shown, as well as discussion of how this information can be used to plan a constitutive model development program.

Caldwell, D.E., R.C. Hallet, M.A. Molecke, E. Martinez, and B.J. Barnhart. 1988. *Rates of CO₂ Production from the Microbial Degradation of Transuranic Wastes Under Simulated Geologic Isolation Conditions*. SAND87-7170. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Transuranic (TRU) wastes containing organic matter can serve as an energy source for microbial growth. The rates of microbial respiration during decomposition of several transuranic-contaminated waste materials were measured under environmental conditions representative of a geologic waste repository in bedded salt. The major observed effect of microbial activity on organic-matrix wastes was the generation of CO₂ gas. Experimental variables studied include incubation temperature (25 to 70°C), atmosphere (aerobic and anaerobic), moisture content, brine content, and plutonium contamination level (0 to 40 microcuries of alpha activity per gram of waste). The maximum rate of CO₂ generation observed was 11 g/day per g of waste. The addition of 300 µg (20 µCi) of defense-grade PuO₂ per g of waste reduced the rate of CO₂ generation by approximately 70%. Results indicate that microbial activity in existing drums of defense-related transuranic wastes has the potential to generate significant quantities of gas under both aerobic and anaerobic conditions. Carbon dioxide was the only gas detected in these studies. No evidence was found for the conversion of europium, thorium, or plutonium to volatile gas species via microbial alkylation reactions such as those known to alkylate mercury and lead.

Callender, J., and T. Ingwell. 1978. *Structural Petrology of Undeformed and Experimentally Deformed Halite Samples from USERDA site #7 and #9*. SAND78-7076. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This paper presents preliminary data on the structural petrology of polycrystalline halite from USERDA test holes ERDA-7 and ERDA-9 in the Salado Formation of southeastern New Mexico. Observations of undeformed and experimentally deformed core samples suggest unique fabric elements for each state.

Cores consist primarily of halite (>80 modal %), clay (≥7%), polyhalite (≥3%), anhydrite (≥3%), celestite (trace), iron oxide (trace), and magnesite (trace). Paragenetic relations are similar to those described by Braitsch (1971, *Salt Deposits: Their Origin and Composition*. Berlin: Springer Verlag) in which gypsum in a primary assemblage gypsum + halite is succeeded by secondary anhydrite, which is commonly recrystallized to halite and subsequently polyhalite.

Macroscopic features of undeformed core include moderately tight grain boundaries, large cavities (≤8 mm²), fluid inclusions, rare intragranular dislocations, and coarse and bimodal textures. Petrographic examination reveals numerous secondary fluid inclusions of variable size, blebby halite, and transected hopper crystals, all of which suggest mobility and recrystallization of the primary evaporite assemblages.

Deformed core shows a complex group of fabric elements, including tight grain boundaries, intercrystalline lattice rotation, cavity deformation and closure, distortion of hopper crystals, polygonization, irregular lattice dislocations, glide dislocations, and climb dislocations. Grain boundaries become tight or locked with deformation, forming "pinned" and "bulged" grains. Intercrystalline lattice rotation causes grains to rotate as much as 17° to develop preferred orientation. Cavity closure appears to be significant with as much as a four-fold decrease in cavity volume with deformation. Hopper crystals are highly distorted by deformation. Polygonization yields fabrics analogous to prophyroclasts in cataclastic rocks. Irregular dislocations, including plumose, en echelon, triangular, and checkerboard patterns, are relatively abundant. Glide dislocations, characterized by birefringent zones and fields, are also abundant in many deformed specimens.

Individual mineral components within deformed halite also exhibit deformational fabrics. Folded layers of clay and anhydrite and bent and broken single crystals of anhydrite are present in some samples. Secondary fluid inclusions apparently migrate in response to differential stress and form along dislocations in halite, "healing" the dislocations by secondary crystallization and forming discontinuous or completely "healed" dislocation fabrics.

Canfield, T.R. 1983. *Stresses Near Waste Canisters Buried in Salt*. SAND82-0525. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Near-field stresses and displacements were estimated for a heated canister buried in a natural salt formation. The results could be used to estimate hole closure and brine migration near the canister. In the event of hole closure, contact stress could be bracketed by calculation extremes.

Caravella, F.J., and A.R. Sanford. 1977. *An Analysis of Earthquakes North of the Los Medaños Site on July 26, 1972, and November 28, 1974*. Geophysics Open-File Report 12a. Socorro, NM: New Mexico Institute of Mining and Technology.

ABSTRACT: Two earthquakes are known to have occurred approximately 40 km northwest of the Los Medaños site; one on July 26, 1972 at 04:35 GMT and the other on November 28, 1974 at 03:35 GMT. The magnitudes (M_L) at these two shocks are on the order of 3.5 to 4.0. Both shocks appear to have occurred near the National Potash Company Eddy County Mine (NPM) because rockfalls were reported there at the time of both events.

We have attempted to obtain a precise location for the July 26, 1972 earthquake using velocities obtained from Project Gnome data. Unfortunately, the analysis leads to a rather large uncertainty in the epicenter of this shock, somewhere within a minimum area of 1900 km². Although the NPM lies within the 1900 km², the seismic data do not favor an epicenter there over any other point within the same area.

A comparison of arrival times for the two events indicates that the epicenters must have differed by about 10 km. Thus if we assume that one earthquake was induced by mining operations at the NPM, the other could not be attributed to the same cause.

Even though the second shock (November 28, 1974) was recorded by a station at the Los Medaños site (CLN), the data for it are also inadequate to place the epicenter at the NPM with a high degree of confidence. Thus one cannot be certain either of the shocks was induced. Therefore, in the absence of additional seismic data on these events, it appears that seismic risk at the Los Medaños site should be estimated on the assumption that both shocks had a natural origin.

Carrera, J., and G. Walters. Unpublished. *Theoretical Developments Regarding Simulation and Analysis of Convergent Flow Tracer Tests*. SAND86-7091. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: An algorithm is presented for the accurate simulation and parameter estimation of convergent flow tracer tests. The algorithm allows including the effects of matrix diffusion, mixing at the pumping and injection wells, arbitrary initial and boundary conditions, various forms of the dispersion coefficient, etc. The simulation methodology is

similar to that proposed by Sauty and matrix diffusion is represented by linking the finite differences grid with an analytic solution of the diffusion equation.

Type curves are presented in terms of both relative and dimensionless concentrations. The latter allows more information to be obtained from the data. A sensitivity analysis, performed in order to evaluate the effects of various assumptions, suggests that matrix diffusion and mixing at the pumping well can be disregarded under normal conditions. The dependence of the solution on the assumption of no upstream dispersion across the outer boundary decreases with increasing dispersivity. The form of the dispersion coefficient cannot be estimated with data from a single test. However, this form may be important for long-term migration. Mixing at the injection well-bore hole may lead to significant changes in the solution. However, this effect can be identified in most situations.

Structural identifiability issues are also examined. The analysis shows that global uniqueness of the parameter estimation problem cannot be guaranteed in most situations. However, the solution appears to be well-behaved in the neighborhood of the global optimum solution.

Case, J.B., and P.C. Kelsall. 1986. *Shaft-Seal Modeling and Analysis of the Small Scale Seal Performance Tests at the Waste Isolation Pilot Plant*. Albuquerque, NM: IT Corporation. (Copy available at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: SHAFT.SEAL is a one-dimensional, radially symmetric numerical model constructed to analyze the normal stress that develops early at the interface between a bore-hole plug and the adjacent rock. The numerical analysis evaluated thermal and thermomechanical behavior of plugs at the Waste Isolation Pilot Plant (WIPP) test series A. These results were also compared to numerical modeling with another code, SALT.SEAL.

SHAFT.SEAL adequately predicts trends of temperature changes in a plug and the host rock, but is inaccurate in detail because of inadequate heat of hydration data. Salt creep is the dominant mechanism based on observed compressive strains in the plug. The observed bore hole closure rates and interface stress development rates are consistent with modeling using SALT.SEAL. Expansivity effects observed in a 91-cm plug are lower than those anticipated from numerical modeling with SHAFT.SEAL or from laboratory measurements of free expansion. The closure rate on the 91-cm bore hole is higher than predicted based on a secondary creep law and reference creep properties for WIPP rock salt. This is consistent with underground observations. The SHAFT.SEAL model does not adequately predict interface stress where creep of the host rock is a dominant mechanism.

It is recommended that SHAFT.SEAL be modified by incorporating SALT.SEAL or by incorporating thermoelastic effects and nonlinear time-dependent constitutive relations for both the concrete plug and rock salt.

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Case, J.B., and P.C. Kelsall. 1987. "Coupled Processes in Repository Sealing," *Coupled Processes Associated with Nuclear Waste Repositories*. Ed. C-F. Tsang. Orlando, FL: Academic Press, Inc. 591-604.

ABSTRACT: The significance of coupled processes in repository sealing is evaluated. In most repository designs, shaft seals will be located in areas of relatively low temperature perturbation, in which case the coupling of temperature with stress and permeability may be less significant than the coupling between stress and permeability that occurs during excavation. Constitutive relationships between stress and permeability are reviewed for crystalline rock and rock salt. These provide a basis for predicting the development of disturbed zones near excavations. Field case histories of the degree of disturbance are

presented for two contrasting types - Stripa granite and southeastern New Mexico rock salt. The results of field investigations in both rock types confirm that hydraulic conductivity or permeability is stress dependent, and that shaft seal performance may be related to the degree that stresses are perturbed and restored near the seal.

Case, J.B., P.C. Kelsall, and J.L. Withiam. 1987. "Laboratory Investigation of Crushed Salt Consolidation," *Rock Mechanics: Proceedings of the 28th US Symposium, University of Arizona, Tucson, AZ, June 29-July 1, 1987.* Eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman. Boston, MA: A.A. Balkema. 189-196.

ABSTRACT: The safe geologic isolation of nuclear waste in an underground repository will require sealing access shafts and drifts for long periods. Crushed salt backfill is being investigated as a potential backfill and seal material through laboratory testing to determine how fundamental properties such as permeability, porosity, and creep rate are reduced by pressure and time through consolidation. The test program reported in this paper consisted of four consolidation tests using crushed salt obtained from the Waste Isolation Pilot Plant (WIPP) and the Avery Island Mine. Tests with one- or two-month durations were conducted on samples with maximum particle sizes of 1, 10, and 20 mm, with initial porosities ranging from 26 to 36%, moisture contents of zero and 2%, and initial permeabilities from 10^3 to 10^5 md. The tests were performed at ambient temperature and confining pressures ranging from 0.34 MPa to 17 MPa. The most significant observation from the tests was the influence of moisture on changes in permeability, porosity and volumetric creep strain rate. The final permeability and porosity of one moist sample were reduced after one month to about 10^{-5} md and 5%, respectively, compared to about 10^2 md and 14 to 19% for the dry samples. In addition, the consolidation rate for the moist sample was more rapid at comparable porosities. In all of the tests, the volumetric creep strain rate ranged from 10^{-8} to 10^{-6} (sec) $^{-1}$, and did not achieve steady state values after 1 to 2 months of load application.

Case, J.B., S.M. Dass, J.G. Franzone, and A.K. Kuhn. 1982. *Analysis of Potential Impacts of Brine Flow Through Boreholes Penetrating the WIPP Storage Facility.* TME 3155. Albuquerque, NM: US Department of Energy.

ABSTRACT: The mechanics and hydrology of a scenario have been analyzed for radionuclide release by the movement of pressurized brine from a brine reservoir through a repository containing contact handled waste and to the surface. The assumed reservoir characteristics include a depth of 3250 ft, infinite size, initial lithostatic pressure, salt-saturated brine, and a maximum steady-state discharge of 20,000 barrels per day through a well with a diameter of 15 in. The drilling is assumed to occur 250 years after closure. Scenario 1 assumes a single hole, while scenario 2 assumes separate bore holes connecting the reservoir to the facility and the facility to the surface.

For scenario 1, up to 1700 ft³ of brine could circulate through the waste before reaching ground surface. No solid wastes, other than those removed by drilling (10.7 ft³), could be removed from the storage room.

For scenario 2, about 800 ft³ of brine, waste, and crushed salt could be flushed during transient flow to form a cavity. Of this volume, about 444 ft³ could be contaminant-saturated brine, 304 ft³ crushed salt, and 52 ft³ waste. During steady flow, about 290 ft³ of light solid wastes could be removed and about 112,300 ft³ of contaminant-saturated brine could be flushed to the surface. Total releases in this scenario are 112,744 ft³ contaminant-saturated brine, 304 ft³ crushed salt, and 342 ft³ waste. DWP

Cauffman, T.L., A.M. LaVenue, and J.P. McCord. 1990. *Ground-Water Flow Modeling of the Culebra Dolomite. Volume II: Data Base.* SAND89-7068/2. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The hydrogeologic data base for the Culebra Dolomite Member at the Waste Isolation Pilot Plant (WIPP) Site presented in this volume includes the following information: coordinates of bore holes; Culebra elevations; transmissivities; storativities; formation-fluid densities; bore hole fluid-density histories; estimates of uncertainties in densities and equivalent freshwater heads; transient freshwater heads; estimates of undisturbed freshwater head, and uncertainty in this value; and shaft histories. A companion report (Volume I) documents the modeling study of groundwater flow in the Culebra dolomite. DWP

ANNOTATION: The comparison volume is included in this bibliography as LaVenue, Cauffman, and Pickens, 1990.

Channell, J.K. 1982. *Calculated Radiation Doses from Radionuclides Brought to the Surface if Future Drilling Intercepts the WIPP Repository and Pressurized Brine.* EEG-11. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Several pressurized brine reservoirs have been encountered by drilling in the vicinity of the Waste Isolation Pilot Plant (WIPP) Site, and significant discharges have occurred at the surface. A scenario has been examined in which a bore hole connects an underlying brine reservoir with the repository, and the waste storage area is saturated. A subsequent bore hole brings contaminated brine to the surface. Radiation doses are calculated at 125, 400, and 1,000 years after repository closing for external and inhalation radiation doses for workers at the bore hole location; external and inhalation doses for a resident located 360 m downwind; ingestion doses for the downwind resident from locally grown produce, milk, and meat; and population doses from inhalation within a 50-mi radius. Several conclusions were reached from this analysis.

The maximum calculated 50-year dose commitment from one year's intake is 0.47 rem for the whole body and 1.9 rem for bone at 125 years after closure caused by use of contaminated produce by a downwind resident. At 400 years, the equivalent bone dose commitment is 12 rems by inhalation for a drilling crew member and a downwind resident. Inhalation and external radiation doses increase with time because of continued leaching of long-lived actinides. Ingestion doses are negligible after 300 years. The cumulative probabilities of doses during the lifetime of the repository equal to or greater than the 125-year doses are less than 5×10^{-7} . The estimated probability of radionuclides coming to the surface and resulting in doses up to those presented above is about 0.00025. The Environmental Protection Agency (EPA) standard for high-level waste (HLW) should be met, but the estimates are only a factor of 3 less than the standard and should be refined. Ingestion dose estimates after 125 years are not of particular concern. Inhalation doses at 400 years exceed doses permitted for the general population, though the dose from inhalation over one year should not produce noticeable health effects. The 400-year doses are the highest expected to occur. Population doses within 50 mi of WIPP over 1500 years might result in 1 or 2 cancer fatalities compared to 500,000 cancer fatalities estimated from all other causes. Calculated amounts of surface contamination warrant more evaluation of the scenario. Active institutional controls able to detect surface contamination for up to 600 years should be considered.

The WIPP-12 brine reservoir currently being analyzed will affect two assumptions made in this study; the probability per bore hole of hitting a brine reservoir beneath the site will be greater than the value of 0.04 used in this analysis, and more than 75,000 ft³ of brine may be brought to the surface during normal drilling operations. DWP

Channell, J.K. 1990. *Environmental Evaluation Group Views on "Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level Transuranic Radioactive Wastes (40 CFR 191)"*. Presented to Advisory Committee on Nuclear Wastes, US Nuclear Regulatory Commission. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Environmental Evaluation Group (EEG) has examined human intrusion scenarios for the Waste Isolation Pilot Plant (WIPP) that are relevant to the containment requirements of the proposed Environmental Protection Agency (EPA) standard. Important factors that contribute to the vulnerability of the site include the following: the site is located in an area rich in natural resources; pressurized brine appears to underlie about half the storage area; stacking the waste increases surface area exposed to drilling; panel single design may allow a large fraction of waste to be involved in a scenario; waste may generate gas that results in fracturing of the formation and delaying room closure, and there is no planning of waste loading to minimize the effects of human intrusion. Our analyses indicate releases "might" exceed the proposed standard. With additional engineering and understanding of key parameters, the Department of Energy (DOE) should be able to comply with the proposed standard. The standard generally appears to be appropriate and should not be reduced. The permissible release fractions for a transuranic (TRU) repository are already relaxed by a factor of three compared to a high-level waste repository and should not be further reduced. DWP

Channell, J.K., C. Wofsy, and S.M. Zand. 1982. "The Effect of Hydrologic Parameter Variation on Radionuclide Transport in the Rustler Aquifer (Southeastern New Mexico)," *Proceedings of the Symposium on Uncertainties Associated with the Regulation of the Geologic Disposal of High-Level Radioactive Waste, Gatlinburg, TN, March 9, 1981*. Ed. D.C. Kocher. NUREG/CP-0022; CONF-810372. Oak Ridge, TN: Oak Ridge National Laboratory. 365-372.

ABSTRACT: A simple mathematical model was used to evaluate the effect of varying hydrologic transport parameters on the movement of ^{239}Pu from the proposed Waste Isolation Pilot Plant (WIPP) radioactive waste repository through the Rustler aquifers to the Pecos River. The evaluation concluded that the parameters with the most significant effects in the dose calculations are the hydraulic conductivity (K) and the distribution coefficient (K_d). This is mostly due to the uncertainty associated with bounding these values in a system where radionuclides may exist in various chemical forms and flow through aquifers dominated by fracture flow. However, in all plausible cases, calculated concentrations were less than permissible levels for drinking water. The evaluation was a useful first approximation to uncertainties analysis. A better understanding of the bounding values of the K_d and K parameters in fracture flow system is needed.

Chapman, J.B. 1986. *Stable Isotopes in Southeastern New Mexico Groundwater: Implications for Dating Recharge in the WIPP Area*. EEG-35. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: If the Waste Isolation Pilot Plant (WIPP) is breached, water-bearing zones of the Rustler Formation are considered the most likely pathways for the transport of radionuclides to the biosphere. The Department of Energy (DOE) is conducting studies of the Rustler that should significantly improve knowledge about radionuclide contaminant transport within the Rustler. Lambert recently examined stable isotope data and concluded that Rustler groundwater in the vicinity of the WIPP Site is not receiving significant modern meteoric recharge. Lambert also concludes that the stable isotope data reveal hydraulic isolation of two possible discharge areas (well WIPP-29 and Surprise Spring) from the Rustler elsewhere in Nash Draw and near the site. These conclusions allow longer residence time of water in the Rustler and reduce the calculated consequences of a breach of the WIPP repository.

Stable isotope data have been compiled from throughout southeastern New Mexico and compared to data from the WIPP area. The stable isotopes of most Rustler water samples are similar to other, verifiably young, groundwater in the area. There is no distinction in stable isotopes between most Rustler groundwater and verifiably young groundwater.

A few samples, primarily from the Rustler/Salado contact east of Nash Draw, have isotopic compositions that are not characteristic of recently recharged meteoric water. These waters are enriched in heavy isotopes, possibly because of mixing with deeper groundwater (supported by the stable isotopic composition of Salado fluid inclusions and Castile brine) or because of exchange between the groundwater and hydrous minerals.

Evaporation enriches heavy isotopes, and the stable isotopes of water at WIPP-29 and Surprise Spring could be derived by evaporating Rustler groundwater. Based on stable isotopes, both WIPP-29 and Surprise Spring could be discharge areas for Rustler groundwater from elsewhere.

Enriched heavy isotopes in water from Carlsbad Caverns were used by Lambert as evidence that the relatively depleted Rustler water was recharged during a more pluvial past time. However, the isotopic composition of the cavern water is unique, suggesting that evaporation and equilibrium exchange in the humid cave environment enriched heavy isotopes. Recharge in karst near the cavern may also favor isotopically heavy precipitation.

Stable isotopes alone cannot determine the age of Rustler water or the presence or absence of modern recharge. Physical measurements of the flow system are the best way to locate and quantify recharge. Regional hydrologic testing of the Rustler has begun and will provide data on the transmissivity and degree of fracture connection. Additional water level measurements in more locations are needed to refine potentiometric surface maps and locate recharge and discharge areas and groundwater divides. Studies are needed of infiltration in suspected recharge areas.

DWP

ANNOTATION: The report by Lambert referred to is Lambert 1987b.

Chapman, J.B. 1988. *Chemical and Radiochemical Characteristics of Groundwater in the Culebra Dolomite, Southeastern New Mexico*. EEG-39. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Major ions, stable isotopes, and radiochemistry of groundwater around the Waste Isolation Pilot Plant (WIPP) have been evaluated to help determine groundwater flow paths and reactions in the event of a breach of the WIPP and hydrologic transport of radionuclides through the Culebra Dolomite Member of the Rustler Formation. Increasing salinity and Na to Cl ratios of Culebra groundwater from west to east are strong evidence of halite dissolution. There is no obvious reason to relate high K and Mg concentrations to low transmissivity and long residence times. A Ca-SO₄ water with lower total dissolved solids (TDS) occurs to the south and southwest because of enhanced recharge. Areas with low TDS and Ca-SO₄ correspond to areas with complete dissolution of Rustler halite and hydration of anhydrite. High TDS and Na+K-Cl brine correspond to areas with Rustler halite. Uranium in Culebra groundwater may be derived from clastic units. Marked disequilibrium between U-238 and U-234 is associated with low transmissivity and low total U content. The three processes related to the lack of fractures that may explain this result from the fact that longer residence time allows more U to absorb onto the rock matrix than in fractured areas, that conditions are more reducing in low transmissive areas, and that U may primarily line fractures with less U available in unfractured parts of the aquifer. Radium isotopes positively correlate with Cl content. Cations in high chloride brines compete for adsorption sites, while radium may coprecipitate in sulfate water with lower TDS. Th-228 was detected in samples from five wells, probably complexed by chloride and sulfate. Several radionuclides associated with waste were not detectable; Cs-137 reported may be an artifact of high potassium content. Relatively oxidizing conditions and the high chloride of these waters may mobilize other radionuclides in

waste; this should be carefully analyzed. Repeat and additional sampling and analysis of Culebra groundwater will provide a better data base. "Accurate knowledge of the Culebra chemical environment is vital to understanding groundwater flow paths and evaluating radionuclide migration." DWP

Chaturvedi, L. 1980. *WIPP Site and Vicinity Geological Field Trip: A Report of a Field Trip to the Proposed Waste Isolation Pilot Plant Project in Southeastern New Mexico, June 16 to 18, 1980.* EEG-7. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Environmental Evaluation Group (EEG) is making an effort to improve the understanding of those geological issues that may affect the radiological consequences of the proposed repository. An important geological issue to be resolved is the timing and the nature of dissolution processes that may have affected the Waste Isolation Pilot Plant (WIPP) Site. The EEG organized a two-day conference of geological scientists in January, 1980. The field trip of June 16-18, 1980, was organized to clarify the different views on the geological processes active at the site. There were participants from state and federal agencies, universities, and the private sector.

Several important geological issues concerning the site are yet to be resolved. Based on the conference and the field trip, the EEG concluded that it has not been established that the site or the surrounding area has been compromised by deep dissolution to render it unsuitable for the nuclear waste pilot repository. Further site characterization regarding "deep dissolution" is recommended in this report. An isolated breccia pipe at the site, unaccompanied by a deep dissolution wedge, is a very remote possibility. However, further work to confirm or deny its existence in the basin probably would not be useful in evaluating the potential impact on the integrity of the WIPP repository. More specific information about the origin and the nature of the brine reservoirs is needed. It is important to resolve whether or not these reservoirs are interconnected. R.Y. Anderson postulates a major fault or a fracture system at the eastern basin margin along the San Simon Swale. The EEG concluded that this should be checked because of its implications to the tectonic stability of the Delaware Basin. The disturbed zone in the northern part of the WIPP Site should be further investigated to clearly understand the nature and significance of this structural anomaly. Other structural anomalies and postulated faults on the WIPP Site should be further investigated. The EEG indicated that topical reports bringing together all information related to particular issues are needed to clarify and aid in the site characterization.

For fiscal year 1981 the EEG recommends the preparation and publication of reports reviewing in detail deep dissolution, structural anomalies, and brine reservoirs; providing detailed plans on recovery of mineral resources at and around the WIPP Site; and investigating breccia pipes.

The EEG further recommends the preparation of a seismic reflection profile across San Simon Swale to confirm or deny the postulated fault; an exploration of Bell Lake sink through shallow holes to see whether it is caused by deep dissolution; the drilling of an exploratory core hole in section 9, 2 mi north of ERDA-9, to explore the "disturbed zone"; and the testing of a brine reservoir by allowing it to flow. DWP

Chaturvedi, L. 1984. *Occurrence of Gases in the Salado Formation.* EEG-25. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Recent gas blowouts in several mines, resulting in one fatality, raise concerns about the possibility of similar blowouts in the Waste Isolation Pilot Plant (WIPP) excavations. Information was collected about specific blowouts in mines since 1973. Small gas flows have been documented underground at the WIPP, and more significant outflows occurred in some drill holes. Several conclusions can be drawn concerning the occurrence of gas in the Salado Formation. Gas can be found at almost any level within the Salado Formation, generally near

clay seams associated with the marker beds. The gas consists primarily of nitrogen with some oxygen and methane. It is not "chemically explosive." Small amounts of gas in isolated pockets at low pressures are very common. Gas has been infrequently encountered under high pressure. Sudden expansion of gas caused by release of high pressure creates an explosion or "outburst" that has occasionally resulted in death and/or injury to miners. Outbursts of gas are more common in the potash mines than reflected in publicly available reports. It is thought that the gas is trapped in fractures that may have been opened because of a geological factor such as the emplacement of a dike. If so, the gas pressure within these vertical fractures would have to be in equilibrium with the horizontal component of the lithostatic stress, approximately 1500 psi. Sudden release of such high pressure would dislodge and move large chunks of rock and machinery if caught in the outburst. Small amounts of gas, some emanating cyclically, have been encountered in zones a few feet above the ceiling and below the floor of WIPP excavations. This gas is similar in composition to the gas found in potash mines, 600 ft stratigraphically above the WIPP repository. The probability of finding pockets of highly pressurized gas at WIPP is low because none have been encountered after 2 mi of drifts have been excavated. However, the possibility should not be ignored. If gas-filled fractures are at pressures equivalent to the horizontal component of lithostatic stress, the pressure drop would be larger than at potash mines.

Several recommendations are made for operations at the WIPP Site. Collect and publish information on even minor encounters of gas "puffs" during the WIPP excavations. Map any fractures and areas of excessive moisture seeps in the excavations. Continue drilling advance exploratory holes before cutting a face with the continuous mining machines. These holes should be slanted upwards to intersect the clay layer near the ceiling. Install protective metal grating on the continuous mining machines similar to, or better than, the ones installed at the Kerr-McGee mine. Remove or re-install any loose parts on mining machines which may fly about in the event of an explosion. Do not allow unnecessary personnel near an operating mining machine. DWP

Chaturvedi, L., ed. 1987. *The Rustler Formation at the WIPP Site. Report of a Workshop on the Geology and Hydrology of the Rustler Formation As It Relates to the WIPP Project.* EEG-34; DOE/AL/10752-34. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Environmental Evaluation Group (EEG) organized a workshop as an opportunity for various scientists to exchange and discuss current information on the geological and hydrological character of the Rustler Formation. Eight papers were presented and discussed; four are printed in this report; while the rest have been included in other EEG reports or US Geological Survey (USGS) open-file reports. The Rustler geologic and hydrologic data are summarized and three unresolved questions are presented. How far east of Livingston Ridge have Nash Draw processes affected the Rustler? How much have the Rustler hydrologic properties been affected by dissolution and collapse? To what degree are these dissolution processes continuing and what hydrologic changes may they cause to the Rustler in the next 10,000 years? Channell examined seven assumptions used to evaluate failure scenarios that might be affected by assuming karst conditions at the site. Individuals drinking from a nearby well could receive excessive radiation doses, and Environmental Protection Agency (EPA) standards could be exceeded. Snyder reviewed core and log information from the Rustler showing thickness changes from the Waste Isolation Pilot Plant (WIPP) to Nash Draw caused by salt dissolution and gypsification. Bachman described Rustler lithology and stratigraphy, concentrating on outcrop features and relationships caused by dissolution and other karst processes. Though geomorphic features relate generally to stages of development and time of formation, calculated rates of dissolution are invalid without more absolute data related to paleoclimate and groundwater associated with ancient drainage systems. Holt and Powers presented information from mapping the Rustler in two shafts at the WIPP, from which they concluded that halite was distributed according to depositional processes. Holt and Powers infer that dissolution of the Rustler has been overestimated. Lambert presented stable isotope data from the Rustler and other groundwaters and concluded that two isotopically distinct populations exist. Much of the Rustler and eastern Capitan Reef waters form one

population, while near-surface and western Capitan groundwater form another. The distinction suggests most of the Rustler is not being recharged by modern meteoric water. Hunter examined the water budget for the area around the WIPP Site, finding that distinct groundwater basin areas exist and that surface and groundwater storage in Nash Draw has increased because of potash refining. Ramey considered the chemistry of Rustler fluids and identified three chemical zones. These zones do not support the directions of fluid flow previously reported. The three fluid-bearing zones appear to be chemically separated. DWP

Chaturvedi, L. 1990. *EEG's Preliminary Comments on US Environmental Protection Agency "Notice Proposing to Grant a Conditional Variance to the Department of Energy Waste Isolation Pilot Plant (WIPP) From Land Disposal Restrictions"* (Federal Register, Vol. 55, No. 67, April 6, 1990). (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Environmental Evaluation Group (EEG) contends that the positions in the petition by the Department of Energy (DOE) and notice by the Environmental Protection Agency (EPA) that "testing with radioactive waste ... is necessary to demonstrate long-term acceptability of WIPP" and "it has already been demonstrated that there will be no migration of hazardous constituents from the repository..." are incorrect. Experiments with waste in the bin and alcove tests do not address critical questions about what rates of gas generation are unacceptable or what future conditions will be like in a repository. These tests also will have to overcome operational problems. Repository seals are used in the petition as barriers to migration though they have not been developed or tested. The petition rejects the possibility of future drilling for resources on the basis of lack of resources and knowledge of resources. EEG does not agree that human intrusion is unlikely or prohibited by institutional controls. The DOE plan for retrieval of waste is incomplete and the EPA determination is unacceptable to EEG. EEG has some questions about air monitoring, but generally favors DOE plans. The EEG believes that the EPA interpretation of site characteristics are not conservative. Examples include statements about brine reservoirs, permeability of marker beds, and recharge to the Culebra. EEG suggests that EPA require DOE to analyze breach scenarios for a gas pressurized repository, demonstrate that alcove tests can be performed and that they will provide usable data for performance assessment, test modified waste form and their effect on gas generation, make decisions about retrieval of waste, and establish a time and volume limit for experiments with waste if the experiments are necessary. DWP

Chaturvedi, L., and J.K. Channell. 1985. *The Rustler Formation as a Transport Medium for Contaminated Groundwater*. EEG-32. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) repository is being excavated in the lower Salado Formation, 2150 ft below the ground surface. Water-bearing zones in the Rustler Formation are considered to be the main pathway for radionuclide transport to the biosphere after breach of the repository.

The Rustler has not yet been characterized sufficiently for realistic modeling of breach and transport scenarios. Published models and scenarios are based on insufficient information about the Rustler and may not be "bounding" or "worst-case." The data, which are insufficient, mainly relate to the dissolution history, present recharge (amount and location), and the hydrologic characteristics (transmissivity, storativity, hydraulic gradient). Current studies will significantly enhance our knowledge about the suitability of the Rustler Formation. A sedimentological study of cores will help establish the causes for the absence of salt from the Rustler Formation. Multi-well flow tests will yield more reliable values for the hydrologic parameters. Rustler water chemistry data will help more accurately establish the flow directions and the pattern of interconnections. Suspected "dolines" will be investigated to help resolve the question of direct recharge at the WIPP Site. Sorbing tracer tests will provide data

for transport modeling of radionuclides. Two scenarios are analyzed for radionuclide transport through karst conduits in the Rustler. One involves drinking treated Pecos River water at Malaga Bend, and the other assumes drinking treated water from a hypothetical well located 2 mi from the site. The estimated annual dose from drinking the Pecos River water would exceed the Environmental Protection Agency (EPA) standard if continuously ingested for more than 20 years. The corresponding annual dose from well water would be greater and would exceed the annual dose permitted for occupational workers after one year.

The karst-conduit assumption can be checked by additional studies. Gravity anomalies over the WIPP Site should be reevaluated using electromagnetic methods to check the lateral variations in the Rustler Formation, and the recommendations from the water-balance study should be implemented.

For an extra measure of safety, the WIPP design should include engineered barriers such as mixing retardant clay with salt backfill, very careful plugging and sealing of the shafts and bore holes, and isolating individual "panels" through carefully designed plugs. DWP

Chaturvedi, L., and K. Rehfeldt. 1984. "Groundwater Occurrence and the Dissolution of Salt at the WIPP Radioactive Waste Repository Site," *EOS Transactions, American Geophysical Union*. Vol. 65, no. 31. (Abstract only).

ABSTRACT: There are two main concerns with regard to the suitability of the Waste Isolation Pilot Plant (WIPP) Site. The water-bearing zones of the Rustler Formation should be thoroughly understood to preclude any possibility of these zones acting as pathways for radionuclide migration to the biosphere. New wells, additional field tests, core studies, and geochemical testing will help refine a hydrologic and contaminant transport model of the Rustler. A water-balance study will be completed and some suspicious surface depressions will be drilled. The mechanics of salt removal from the Rustler will be studied. These studies will help resolve the question of karst conditions in the Rustler. The second concern is the effect of salt dissolution on the integrity of the repository. The Salado Formation does not appear to have been affected around the WIPP Site. A suspicious location north of the site will be drilled. Stratabound dissolution of the Rustler salt across the site does not appear to have affected the top of the Salado, though the collapsed depression of Nash Draw is only about 6.5 km west of the site. The mechanics of salt removal are therefore important to understand. "If the additional work indicates a possibility of release of hazardous quantities of radioactivity to the biosphere, the EEG will recommend additional engineered barriers or investigations for a new site." DWP

Chaturvedi, L., J.K. Channell, and J.B. Chapman. 1988. "Potential Problems Resulting from the Plans for the First Five Years of the WIPP Project," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 355-364.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is scheduled to start receiving defense transuranic (TRU) waste in October 1988. The US Department of Energy (DOE) has planned to store up to 126,000 drums of contact handled (CH TRU) waste without backfill during the first 5-year period. This waste will have to be removed and restacked with backfill during the next 10 years while new waste will be arriving for disposal. To make matters more complicated, it appears that the existing drums of CH TRU waste have too much void space; because the drums are expected to become corroded in a few tens of years, the brine issuing from the salt walls may form a slurry of waste in a few hundred years after closure. Preliminary calculations indicate that such conditions may violate the Environmental Protection Agency (EPA) Standards (40 CFR 191.13) on the basis of analyses of human intrusion scenarios. DOE does not plan to complete the performance assessment work to assess WIPP's compliance with the EPA Standards until 1993. If the waste drums and boxes

have to be reprocessed to reduce void space in them and the backfill is redesigned to include cement or chemical grout mixtures instead of the presently planned salt/bentonite mixture, each drum may have to be brought up to the surface for reprocessing and taken down again for final disposal. It would be simpler and less hazardous to emplace substantial quantities of waste underground only after the decisions about any needed reprocessing of the waste drums and the design of backfill have been finalized.

Chaturvedi, L., J.B. Chapman, R.H. Neill, and J.K. Channell. 1987. "Performance Assessment for a Nuclear Waste Repository - The WIPP Experience," *Waste Management 87, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 1-5, 1987*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 141-145.

ABSTRACT: Performance Assessment to show compliance with the standards for a nuclear waste repository requires thorough site characterization and understanding of potential pathways for a breach of the repository. Although the Waste Isolation Pilot Plant (WIPP) Project will not be licensed by the Nuclear Regulatory Commission (NRC) under 10 CFR 60, it is subject to Environmental Protection Agency (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Wastes (40 CFR Part 191)*. NRC has incorporated 40 CFR 191 into 10 CFR 60 and requires the demonstration of compliance before construction of the high level waste (HLW) repositories can begin. The Environmental Evaluation Group (EEG) of the State of New Mexico has independently evaluated the WIPP Project since 1978 and believes that compliance for WIPP should be demonstrated prior to emplacement of waste for disposal. The US Department of Energy (DOE) schedule calls for the arrival of waste at WIPP in late 1988. DOE considers WIPP to be a research and development facility for the first 5 years of operation, and believes that compliance with the EPA Standards need not be demonstrated until after the decision is made not to retrieve the waste. It appears that DOE's mission plan for the first HLW repository has not provided sufficient time to resolve the site characterization issues and complete the performance assessment for each of the three sites before submitting a license application to NRC.

Chavez, P.F., and P.R. Dawson. 1978. *COUPLEFLO - A Computer Program for Coupled Creeping Viscous Flow and Conductive-Convective Heat Transfer. Part II. User's Manual*. SAND78-1407. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: COUPLEFLO is a two-dimensional finite-element code for plane strain or axisymmetric analyses of thermomechanically coupled systems. It is capable of analyzing the creeping flow of non-Newtonian fluids or the secondary creep of solids. COUPLEFLO solves equations for conductive-convective heat transfer to determine the thermal response of a system. Thermomechanical coupling between the flow field and temperature distribution can exist in terms of temperature-dependent material properties, temperature-dependent body forces, viscous dissipation, material convection, and changing system geometry. Either transient or steady-state problems can be analyzed in Eulerian or quasi-Lagrangian reference frames. Part I, Theoretical Background, contains the governing equation, finite-element formulation, and verification of the code capabilities. Part II, User's Manual, contains instructions for code use. Currently, COUPLEFLO is available at Sandia National Laboratories in Albuquerque on the 7600, 6600, and NOS systems.

ANNOTATION: Part I, Theoretical Background, is included in this bibliography under Dawson and Chavez, 1978.

Christensen, C.L. 1979a. *Test Plan: Bell Canyon Test WIPP Experimental Program Borehole Plugging*. SAND79-0739. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Location: Exploratory Well AEC-7 Section 31, T21S, R32E Lea County, NM.

Objective: To verify the capability to plug a bore hole penetrating a unit (Bell Canyon) of high hydrostatic head in the Delaware Formation underlying the evaporite rocks of the Rustler, Salado, and Castile Formations.

Description: The Bell Canyon Test (BCT) will be conducted in the abandoned exploratory well AEC-7. The hole will be reconditioned and deepened as necessary to intercept the production zone in the Bell Canyon (Ramsey Sands). Wellbore characteristics and media permeability data will be obtained prior to plug installation. A minimum length plug will be installed to demonstrate that a cement grout plug can be installed to withstand hydrostatic pressure on the order of 2000 psi in a bore hole. The wellbore will be instrumented to monitor and identify fluid migration to the top of the plug. A time-controlled-release tracer gas (SF_6) canister will be emplaced below the plug to permit measurement of gas migration through or around the plug.

Christensen, C.L. 1979b. *Test Plan - Potash Core Test WIPP Experimental Program Borehole Plugging*. SAND79-1306. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The plan has been developed to obtain an in situ cured plug of known mix constituents to determine bench-scale properties for comparison to Plug 217. Plug 217 was earlier recovered from a potash exploration hole for bond testing. Plug 217 is a 17-year-old plug, but the lack of detailed information about the emplacement precluded determining plug performance.

The potash core test will utilize a Waste Isolation Pilot Plant (WIPP) emplaced plug to obtain samples of an in situ cured plug of known mix constituents for bench scale testing. The plug will be obtained from potash exploration well P-13, located in section 18, T22S, R31E. The total depth of P-13 is 1576 ft. It was plugged September 17, 1976. DWP

Christensen, C.L. 1980a. "Sandia Borehole Plugging Program for the Waste Isolation Pilot Plant (WIPP)," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980*. SAND80-0390C. Paris, France: Organisation for Economic Co-Operation and Development. 225-231.

ABSTRACT: This paper presents the current program underway at Sandia that addresses the four major functional tasks considered necessary for a successful program: project management, identification of candidate materials, development of test instrumentation, and field test. Current programs on wellbores, cementitious grouts, and available technology will be compared with planned extension to shafts and drifts, alternate materials, and improved instrumentation. Relationship of this program with assessments of long-term suitability performed in the geochemical program will be presented. A brief presentation of current and planned field tests will be given, along with projections for future activities.

Christensen, C.L. 1980b. "Results from the Bell Canyon Borehole Plugging Tests," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980*. ONW1-212; SAND80-2376C. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 175-177.

ABSTRACT: The Bell Canyon Test (BCT) evaluated candidate grout plugging mixes, plug emplacement techniques, and plug performance under in situ curing conditions. Grout plugging is routine in oil-field operations; however, quantitative measurements of plug performance are rare.

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The experiment was conducted in a 20-cm (8-in.) diameter well bore that intercepted an aquifer having a shut-in pressure of 12.4 MPa (1800 psi) and a production capability of 240 SBD (standard barrels/day; 10⁴ gal/day). A 2-m (6-ft) grout plug was emplaced above the aquifer between 1368 m and 1370 m (4495 ft). The well bore fluids were unloaded above the plug, applying the full 12.4 MPa pressure differential to the plug for flow testing.

Six test periods at forty-day intervals were scheduled to evaluate plug performance. Following the first four periods the plug was extended an additional 4 m (12 ft). Tests on this extension are not complete.

A fresh water grout mix was selected for the BCT plug to avoid forming salt at the grout-rock interface, resulting in a poor seal.

Fluid build-up tests, shut-in tests, and tracer transit-time tests were conducted. An "umbrella" packer above the plug was necessary because of uphole fluid production. Leakage in the tubing and packer plumbing was found to be as high as or higher than the leakage around the plug (0.2 gal/day), leading to complications in the analysis. The shut-in tests and the tracer transit times worked satisfactorily.

Downhole passive pressure recorders or a limited system for uphole monitoring of downhole conditions both have serious drawbacks in field testing. The passive systems have limited resolution and require recovery of the sensing system, thus terminating the test sequence. The active system, while having adequate resolution (0.1 psi), was not readily compatible with the packers that were initially used. By suitable field modifications, both systems were successfully used.

The BCT plug performed as a nominal 50 microdarcy emplacement in the 20-cm (8-in.) bore hole against a pressure differential of 12.4 MPa. This corresponds to a reduction in flow from 240 STB/day (10⁴ gal/day) to 5 x 10⁻³ STB/day (0.2 gal/day). DWP

Christensen, C.L. 1983. "Compliance with Prescribed Plugging Criteria for Reentry, Preparation and Cementing of the B-25 Borehole at the WIPP Site," *Waste Management 84, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 11-15, 1984*. SAND83-2189A. Albuquerque, NM: Sandia National Laboratories. (Abstract only; Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The B-25 borehole on the Waste Isolation Pilot Plant (WIPP) Site proper became a plugging candidate when it was determined that it was situated where the waste handling building was to be erected. Since movement of the building would be disruptive to the overall site layout, it was decided to plug the borehole instead. This decision provided an opportunity to exercise a quality assurance (QA) activity based on prescribed criteria for an actual plugging operation.

Some considerations that went into the plugging operations include discussions of the following topics: designation of the appropriate QA level category; review of hole historical records and conditions as found during reentry for casing removal, logging activities, cementing operations and report requirements.

Some conclusions on this experience and recommendations for making similar reentries on other holes easier by more careful initial planning are included as lessons learned.

Christensen, C.L., and T.O. Hunter. 1979. *Waste Isolation Pilot Plant (WIPP) Borehole Plugging Program Description, January 1, 1979*. SAND79-0640; ONWI/SUB/79/E511-03700-2. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The bore-hole plugging program (BHP) is designed to investigate controls on fluid circulation and possible radioactive waste release through man-made penetrations of the repository and surroundings. It is a reasonable and scientific program to establish a quantitative data base on bore hole plugging techniques. The tests and experiments mix bore-hole (with limited access) and in-mine (with relatively unlimited access) environments. The Bell Canyon Test provides the opportunity to instrument and analyze a grout plug under high pressures. The shallow test hole applies the best techniques for plugging and then allowing access to both the top and bottom of the plug for further analysis. The diagnostic test hole will recover bench-scale size samples for analysis and establish an in-bore-hole laboratory to test and analyze strata from the surface into salt. The experiments in the mine will investigate plugs in salt and evaluate instrument systems.

Site specific data permit plug design modeling and consequence analysis. Following this, laboratory testing and refinements lead to field tests. Plug materials and immediate results will be examined with geochemical techniques and principles to evaluate the long-term results. Finally, when both short- and long-term tests have been completed, a plug design will evolve to achieve isolation. DWP

Christensen, C.L., and T.O. Hunter. 1981. "The Bell Canyon Test and Results," *Scientific Basis for Nuclear Waste Management, Proceedings of the Third International Symposium, Boston, MA, November 17-20, 1980*. Ed. J.G. Moore. SAND80-2414C. New York, NY: Plenum Press. Vol. 3, 561-568.

ABSTRACT: The bore-hole plugging program (BHP) was established to identify issues associated with sealing bore holes and shafts, to establish a data base to assess these issues, and to develop sealing criteria, materials, and tests for the Waste Isolation Pilot Plant (WIPP). For the Bell Canyon Test (BCT), a 2-m long grout plug was emplaced 1370 m below the surface in a 20-cm diameter bore hole and exposed to 12.4 MPa (1800 psi) pressure differential. The state of the art in bore-hole plugs was evaluated in situ, and problems encountered in evaluating a "typical" plug installation in anhydrite were identified and resolved.

Field and laboratory data suggest that flow into the test region of the plug occurs predominantly through the interface between the cement plug and bore hole, with smaller contributions through the damage zone of the bore hole, the plug, and the surrounding undisturbed anhydrite bed. The plug limits flow from the Bell Canyon to 0.6 l/day. Assuming the flow path cross-section is equal to the bore-hole diameter, the permeability would be 50 microdarcies and the porosity would be 0.015. Shut-in test data indicate that the formation permeability is at least an order of magnitude less than the plug/formation system. New techniques and equipment will be required to obtain more precise measurements of systems with effective permeabilities around 1 microdarcy. DWP

ANNOTATION: See Christensen, C.L., 1980b, on same subject.

Christensen, C.L., and E.W. Peterson. 1981a. "Field-Test Programs of Borehole Plugs in Southeastern New Mexico," *The Technology of High-Level Nuclear Waste Disposal, Advances in the Science and Engineering of the Management of High-Level Nuclear Wastes*. Eds. P.L. Hofmann and J.J. Breslin. DOE/TIC-4621; SAND79-1634C. Columbus, OH: Office of Nuclear Waste Isolation. Vol. 1, 354-369.

ABSTRACT: The Bell Canyon Test (BCT) evaluated plugging materials, techniques to place the plug, and the plug performance in situ. A 2-m plug was placed between 1368 and 1370 m in an anhydrite bed. The underlying aquifer produced 12.4 MPa pressure and had a capability to produce 38,000 L/day through the bore hole. The plug was tested over about 8 months. The plug has been extended by 4 m, but tests on the extension are not yet complete.

The plug was tested with fluid build-up tests, shut-in tests, and tracer transit time tests through packers above the plug. Flow occurs predominantly through the plug/bore hole interface region, with lesser flow through the wellbore damage zone, plug core, and surrounding undisturbed anhydrite bed. Flow was reduced by a factor of about 10^5 , yielding about 0.6 L/day. The reduction in flow is far in excess of what is required by bounding safety assessments.

Testing was successful, but equipment should be modified to be more effective. Each site will need to be assessed to determine compatible plug materials. Testing will continue at the BCT and in a test bank for long-term analysis of plugging materials.

DWP

Christensen, C.L., and E.W. Peterson. 1981b. *The Bell Canyon Test Summary Report.* SAND80-1375. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Bell Canyon Test (BCT) was an in situ evaluation of the ability of a cement grout plug to seal bore holes. It consisted of a 2-m-long, 20-cm diameter grout plug in an anhydrite formation at a depth of 1370 m, directly above an aquifer that provided a 12.4 MPa (1800 psi) differential pressure. The aquifer had a production capability of 38,000 L/day (240 bbl/day, 10^4 gal/day). The observed leakage after plug installation was 0.6 L/day, which is equivalent to a 50 microdarcy flow path assuming all flow occurred through the plug cross-sectional area. Laboratory results and analysis of field data indicate that the bulk of the flow occurred through a microstructure at the interface between the plug and the host rock.

The BCT demonstrated that a plug could be formulated, emplaced, and tested under actual conditions and provide acceptable performance. When these results are related to the Waste Isolation Pilot Plant (WIPP) performance assessment models, they provide additional confidence that bore hole plugging can be accomplished satisfactorily.

The Bell Canyon results can also be used as basis for future activities in the generic repository sealing program for similar emplacements and performance assessment evaluations. If the observed leakage rates are not acceptable at other sites, the BCT results would indicate that the first step in improving such emplacements should deal with improved bonding of the plug to the rock at these sites. The results obtained from the BCT, when coupled with results from long-term durability assessments, form a plug performance data basis for repository designers at other proposed waste repository sites.

Christensen, C.L., C.W. Cook, and C.W. Gulick. 1980. *Borehole Plugging Program Status Report, October 1, 1978-September 30, 1979.* SAND79-2141. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The borehole plugging program (BHP) was begun in FY 1979 to provide data supporting materials development, instrumentation, and field testing for WIPP. Properties of grout for plugging were studied with WES, and grout mixture BCT-1-FF was developed and placed as plug in borehole AEC-7. Samples from a 17 year old grout plug in potash were analyzed for permeability and shear-bond resistance. Instruments developed or tested included a conductivity probe (for fluid conductivity), a water level indicator, circuitry for conditioning signals, and transducers to be grouted in-place. The Bell Canyon Test was completed during the fiscal year to evaluate the plug in AEC-7.

Proposed activities for FY 1980 include evaluating aging grout samples and the borehole/grout contact, evaluating potash core test samples, developing and testing wire line systems and downhole instruments, conducting the potash core test (PCT), and initiating the surface wellbore test bank (SWTB).

Christensen, C.L., C.W. Gulick, and S.J. Lambert. 1983. *Sealing Concepts for the Waste Isolation Pilot Plant (WIPP) Site.* SAND81-2195. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents the current intentions and directions of the Waste Isolation Pilot Plant (WIPP) Plugging and Sealing Program and provides a basic structure for the engineering activities that may be required for final WIPP decommissioning and abandonment. It is intended as a guide in determining further directions for the sealing program. Obvious issues that require further development and understanding are identified.

Christensen, C.L., R.D. Statler, and E.W. Peterson. 1980. "Down-Hole Television (DHTV) Applications in Borehole Plugging," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980.* SAND80-0459. Paris, France: Organisation for Economic Co-operation and Development. 385-387.

ABSTRACT: A closed circuit downhole television (DHTV) system has been used to support the bore-hole plugging program. Both dry and underwater lamps were used on a 6-in. outside diameter video camera, with the cable reel footage superimposed on the display. The DHTV was an invaluable tool, in conjunction with caliper logs, to select suitable intervals for seating packers to test formation intervals and bore-hole plugs of low permeability. DWP

Claiborne, H.C., and F. Gera. 1974. *Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico.* ORNL-TM-4639. Oak Ridge, TN: Oak Ridge National Laboratory.

ABSTRACT: This report examines potential containment failure mechanisms and estimates their probabilities and consequences, when possible, for a hypothetical waste repository located in bedded salt in southeastern New Mexico.

The primary conclusion of this study is that a serious breach of containment for such a repository, either by human action or natural events, is only a very remote possibility and falls into the category of least likely occurrences that affect society.

A sealed repository 600 m underground would be virtually sabotage proof; even the surface burst of a 50-megaton nuclear weapon could not breach the containment. Accidental drilling of bore holes through the disposal horizon could cause relatively minor local contamination.

The mechanism of containment failure with the most serious potential consequences seems to be the impact of a meteorite that produces a crater extending to the disposal horizon. The probability of such a catastrophic meteorite impact was estimated at 1.6×10^{-13} /year. The calculated exposure from the global fallout resulting from such an event would be of the same order of magnitude as that from nuclear bomb tests, provided the impact did not take place during the first few hundred years after closure of the mine. The ejecta falling back into the nearby area would cause a serious and protracted contamination problem. A pathway analysis showed that individuals living exclusively on foodstuffs produced in the contaminated area would be exposed to high radiation doses.

Based on the tectonic activity of the Delaware Basin over the past 200 million years, the probability of faulting through the repository has been estimated at 4×10^{-11} /year; however, the probability that faulting would cause failure of waste containment is only a small but unknown fraction of this value.

Exposure of the waste horizon to the action of groundwater by a large fault with a vertical displacement of at least 350 m cannot be proved impossible. However, at least a few hundred

thousand years would be required for an offset of 350 m to take place. A more sudden breach of containment could be effected by a large fault that cuts through the disposal zone and hydraulically connects the over- and underlying aquifers. In this case, any water flow along the fracture zone would be downward into the deep aquifers. Fortunately, the geologic evidence indicates that such a fracture could eventually be healed by plastic flow of the salt beds. Even in the event that the deep aquifers became contaminated, it is extremely unlikely that activity could be brought to the surface because the normal flow velocities in these aquifers are on the order of only a few km/million years.

In view of the hydraulic heads of the various aquifers, it is difficult to visualize circumstances that could result in an upward flow and contamination of the fresh water in the Culebra dolomite aquifer. The only possibility for the release of radioactive material to the Culebra dolomite aquifer would appear to be on the basis of a model that permits faulting and progressive displacement of the disposal horizon until waste contacts the circulating groundwater. The contamination of surface aquifers caused by this mechanism of release could be relatively serious, despite the very long time necessary to produce such a displacement.

Cockman, J.S. 1988. "Salt Impact Studies at WIPP: Effects of Surface Storage of Salt on Natural Vegetation," *Waste Management 88. Waste Processing, Transportation, Storage and Disposal. Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988.* Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 665-672.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a research facility operated for the Department of Energy (DOE) to demonstrate the safe disposal of transuranic (TRU) wastes derived from the defense activities of the United States. The facility is located in an area of stabilized sand dunes with the actual waste repository positioned in a deep geologic formation of bedded salt. Prior to waste emplacement, salt is mined to create repository rooms and stock piled on the surface. Windblown salt from the stockpiles may have an impact on adjacent vegetation and soils. Control and experimental plots have been established at the facility to monitor the effects of windblown salt on the surface ecosystem. Vegetation is sampled as part of a series of subprograms to monitor foliar cover, species richness, annual plant density, and community structure.

Colton, I.D., and J.G. Morse. 1985. *Water Quality Sampling Plan.* WIPP-DOE-215. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The *Water Quality Sampling Plan* is designed "to obtain representative and repeatable groundwater quality data from selected wells under rigorous field and laboratory procedures and protocol." Groundwater will be serially sampled during pumping to establish steady-state chemical parameters for collecting a final groundwater sample for analysis. The report describes the sampling and analytical program. During 1985, about 23 wells will be sampled. Eighteen wells produce from the Culebra Dolomite Member of the Rustler Formation, three wells sample the Magenta Dolomite Member of the Rustler Formation, and two wells sample the Dewey Lake Formation. A variety of chemical parameters will be measured as well as major cations, major anions, minor and trace elements and metals, organics, stable isotopes, gases, redox couples, and radionuclides. DWP

Combs, D.W. 1975. "The Mineralogy, Petrology, and Bromine Geochemistry of Selected Samples of the Salado Salt, Lea and Eddy Counties, New Mexico - A Potential Horizon for the Disposal of Radioactive Waste." MS thesis. Knoxville, TN: University of Tennessee.

ABSTRACT: The main purpose of this study is to evaluate the mineralogy, petrology and dehydration characteristics of the Salado Salt near Carlsbad, NM which is a potential radioactive waste (radwaste) repository. Bedded evaporite deposits were previously selected by the National Academy of Sciences/National Research Council because of their general lack of water, self-healing property when fractured and thermal conductivity and stopping power of high energy radiation. The Salado Salt was chosen using these guidelines. It is a bedded evaporite sequence (about 2000 ft-thick) of Late Permian age located in southeastern New Mexico and West Texas. The Salado is composed primarily of halite with lesser amounts of anhydrite, polyhalite, and a zone of economic potash minerals (McNutt Potash zone).

Several techniques were employed in this study. X-ray diffraction was used to determine the bulk mineralogy and the relative amount of each mineral. Thin section analyses were used to study the mineral assemblages, textures, and paragenesis. Non-dispersive X-ray spectroscopy was used to analyze the bromine content of each sample and to give insight into the origin of the Salado. Samples from a previous study of the Hutchinson Salt Member (Lower Permian) of the Wellington Formation (near Lyons, KS) were also analyzed for bromine in order that a comparison could be made between two deposits of Permian age. Static dehydration tests made of each sample to estimate the amount of water that would be released when the sample was subjected to heat of decaying radioactive waste were reported separately in the Final Report for this project.

Samples were prepared for thin sectioning by cutting a slab from each core section and sending the slab away to be made using oil during cutting and grinding rather than water and using epoxy cement that was not heated. These steps were necessary to prevent dissolution and/or changes of the evaporite minerals.

Pressed pellets were made for spectroscopic analysis of bromine, chlorine, sulfur, and iron using clear, cubic halite crystals with a minimum of inclusions. This procedure was used to be sure that the bromine analyses were only for halite without dilution or addition of bromine from other minerals. Bromine values determined for 73 samples of the Salado Salt ranged from 17 to 50 ppm. Semi-quantitative analyses for sulfur and chlorine were run to measure the amount of contamination by sulfates and to insure that relatively equal amounts of chlorine were present. Sulfur contents were roughly less than 10 ppm.

The results of this study show that halite is the dominant mineral in all but a few samples; anhydrite is next most abundant in the lower portions of the Salado salt; and polyhalite is second most abundant in the upper part of the unit. Thin section analyses reveal several shallow-water features such as hopper crystals, halite embedded in clay, and nodular anhydrite. Polyhalite commonly occurs as a secondary mineral at the expense of anhydrite and both anhydrite and polyhalite exist in various habits and associations. Spectroscopic analyses reveal low bromine concentrations for the Salado and the Hutchinson Salt, Lyons, KS, suggesting that both are second generation deposits. Dehydration studies show the Salado to lose 0.0 to 3.5% water upon heating to $102 \pm 5^\circ\text{C}$. Most of the higher weight losses ($>0.5\%$) can be related to zones rich in clays and/or polyhalite. The Salado is a potential site for a radwaste repository if clay- and polyhalite-rich zones are avoided.

Comes, G.D., L.D. Wakeley, and E.F. O'Neil, III. 1987. *Properties of Laboratory-Tested Specimens of Concrete from Small-Scale Seal Performance Tests at the Waste Isolation Pilot Plant*. Miscellaneous Paper SL-87-9. Vicksburg, MS: Waterways Experiment Station.

ABSTRACT: Development and field placement of a salt-saturated concrete at the Waste Isolation Pilot Plant (WIPP) included extensive testing of field-cast specimens in the laboratory. Such test specimens were cast during two field events, each part of the Small-Scale Seal Performance Tests (SSSPT) at the WIPP, designated Test Series A and B. This report presents data from laboratory tests of SSSPT specimens at ages of three days to one year. The concrete maintained desired physical properties throughout the testing program, maintaining a volume increase and achieving a compressive strength of near 7,000 psi at one year. Data were

analyzed by a curve-fitting computer program, and are presented in figures showing best-fitting curves, which are models of the concrete properties with time.

Cook, C.W. 1979. *Instrumentation Development for the Waste Isolation Pilot Plant (WIPP) Borehole Plugging Program (BHP)*. SAND79-1902. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report discusses the instrumentation development needs of the bore-hole testing program as it now exists. Although requirements may change as the program progresses, the items indicated are basic to any bore-hole plugging program. Instrumentation is discussed both for the plug environment and for the plug itself. For the plug environment, a probe for measuring the disturbed region and a coordinate logging tool are required. For the plug itself, instrumentation includes measurements above, within, and below the plug. Instrumentation for most measurements above the plug is currently available; for measurements within and below the plug, however, further development is required. Specifically, resistivity, induction, and acoustic probes, an in situ stressmeter, and a hardwire feedthrough system need to be developed.

Cook, C.W. 1982. *Underground Scanning With an Impulse Radar*. SAND82-0470. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Impulse radar is being evaluated for possible applications at the Waste Isolation Pilot Project (WIPP) in southeastern New Mexico. Potential applications are scanning salt to identify inclusions, structural discontinuities, and other anomalies before excavation; and verifying the locations of stored radioactive-waste canisters. Four underground experiments were run. The extent and shape of dome-salt pillars and a langbeinite pillar were measured with the radar. Metal targets that simulated waste canisters were located to within a few centimeters after they had been buried for 18 months. If the material being scanned contains clay seams and other conductive inclusions, penetration by radar is limited. It is anticipated that clean bedded salt will be an excellent medium for scanning with an impulse radar. The impulse radar as it now exists can be used for WIPP applications.

Cook, C.W., and E.S. Ames. 1980. "Borehole-Inclusion Stressmeter Measurements in Bedded Salt," *Proceedings of the 20th US Symposium on Rock Mechanics, Austin, TX, June 4-6, 1979*. SAND79-0377. Austin, TX: University of Texas. 481-489.

ABSTRACT: Sandia purchased bore hole inclusion stressmeters from a commercial supplier to measure in situ stress changes in bedded salt. However, the supplied stressmeters were difficult to set in place and gave erratic results in bedded salt. These problems were overcome with a new extended platen design. Also, a strain-gaged transducer that can be read with a conventional data logger was designed.

Because of the nonlinear behavior of bedded salt under uniaxial loading, a new empirical calibration scheme was devised. In essence, the stressmeters are calibrated as force transducers and this calibration curve is then used to determine the relationship between uniaxial stress changes in bedded salt and the gage's output.

The stressmeter and calibration procedures have been applied under mine conditions and produced viable results.

Future work will involve finite element analysis to calculate the observed behavior of the stressmeters. The response of the stressmeters in bedded salt is neither that of a true

stressmeter or of a true strainmeter. However, repeatable calibrations make the gages very useful.

Cook, C.W., C.B. Kinabrew, P.L. Lagus, and R.D. Broce. 1980. "Bell Canyon Test (BCT) Instrumentation Development," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980*. SAND80-0408C. Paris, France: Organisation for Economic Co-Operation and Development, 299-338.

ABSTRACT: This report discusses the instrumentation used to assess the performance of the Bell Canyon Test (BCT) plug and addresses the future direction of instrumentation development. The BCT was initiated with a timed-release packer system below the plug and six time-release tracer gas bottles were included to provide a method of measuring permeability through the plugged region. A geophone package installed above the plug verified the initial operation of the below-the-plug system. In addition to tracer gas arrival times, fluid buildup and shut-in pressure measurements were made with current oil field systems--Digital Memory Recorder (DMR) and Conductor Wire Line (CWL)--to evaluate plug performance. A probe for measuring discrete fluid levels, fluid conductivity pressure, and temperature above a bore hole plug has been developed. The conductivity measurement provides a rough measure of dissolved salts that can be useful in identifying the source of the water. Development has started on two probes that can be grouted in place to monitor the leakage of brine past a plug. A wireline closed circuit TV capable of operating underwater in 5000-ft-deep holes is being set up to ascertain the well bore conditions.

Cooley, C.H., and S.W. Butters. 1979. *Pressure and Time Effects on Permeability of Salt Cores*. TR 79-45. Salt Lake City, UT: Terra Tek, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Salt samples from WIPP Drillhole ERDA-9 were tested to determine, over time, changes in permeability caused by temperature and pressure. Microfractures develop after coring from change in effective stress. Permeability in these samples decreases after hydrostatic pressure is reapplied for a period of time. This testing measures changes caused by controlled temperature and pressure changes in the laboratory.

Permeability of salt samples decreases from original values of about 71 microdarcies to values equal to or less than 0.03 microdarcies with hydrostatic stress and time. Release in hydrostatic stress results in small elastic recovery but no measureable plastic recovery. The resulting increase in permeability was less than 0.03 microdarcies, at least for periods up to 175 hours.

At hydrostatic stresses up to 4000 psi, temperature increases to 95°C did not measureably change gas permeability, although there is evidence to indicate that temperature enhances the rate of "healing." DWP

Cooley, C.H., S.W. Butters, and A.H. Jones. 1978. *Permeability of Rock Salt to Gases and Liquids*. TR 78-62. Salt Lake City, UT: Terra Tek, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Permeability of rock salt to gas and liquid is important to isolation of radioactive waste. Two gases (nitrogen and hydrogen) and two liquids (Dow 200 silicone fluid and salt brine) were used in laboratory experiments. Transient techniques revealed gas permeability in the range of microdarcies with no significant difference between these gases. Permeabilities were 4.2 to 6.8 microdarcies at 100 psi confining pressure and 0.06 to .25 microdarcies at 4000 psi. Initial brine permeability tests showed permeability increasing with time because of salt solution during the tests. Brines were made by heating and then cooling;

these brine tests did not differ significantly from tests using Dow 200 silicone fluid. Dow 200 permeabilities range from 0.07 to 3.50 microdarcies at confining pressures of 100 psi. At confining pressure of 4000 psi, permeability to Dow 200 ranged from 0.01 to 0.07 microdarcies. Hydrostatic cycling during testing showed variable response, and there are some indications that in situ permeabilities may be lower than laboratory measurements. DWP

Core Laboratories, Inc. 1977. *Special Core Analysis Study for Sipes, Williamson & Aycock, Inc. ERDA No. 9 Well Eddy County, New Mexico.* Dallas, TX: Core Laboratories, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Thirty-three full-diameter core samples from ERDA-9 were tested for air permeability and porosity. Sample depths ranged from 2037.4 to 2684.7 ft in depth. Thirty-one samples showed air permeability between 0.29 and 0.0003 md; two samples measured 1.5 and 16 md, respectively. Porosity of all samples ranged from 1.1 to 0.1 %. Drilling fluid was injected under pressure into two samples to test the effects on air permeability. Air permeability in both forward (in the direction of fluid injection) and reverse directions was reduced after drilling fluid injection by more than an order of magnitude in each sample. DWP

Costin, L.S., and W.R. Wawersik. 1980. *Creep Healing of Fractures in Rock Salt.* SAND80-0392. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Fracture and healing experiments were performed on specimens of bedded salt from the Salado Formation, southeastern New Mexico. Short rod specimens (100 mm in diameter) were loaded to failure in tension. During each test, a crack was initiated along the axis of the specimen. The fracture toughness of the salt was determined from the resulting load-crack opening displacement record. After the test, each specimen was pieced back together, jacketed, and placed in a pressure vessel under hydrostatic pressure for several days. The confining pressure (10-35 MPa), temperature (22-100°C), and healing time (4-8 days) were varied to determine the effect of each on the healing process. Upon removal from the pressure vessel, each sample was retested and the toughness of the healed fracture was determined. Results show that the salt specimens regained 70-80% of their original strength under all conditions, except at the lowest temperature and pressure where specimens regained only 20-30% of their original strength. It is suspected that the primary mechanism involved is creep of asperities along the fracture surface, which forms an interlocking network. Thus, the healing pressure is probably the most significant variable.

Crawley, M.[E.] 1987a. *Pressure Density Survey Program Plan.* Albuquerque, NM: International Technology Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Formation pressures and fluid densities are essential to analyze groundwater flow direction of the Culebra Dolomite Member of the Rustler Formation. The Culebra dips eastward and contains water of variable density. This plan addresses technical constraints, operational plan, data reduction, equipment calibration, and schedule for a pressure-density survey.

Constraints include access, disturbed water levels in wells and shafts caused by drawdown, waiting time for the slug (caused by placing instruments) to dissipate, available equipment, and cumulative errors such as depths based on geophysical log picks. The operational plan covers measuring barometric pressure and water level, setting up equipment, measuring pressures inside well casing, measuring pressures and temperatures at formation levels, sampling

formation fluid, specifying procedures for wells with production-injection-packers, checking equipment, analyzing fluids, and decontaminating equipment. Data reduction specifies quality control, verifying pressures for computing density and for comparing formation pressures from hole to hole, and managing the data base. Equipment calibration concerns procedures and records for all instruments to be calibrated. An initial survey is scheduled in 1986 with the first data report in 1987. DWP

Crawley, M.E. 1987b. *Second Data Release Report for the Pressure-Density Survey Program.* [Albuquerque, NM:] IT Corporation/Westinghouse WID. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Formation pressures and density data for the Culebra Dolomite Member were acquired during two field survey periods in late 1986 and early 1987. These data indicate the fluid is density stratified in these bore holes. Some differences in density profiles of a few wells were observed, but there was generally very little change in density stratification. The observed differences in the survey are attributed to hydrologic testing during the period between the surveys. DWP

Crawley, M.E. 1988a. *Hydrostatic Pressure and Fluid-Density Distribution of the Culebra Dolomite Member of the Rustler Formation Near the Waste Isolation Pilot Plant, Southeastern New Mexico.* DOE/WIPP 88-030. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The pressure-density survey was initiated in 1986 to provide groundwater density and pressure information needed for hydrologic analysis of the Culebra Dolomite Member of the Rustler Formation. The Culebra contains fluid of highly variable density. Accurately defined formation pressures and formation water densities are required to calculate groundwater flow directions and velocities in structurally dipping geologic units having variable density fluids. In the past, formation pressures have been calculated or estimated using measured water levels from wells and single water-density values measured or estimated for various points across the project area. The data collected as part of this program indicate that many of the wells tested have density stratified fluid and that other well testing activities, such as sampling and permeability testing, can alter density stratification. Estimated formation pressures using measured water levels are often in error relative to actual measured pressures and can impact the interpretation of groundwater flow directions in the Culebra. These data have been useful to several hydrologic evaluation programs. The groundwater level and pressure monitoring program will also use the data to more accurately define equivalent freshwater heads. DWP

[**Crawley, M.E.** 1988b.] *Third Data Release Report for the Pressure-Density Survey Program.* [Albuquerque, NM: International Technology Corporation.] (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Fluid pressure and density data were collected from 27 wells in the Culebra Dolomite Member during the last half of 1987. This final field survey shows that fluid is density stratified in many of the wells. There is very little change in density stratification compared to earlier surveys. Some observed differences are attributed to well testing and sampling activities between fluid density surveys. The data from these surveys indicate that groundwater flow gradients and directions may not be defined by measuring only water levels and assuming density values. DWP

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Dames & Moore. 1979a. *Final Report, Laboratory Soil Test Results, US Department of Energy, Waste Isolation Pilot Plant, Carlsbad, New Mexico.* San Francisco, CA: Dames & Moore. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Laboratory tests for the Waste Isolation Pilot Plant to be constructed near Carlsbad, NM were performed on undisturbed and remolded specimens of caliche, Gatuña Formation, and sand materials. The tests included strain-controlled cyclic triaxial tests; resonant column tests; unconsolidated undrained triaxial tests; consolidated undrained triaxial tests with pore pressure measurements; consolidated drained triaxial tests; permeability tests; and index properties tests (sieve and hydrometer analyses, Atterberg limits tests, and specific gravity tests). The data for each test type are presented in a separate section. DWP

Dames & Moore. 1979b. *Supplemental Report, Laboratory Soil Test Results, US Department of Energy, Waste Isolation Pilot Plant, Carlsbad, New Mexico.* San Francisco, CA: Dames & Moore. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Samples of caliche, Gatuña Formation, and sand from the road access area to the Waste Isolation Pilot Plant (WIPP) Site were tested in the laboratory for the following soil tests: unconsolidated undrained triaxial compression; consolidated drained triaxial compression with volumetric strain; sieve and hydrometer analysis; and specific gravity. The data for each test are included in separate sections. DWP

D'Appolonia Consulting Engineers, Inc. 1979. *Final Report, Potential for Salt Fracturing Due to Gas Generation, CH Level of WIPP Repository, Carlsbad, New Mexico.* Pittsburgh, PA: D'Appolonia Consulting Engineers, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This study was undertaken to evaluate the mechanisms, conditions, and direction and extent of fracturing that might occur because of gas pressure generated by decomposing contact handled (CH) waste. The tasks identified for this study were to review models and select the most applicable fracturing model for the Waste Isolation Pilot Plant (WIPP) repository, assess gas generation rates and salt permeability to determine the pressurization of the repository, determine a conservative model of gas transport through rock salt, and develop an integrated model coupling gas generation, transport, and fracture models. Available data from the literature were used for the first three tasks. It was assumed that fractures would most likely occur in the roof and would propagate upward to planes, such as clay seams, with a weaker tensile strength. The crack would then propagate along the bedding plane. Gas was assumed to generate at constant rates, filling cracks. Permeabilities were taken as equal to or greater than for salt. Gas viscosity was used, which corresponds to maximum pressures. Steady-state transport solutions were used.

These studies permit a reasonably high level of confidence that conditions required to initiate fracturing can be predicted. The available data also indicate that fracturing at the contact handling (CH) level of WIPP is highly unlikely. It is anticipated that refined parameters will show that fracturing will not occur.

Several conclusions expand this summary statement. A credible model can be developed to predict reliably fracture potential for the WIPP Site using existing, accepted, hydraulic fracturing knowledge. For the measured permeabilities, gas generation, and transport characteristics used, it is unlikely that a crack will form; there is a small possibility that a

horizontal fracture less than 300 m (1,000 ft) in length could propagate. Gas generation rates lower than 5 moles/drum/year decrease the probability of propagating a fracture. Fracturing will not occur for gas generation rates lower than about 1.5 moles/drum/year for 400 years. A more realistic gas convection model substantially reduces the probability of initiating a fracture. The fracture model used in this study is realistic and current. However, the model does not consider any fracture toughness of the materials along horizontal bedding planes. Increasing the volume available at the sealed repository to "absorb" the generated gas volume reduces the potential for initiating cracks. This could be accomplished by modifying the pack next to the waste, increasing the void ratio in the backfill pack, and/or by increasing the initial volume at the excavated repository. Gas generation rates and the fracture model are conservative. It appears easier to quantify the conservatism in gas generation rates. Future investigations should emphasize these rates and gas generation/pressure interaction. DWP

D'Appolonia Consulting Engineers, Inc. 1981a. *Second WIPP Benchmark Problem Using the DAPROK Computer Code*. D'Appolonia-TSC Report. Albuquerque, NM: Westinghouse Electric Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The second benchmark problem for the Waste Isolation Pilot Plant (WIPP) was developed to demonstrate and compare numerical codes to model mechanical behavior of rooms designed for the WIPP. Common input includes material properties and geologic conditions. The room design, based on operational concerns and local mining experience, may be verified as stable through the results of different codes. D'Appolonia limited its analysis to isothermal conditions with a room floor at 659-m-depth. The problem was subdivided based on clay seam friction. The finite element code DAPROK used to solve the problem is a modification of a code commonly called BMINES.

Clay seams and sulfates strongly influenced creep response of halite materials in the model. Pure halite around the upper part of the room design showed most creep. High Von Mises stress was created around the room by the no-friction clay seam model, while the friction clay seam model greatly reduces creep response. The underlying anhydrite restrains creep closure of the room mildly for the no-friction clay seam model and more strongly for the friction model. Modeled room closure for the no-friction clay seam is larger than expected and is probably too low with the friction clay seam model. Little creep occurs in halite below the anhydrite layer. The anhydrite markedly affects the horizontal stress field, but the influence of bending the anhydrite unit was not modeled. Separation of either floor or roof will not be a major problem.

The calculated closure rate for the no-friction clay seam model is 126% greater than for the friction model. Closure rate is likely to be between the two values. The modeling indicates the need for better material properties for sulfate beds and clay seams. The analysis should be performed using a tension continuum element failure criterion. DWP

D'Appolonia Consulting Engineers, Inc. 1981b. *Modeling Verification Studies, Long-Term Waste Isolation Assessment, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. Albuquerque, NM: Westinghouse Electric Corporation.

ABSTRACT: The *Safety Analysis Report (SAR)* of 1980 includes an assessment of long-term waste isolation by the Waste Isolation Pilot Plant (WIPP) based on hypothetical release scenarios. Hydraulic communication with the biosphere is represented or bounded by one of three basic events, which were modeled for the SAR. This study was conducted to verify basic calculational procedures and evaluate the effects of procedure variations, evaluate the sensitivity of SAR results to source terms and hydrogeological and geochemical parameters, and review and comment on the basic data used and on the radionuclide transport mechanism. The study used the same events and assumptions about transport as the SAR.

"The most important conclusion ... is that the computational models used to calculate the radionuclide releases resulting from the events analyzed in the SAR are verifiable using independently derived calculation techniques. Furthermore, reasonable extrapolation of key input data do not change the fundamental result of the analyses." The hydrogeologic data for the SAR are generally defensible, but the data for the Rustler and effects of fracture permeability are incomplete. Radionuclide sorption data need to be improved. Alternative regional hydrologic models show longer travel times with minimal net effects on radionuclide release at Malaga Bend. Waste-release rates for release events are extremely conservative. Nuclide transport modeled independently is similar to SAR results; the most effective barrier is the long travel path to the biosphere at Malaga Bend. DWP

D'Appolonia Consulting Engineers, Inc. 1982. *Data File Report, ERDA-6 & WIPP-12 Testing*. Albuquerque, NM: Westinghouse Electric Corporation. Vols. I-IVB. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Hydrologic, geologic, and chemical data are reported from field testing of ERDA-6 and WIPP-12 during late 1981 and early 1982. Most analyses of the data are presented elsewhere.

ERDA-6 was tested to characterize the brine reservoir encountered in 1975 and to determine the condition and integrity of the grout plug placed in the borehole in 1976. Fluids from the borehole were tested chemically to evaluate the brines. Further drilling was planned to determine the deformation of the units, but this was postponed. Geophysical logs were run to determine fluid sources and to evaluate casing/cement bond. One drill stem test and three flow tests were conducted on the reservoir to provide data for hydrologic interpretations and samples for chemical testing. Fifty brine and twenty gas samples were obtained for analysis. Sixty feet of core were obtained, including nine feet of cement plug. The cement plug/rock contact is commonly unbonded and open, possibly due to drilling and handling. Logs confirm that the brine is produced from fractures at about 2711 ft depth.

WIPP-12 was deepened to determine the nature and extent of Castile Formation deformation over a subdued domal structure. A pressurized brine was encountered in the upper Castile, and the hydrologic and chemical studies were initiated. Hydrologic testing included drill stem testing, pressure build-up monitoring, and flow monitoring during drilling to provide volume estimates. Surface samples of brine (16) and gas (4) and subsurface samples (2) were obtained for analysis in the field and laboratory. Core was obtained from 2776 to 3925 ft, through the fluid-producing zone. Fractures occur exclusively in the Anhydrite III member; "...fluid-producing fractures are probably between 3016 feet and 3021 feet." Geophysical logs were obtained after the brine reservoir was encountered and after drilling to total depth. DWP

Davies, P.B. 1986. "Pleistocene-To-Present Flow-System Evolution in the Northern Delaware Basin, Southeastern New Mexico -- Analysis Using Transient Cross-Sectional Flow Simulations," *Abstracts with Programs, 1986, Geological Society of America, 99th Annual Meeting and Exposition, San Antonio, TX, November 10-13, 1986*. Vol. 18, no. 6, 580. (Abstract Only).

ABSTRACT: Several types of geologic evidence indicate that the groundwater flow system in the northern Delaware Basin contained more water during past glacial pluvial periods than it does at present. This evidence includes Pleistocene-age gypsite spring deposits at elevations well above the current water table, veinlets and pods of selenite in currently unsaturated rock, and Pleistocene-age stream deposits indicating the presence of significant quantities of surface water available for recharge. Isotopic studies indicate the presence of relatively old, slow-moving ground water at depth in the current flow system.

A transient cross-sectional flow model has been used to examine evolution of the current flow system from a Pleistocene system that contained higher groundwater levels. The 30-kilometer cross-section includes post-Salado Formation (Permian age) units from a topographic divide in the east to a valley (Nash Draw) produced by evaporite dissolution and subsidence in the west. Variations in hydraulic-conductivity distribution, initial conditions, and boundary conditions provide the basis for examining flow-system evolution.

Simulation results indicate that the flow system drains very slowly from its initially "charged" state at the termination of the last glacial pluvial, and that present flow patterns in this semiarid region may be affected by this transient drainage process. Drainage is concentrated in the area just east of Nash Draw, where deformation associated with evaporite dissolution and subsidence has increased rock permeability. Substantial underpressuring develops in a relatively permeable dolomite unit that is well connected to a discharge area in the west but poorly connected to a source of recharge in the east.

Davies, P.B. 1987. "Modeling Areal, Variable-Density, Ground-Water Flow Using Equivalent Freshwater Head -- Analysis of Potentially Significant Errors," *Proceedings of the Solving Ground Water Problems with Models*, Denver, CO, February 10-12, 1987. Dublin, OH: National Water Well Association. Vol. 2, 888-903.

ABSTRACT: The concept of equivalent freshwater head is widely used in modeling groundwater flow systems that contain water with substantial spatial variation in fluid density. The use of equivalent freshwater head implicitly assumes that groundwater flow is approximately horizontal, and, therefore, density-related gravity effects are small and can be ignored. The relative importance of density-related gravity effects can be examined by expanding the gravity term Darcy's Law and separating an equivalent freshwater head term, which represents the pressure-driven component of flow, from a density-related error term, which represents the gravity-driven component of flow. The resulting expression illustrates that it is not the absolute magnitude of the density-related error term, but rather the relative magnitude of this term versus the magnitude of the equivalent freshwater head term that determines whether density-related gravity effects will be significant in a given situation. A useful measure of the relative importance of density-related gravity effects is the dimensionless ratio of the magnitude of the density-related error term to the magnitude of the equivalent freshwater head term. An analysis of the relative magnitude of density-related gravity effects has been made as part of a regional study of the groundwater flow system in a gently dipping dolomite aquifer in the vicinity of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. A comparison of equivalent freshwater head simulations with variable-density simulations reveals an area along the flow path leaving the site where equivalent freshwater head simulations produce errors in predicted flow direction of as much as 170° and underestimate predicted velocity magnitudes by as much as a factor of 10.

Davies, P.B. 1989a. "Analysis of Variable-Density Groundwater Flow in Vicinity of Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico," *Abstracts, 28th International Geological Congress*, Washington, DC, July 9-19, 1989. SAND88-2637A. Vol. 28, no. 1, 1-371. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a US Department of Energy (DOE) project designed to provide a research and development facility to demonstrate the safe disposal of transuranic (TRU) waste from defense-related activities. The WIPP consists of an underground repository mined from a thick bedded-salt unit and associated waste-handling facility at land surface. The facility is located in southeastern New Mexico in an evaporite-bearing sedimentary basin known as the Delaware Basin. A key component in the assessment of the long-term performance of the facility is evaluating the potential for radionuclide transport from the underground repository to the biosphere by groundwater.

The WIPP repository is located approximately 650 m below land surface in the lower part of the predominantly halite Permian Salado Formation. Overlying the Salado is the Permian Rustler Formation, which is composed of interbedded halite, anhydrite, fine-grained clastics, and two dolomite units. The Culebra Dolomite Member of the Rustler Formation has been identified as being the most transmissive water-bearing unit and is considered an important potential pathway for the transport of radionuclides to the biosphere in the event of a repository breach. Within the Rustler, secondary processes of halite dissolution, subsidence, and calcium sulfate hydration have produced complex hydrologic conditions. Complexities include spatial variation in permeability of several orders of magnitude within the same rock unit, local areas of fracture-dominated flow, and variation in fluid density ranging [sic] from 1.0 g/cm³ (freshwater) to 1.2 g/cm³ (NaCl saturated brine). Secondary processes have been most active in an area west of WIPP, producing a pronounced north-south trending valley called Nash Draw. East of Nash Draw, halite dissolution and other secondary processes have been less active, and there is a transition from fractured to intact rock with associated decreasing permeability. The WIPP Site is located within this transition zone, which generally is characterized by large spatial variation in permeability and fluid density.

A new analytic technique was developed to facilitate the construction of numerical simulations of groundwater in variable-density flow environments. Based on a dimensional analysis of Darcy's Law, the technique provides a dimensionless parameter characterizing the relative magnitude of pressure-related versus density-related flow-driving forces. This parameter can be evaluated using field data on aquifer structure, fluid density, and equivalent freshwater head. Mapping the dimensionless driving-force parameter over the WIPP region provided the information necessary to locate model boundaries in areas where fluid-density effects are not significant, thereby reducing boundary condition complexity and uncertainty. Mapping of the driving-force parameter also identified an important area along the flow paths leaving the site where numerical simulations based solely on equivalent freshwater heads produce errors in predicted flow direction of as much as 105° and errors in predicted velocity magnitude of as much as 80%.

Assuming that solute transport takes place slowly relative to pressure redistributions, an approximate steady-state solution was calibrated to the observed equivalent freshwater heads using the observed fluid densities to specify a constant-in-time density distribution. The assumption of a specified density distribution was then examined using a 1000-year transient transport simulation. This transient simulation shows that solute redistribution has very little impact on flow over a 100-year time period and only minor effects in local areas over a 1000-year time period. The flow field from the steady-state simulation, along with transient transport patterns, indicate that flow velocities are relatively fast west of the site (10⁻⁶ m/s) and extremely slow (10⁻¹² m/s) east and northeast of the site. In the transition zone between these two extremes, which includes the WIPP Site, velocities are highly variable.

A series of sensitivity simulations was used to analyze boundary effects and vertical flux. These simulations indicate that if the Culebra is as impermeable to the east and northeast as geologic conditions indicate, the central and western parts of the region, including the WIPP Site, are fairly well insulated from the eastern and northeastern boundaries. Simulation of a 5 m head increase along a river boundary to the southwest indicates that if the Culebra were tightly confined throughout the entire region, approximately 50% of any change in river elevation eventually would be manifested as head change in the Culebra at the WIPP Site. A series of vertical-flux simulations indicate that as much as 25% of total inflow to the Culebra could be entering as vertical flux. These simulations also indicate that if water enters the Culebra vertically, most of the influx is geographically restricted to the westernmost part of the transition zone adjacent to Nash Draw.

The dimensionless driving-force analysis and numerical flow simulations provide important insight to variable-density flow behavior in the WIPP region. These simulations also will be used to provide transient boundary condition information for numerical simulations that examine flow and transport in the immediate vicinity of the WIPP repository, which are being developed by INTERA Technologies under contract to Sandia National Laboratories (SNL).

This work was funded by the US DOE and carried out by the US Geological Survey (USGS) and SNL.

Davies, P.B. 1989b. "Assessing Deep-Seated Dissolution-Subsidence Hazards at Radioactive-Waste Repository Sites in Bedded Salt," *Engineering Geology*. Vol. 27, 467-487.

ABSTRACT: Deep-seated salt dissolution and associated subsidence have occurred in many salt-bearing sedimentary basins. Because of its capacity for breaching the hydrologic integrity of a thick salt unit, the dissolution-subsidence process is a potential hazard requiring thorough assessment at proposed radioactive waste repository sites in bedded salt. In order to develop a better understanding of this potential hazard, a combination of field studies and theoretical analyses are used to delineate the physical processes that control dissolution and subsidence. This information is used, in turn, to develop strategies for assessing this hazard at any given bedded salt repository site.

A generalized hydrogeological model of dissolution has been developed consisting of a salt unit separated from an underlying aquifer by a low-permeability unit. This model suggests that local salt-removal rates can vary over many orders of magnitude, from microns per year to meters per year, depending on the hydrogeologic conditions beneath the salt unit.

Salt deformation is strongly rate sensitive, so the rate of salt removal strongly influences the structural form of subsidence. Low salt-removal rates produce predominantly ductile subsidence, which is characterized by the gradual formation of a broad shallow depression that is narrower and deeper in successively lower horizons. On the other hand, high salt-removal rates produce predominantly brittle subsidence, which is characterized by the formation of a steep-walled chimney, filled with down-dropped, brecciated rock. Ductile subsidence depressions and brittle subsidence chimneys most likely represent the endpoints of a continuous range of structural forms.

Assessing potential dissolution-subsidence hazards at a given repository site begins with the identification and characterization of existing dissolution-subsidence features in the site area. Studies of existing features should be complemented by an evaluation of the potential for undetected or future dissolution activity, based on the deep hydrogeologic conditions at the site. Potential salt-removal rates predicted by this analysis are then used as an analysis of the structural character and timing of potential subsidence.

Davies, P.B. 1989c. *Variable-Density Ground-Water Flow and Paleohydrology in the Waste Isolation Pilot Plant (WIPP) Region, Southeastern New Mexico*. Open-File Report 88-490. Albuquerque, NM: US Geological Survey.

ABSTRACT: A series of analyses, including variable-density flow simulations, was used to examine groundwater flow in the vicinity of the Waste Isolation Pilot Plant (WIPP) in the context of the regional flow system. WIPP is an underground repository mined from a thick bedded-salt unit to provide a facility for the disposal of radioactive waste. WIPP is located in southeastern New Mexico. The analyses primarily examined the Culebra Dolomite Member of the Rustler Formation, which is a potential pathway for the transport of radionuclides to the biosphere in the event of a breach of the WIPP repository.

An analysis of the relative magnitude of pressure-related and density-related flow-driving forces indicates that density-related forces are not significant at the WIPP Site and to the west but are significant in areas to the north, northeast, and south of the site. The area to the south is important because it lies along potential transport pathways from the site. In this area, groundwater flow simulations based on equivalent freshwater head produce very misleading information on predicted flow directions and velocity magnitudes.

A regional-scale, variable-density model of groundwater flow in the Culebra Dolomite Member was developed in which a baseline, approximate steady-state simulation was calibrated to the distribution of equivalent freshwater heads. The flow field from the baseline simulation, along with long-term brine transport patterns, indicates that flow velocities are relatively fast west of the site and extremely slow east and northeast of the site. In the transition zone between these two extremes, which includes the WIPP Site, velocities are highly variable.

A series of sensitivity simulations was used to analyze boundary effects and vertical flux. These simulations indicate that if the Culebra is as impermeable to the east and northeast of the WIPP Site as geologic conditions indicate, the central and western parts of the region, including the WIPP Site, are fairly well insulated from the eastern and northeastern boundaries and are insensitive to whatever conditions are assumed to be present along these boundaries. A simulation of a 5-m head increase along the Pecos River boundary indicates that if the Culebra were tightly confined throughout the entire region, approximately 50% of any change in river elevation would eventually reach the WIPP Site. Uncertainty in the regional distribution of storage characteristics in the Culebra makes it difficult to accurately predict how long it would take for Pecos-related stresses to propagate through the WIPP region. A series of vertical-flux simulations indicates that as much as 25% of total inflow to the Culebra could be entering as vertical flux. These simulations also indicate that if significant volumes of water enter the Culebra vertically, most of the influx must be occurring in the westernmost part of the transition zone adjacent to Nash Draw.

Motivated by recent isotopic and geochemical analyses, a simple cross-sectional model was developed to provide a physically based analysis of the flow system as it may have drained through time following recharge during a past glacial pluvial. Drainage for 20,000 years was simulated using a variety of hydraulic-conductivity distributions for rock units overlying the Culebra. These simulations indicate that the system as a whole drains very slowly and that it apparently could sustain flow from purely transient drainage following recharge of the system during the Pleistocene. Although these simulations do not prove that this has been the case, they do show that such long-term transient drainage is physically possible. The simulations also indicate that the observed underpressuring of the Culebra in the vicinity of the WIPP Site is most likely the hydrodynamic result of the Culebra having a relatively high hydraulic conductivity and being well connected to its discharge area but poorly connected to sources of recharge.

Davies, P.B., and G.A. Freeze. 1990. "The Role of Geologic Heterogeneities in Controlling the Flow of Waste-Generated Gas from the WIPP Repository," *Abstracts with Programs, Geological Society of America, Dallas, TX, October 29-November 1, 1990*. Vol. 22, no. 7, A100. (Abstract Only).

ABSTRACT: Recent analysis of the post-closure evolution of disposal rooms in the Waste Isolation Pilot Plant (WIPP) repository indicate that microbial degradation of organic waste and anoxic corrosion of steel drums and metallic waste may be capable of generating significant gas pressures. Assessing the impact of waste-generated gas on long-term repository performance requires an evaluation of the hydrologic response of the surrounding bedded salts of the Salado Formation.

Early hydraulic testing and analyses of the Salado conceptualized this bedded salt as a relatively homogeneous, low-permeability medium, with permeability of the order of 10^{-21} to 10^{-20} m² (1 to 10 nanodarcy). However, while the Salado is primarily halite, it contains interbeds of clay and anhydrite, and the halite itself is characterized by stratigraphically controlled variations in grain size, texture, and impurity content (mostly clay). Recent improvements in the resolution of in situ permeability measurements have revealed significant variability, with permeabilities ranging from less than 10^{-23} m² (less than 0.01 nanodarcy) in relatively pure halite beds to as high as 10^{-18} m² (1 microdarcy) within some of the anhydrite interbeds. A second important factor influencing the release of waste-generated gas is the

threshold pressures required to overcome capillary resistance and drive gas into brine-filled rock pores. Estimates of threshold pressure based on an empirical correlation dependent on intrinsic permeability and on capillary tube model yield values ranging from less than 1 MPa in the higher permeability anhydrite interbeds to greater than 50 MPa in relatively pure halite.

A multiphase flow model has been used to examine the hydrologic response of the bedded salt to gas pressurization of the repository. Preliminary simulations suggest that early-time brine flow toward the repository is reversed as gas pressures rise, causing brine and dissolved gas to flow from the repository into the formation. Once gas pressure in the disposal room exceeds the sum of brine and threshold pressures in the rock pores, free gas flows outward into the formation. Because of the combination of relatively high intrinsic permeability and relatively low threshold pressure, gas flow is predominantly into the relatively high permeability anhydrite interbeds.

Dawson, P.R. 1979. *Constitutive Models Applied in the Analysis of Creep of Rock Salt*. SAND79-0137. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Constitutive equations for the creep of rock salt that have been utilized in the analyses of salt deformations are summarized. Primary creep, secondary creep, and elastoviscoplastic models are discussed. The strains predicted by several of the primary creep constitutive models are compared for identical conditions of deviatoric stress and temperature. Steady-state creep rates are compared under identical conditions of deviatoric stress and temperature for the secondary creep equations.

Dawson, P.R., and P.F. Chavez. 1978. *COUPLEFLO—A Computer Code for Coupled Creeping Viscous Flow and Conductive-Convective Heat Transfer, Part I. Theoretical Background*. SAND78-1406. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: COUPLEFLO is a two-dimensional finite element code for plane strain or axisymmetric analyses of thermomechanically coupled systems. It is capable of analyzing the creeping flow of non-Newtonian fluids or the secondary creep of solids. COUPLEFLO solves equations for conductive-convective heat transfer to determine the thermal response of a system. Thermomechanical coupling between the flow field and temperature distribution can exist in terms of temperature dependent material properties, temperature dependent body forces, viscous dissipation, material convection, and changing system geometry. Either transient or steady-state problems can be analyzed in Eulerian or quasi-Lagrangian reference frames. Part I - Theoretical Background contains the governing equations, finite element formulation, and verification of the code capabilities. Part II - User's Manual [Chavez and Dawson, 1978] contains instructions for code use.

Dawson, P.R., and D.E. Munson. 1983. "Numerical Simulation of Creep Deformations Around a Room in a Deep Potash Mine," *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*. SAND82-0184J. Vol. 20, no. 1, 33-42.

ABSTRACT: A finite-element technique is used in this work to simulate the closure of an in situ test room developed during excavation of a deep potash mine. For the calculations, a constitutive model for creep was determined from laboratory triaxial tests of salt and short cylinder compressive tests of potash, and was incorporated into a coupled thermomechanical formulation for analyzing creeping viscous flow. The model is a multimechanism representation of three thermally activated deformation mechanisms acting in parallel. Because the field test was a well-documented, two-dimensional configuration and because the constitutive model was uniquely determined by independent laboratory data, the good agreement obtained between calculations and field data for the significant duration of the test

is an important first step in verifying the simulation technique. The constitutive model and numerical methods presented here can be used to understand creep in deep potash mines, and (very importantly) can aid in the design of facilities for isolating radioactive wastes and storing petroleum reserves.

Dawson, P.R., and J.R. Tillerson. 1977a. *Comparative Evaluations of the Thermomechanical Responses for Three High Level Waste Canister Emplacement Alternatives.* SAND77-0388. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Three alternative configurations of room design and waste canister emplacement for disposing of high level waste in salt at a depth of 2700 ft have been modeled to determine their structural response. Thermal loading is specified as 37 W/m² (about 150 kw/acre). The numerical analyses use Sandia versions of finite element codes COUPLEFLO and SANDIA-BMINES for heat transfer/creep responses and thermoelastic analyses, respectively. The results are judged by the criterion that the wastes be retrievable for several years after being placed in the repository. Coupled secondary creep and heat transfer computations indicate that the future retrieval of waste is most readily assured with a design that combines a low extraction ratio (large pillars) with waste canisters placed in the floors of each storage room. Room closure caused by thermoelastic behavior is computed to be minimal compared to room closure caused by creep deformation. DWP

Dawson, P.R., and J.R. Tillerson. 1977b. "Thermally Induced Movement of Nuclear Waste Canisters in Salt Formations," *Transactions of the American Nuclear Society, 1977 Annual Meeting, San Francisco, CA, November 27-December 2, 1977.* Vol. 27, 438-440. (Abstract Only).

ABSTRACT: Canisters of heat-generating radioactive waste may rise by buoyant forces after burial in a salt repository. Creeping viscous flow and heat transfer were coupled thermomechanically to model canister motion with varied conductivity, viscosity, and canister density over as long as 3000 years. The canister initially sinks until a convective cell forms and reverses the direction. The canister sinks again as the heat diminishes. Velocities and total displacement are both insufficient to breach waste isolation; total distance travelled by the canister over the cycle ranges up to about 2.5 m for cases considered. DWP

Dawson, P.R., and J.R. Tillerson. 1978a. *Nuclear Waste Canister Thermally Induced Motion.* SAND78-0566. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The movement of canisters containing heat producing nuclear wastes has been analyzed using a single canister model in a salt environment. Steady-state and transient analyses both indicate that only minimal canister movement will result from buoyancy of heated salt.

Dawson, P.R., and J.R. Tillerson. 1978b. "Salt Motion Following Nuclear Waste Disposal," *Proceedings of the International Conference on Evaluation and Prediction of Subsidence, Pensacola, FL, January 15-20, 1978.* CONF-780136-1; SAND77-1226C. (Available from National Technical Information Service, Springfield, VA).

ABSTRACT: Heat from radioactive wastes can produce ground movements in the vicinity of storage rooms and extending to the repository surface. Heat can accelerate the rates of creep caused by overburden loads and accentuate room closure. Salt can rise and move the radioactive wastes upward with it specifically because of the buoyancy of heated salt relative to its surroundings. The induced ground motion can extend from the mine horizon to the ground surface.

Two finite element models have been used to analyze heated salt behavior. One model uses a thermomechanical secondary creep approximation. The second finite element model determines stresses and deformations resulting from changes in temperature.

Three configurations of rooms and high level waste canister emplacements were modeled with these codes. Low extraction ratios and placing canisters vertically in the floor of excavated rooms provide the best alternative to be able to retrieve wastes for several years after storage.

Heat-generating waste canisters might be expected to rise from buoyant salt movement. Analysis suggests the canister will initially sink, then rise, and then sink through its thermal history. The velocities are small, and the total displacement is less than 1 m.

The buoyant motion of salt for the repository region was analyzed for a thermal load of 25 W/m² (100 kW/acre) which decays with a thirty year half life. The ground surface shows movement on the order of 0.5 m after 400 years. The results also show that it is valid to assume that creep strains dominate over elastic strains during the period in which most of the deformation occurs. DWP

Deal, D.E. 1988. "Brine Seepage into the Waste Isolation Pilot Plant (WIPP) Excavations," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 649-657.

ABSTRACT: Although the Waste Isolation Pilot Plant (WIPP) underground workings are considered "dry," small amounts of brine (on the order of 0.1 to 2% by weight) are present. This amount of brine is not unexpected in rocks of marine sedimentary origin and some migrates into the repository in response to pressure gradients, at essentially isothermal conditions. These small quantities of brine have little effect on the day-to-day operations, but are pervasive throughout the repository and may contribute enough moisture over a period of years to effect resaturation and repressurization after sealing and closure.

The observations reported here were obtained in the course of the WIPP Brine Sampling and Evaluation Program (BSEP). Over 2900 brine accumulation measurements have been made in over 14km of drifts and associated drill holes. The BSEP Data Collection began in 1984 and many of the brine seeps have been monitored for more than 900 days.

Brine occurs as "weeps" on exposed surfaces and as seeps of brines at various locations, most noticeably in holes drilled from the underground workings. Over 1400 underground drill holes, most 15 m or less in length, exist at WIPP. Small amounts of gas are usually associated with the brine. Gas bubbles are observed in many of the brine occurrences. Gas is known to exsolve from solution as the brine is poured from container to container.

Measured occurrences have seepage rates that range from less than surface evaporation rates to approximately 0.5 L/day. Most of the seepage rates range between a few tenths and a few hundredths of a liter per day. Individual occurrences vary greatly and some dramatically, making the discussion of "averages" or "typical occurrences" difficult or misleading. Most occurrences have an initial period of no flow followed by peak seepage rates that declined to relatively steady or slightly decreasing rates over the observation period.

It is clear from these preliminary data that the brine, gas, and salt creep phenomena are intimately associated. Pressure-driven brine inflows that are not the result of brine migration in a thermal gradient may occur at any time a pressure difference exists, including after sealing and closure of the repository. It is likely that the observed seepages into the repository excavations are dominated by the response to transient pressure gradients resulting from the excavation of the repository itself. A component due to regional hydraulic head cannot be ruled out at this time, but if it exists, it appears to be relatively very small.

Deal, D.E., and J.B. Case. 1987. *Brine Sampling and Evaluation Program Phase I Report*. DOE-WIPP 87-008. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: This interim report presents preliminary data obtained in the course of the Waste Isolation Pilot Plant (WIPP) Brine Sampling and Evaluation Program. The investigations focus on the brine present in the near-field environment around the WIPP underground workings that is easily moved under existing pressure gradients. Observations began in 1983 and were expanded in 1984 and 1985. Most of the data reported in this document were acquired in the 600 days after January 1, 1985.

Although the WIPP underground workings are considered "dry," small amounts of brine are present, probably on the order of 0.1 to 0.5% by weight of the surrounding rocks. This amount of brine is not unexpected in rocks of marine sedimentary origin. Part of that brine can and does migrate into the repository in response to pressure gradients, at essentially isothermal conditions. These small volumes of brine have little effect on the day-to-day operations, but are pervasive throughout the repository and may contribute enough moisture over a period of years to affect resaturation and repressurization after sealing and closure.

The inflows occur as "weeps" on the exposed surfaces and as very small inflows of brine at various locations, most noticeably in holes drilled outward from the underground workings. Over 1400 underground drill holes, most 15 m or less in length, exist at WIPP. Gas is usually associated with the brine inflows. Gas bubbles are observed in many of the brine occurrences. Gas is also known to exsolve from solution as the brine is poured from container to container.

Measured brine occurrences have inflow rates that range from less than surface evaporation rates to approximately 0.5 L/day. Most range between a few tenths and a few hundredths of a liter per day. Individual occurrences vary greatly and some drill holes less than a meter apart have brine inflows that contrast dramatically, making the discussion of "averages" or "typical occurrences" difficult or misleading. Most occurrences have initial peak inflow rates that decline to steady rates over the observation period. Some have ceased entirely, and a few have increased inflows.

The largest individual production that was measured during this reporting period produced an aggregate of over 235 L of brine. It was clearly an unusual and exceptional occurrence, and inflow rates for that occurrence have declined over the observation period.

It is clear from these preliminary data that the brine, gas, and salt creep phenomena are intimately associated. Pressure-driven brine inflows that are not the result of brine migration in a thermal gradient may occur at any time a pressure difference exists, including after sealing and closure of the repository. It is likely that the observed inflows into the repository excavations are dominated by the response to transient pressure gradients resulting from the excavation of the repository itself. A component caused by regional hydraulic head cannot be ruled out at this time, but if it exists, it appears to be relatively very small.

Investigations of the occurrence and chemistry of the brines are continuing.

Deal, D.E., and W.M. Roggenthen. 1989. "The Brine Sampling and Evaluation Program (BSEP) at WIPP: Results of Four Years of Brine Seepage Data," *Waste Management 89, Waste*

Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 26-March 2, 1989. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 1, 405-406.

ABSTRACT: The Permian salt beds of the Waste Isolation Pilot Plant (WIPP) Facility are virtually dry. The amount of water present in the rocks exposed in the excavations that is free to migrate under pressure gradients was estimated by heating salt samples to 95°C and measuring weight loss. Clear halite contains about 0.22 weight % water and the more argillaceous units average about 0.75 weight %. Measurements made since 1984 as part of the Brine Sampling and Evaluation Program (BSEP) indicate that small amounts of this brine can migrate into the excavations and do accumulate in the underground environment. Brine seepage into drill holes monitored since they were drilled show that brine seepage decreases with time and that many have dried up entirely. "Weeping" of brine from the walls of the repository excavations also decreases after two or more years. Chemical analyses of the brines show that they are sodium chloride saturated and magnesium rich.

Deal D.[E.], and W.[M.] Roggenthen. 1990. "Evolution of the Hydrologic System in a Deforming Salt Medium," *Abstracts with Programs, Geological Society of America, 1990 Annual Meeting, Dallas, TX, October 29-November 1, 1990. Vol. 22, no. 7, 100. (Abstract Only).*

ABSTRACT: Low permeabilities in the evaporitic sequence of the Waste Isolation Pilot Plant (WIPP) repository horizon limit brine flow. These bedded halite and argillaceous halite units with minor anhydrite and clay interbeds have bulk water contents of about 0.5 to 0.75 weight %. Features, which indicate brine flow, such as small weeps on the sides of the drifts, salt stalactites, and brine seepage (< 0.05 L/day) into shallow (15 to 45 m) bore holes within the facility are common. Two possible flow systems have been proposed; first, flow of far-field brines in a hydrologic system similar to usual hydrologic systems, and/or second, flow of near-field interstitial brines within the deforming rock zone induced by the presence of the excavations. Construction of the WIPP at 655 m depth creates a deviatoric stress that drives the flow of near-field salt, brine, and gas toward the excavation. The depositional history suggests that the clays in the system are underconsolidated because they were sealed within impermeable evaporites shortly after deposition. Deforming salt may squeeze water from the near-field clays into fracture openings. The weeps represent the early stage of flow. They are well developed on the sides of the excavations but are virtually nonexistent on the roofs of the drifts, suggesting that most initial flow is parallel to bedding. As the excavations age, fractures develop in response to underlying salt creep and intercept horizontally-flowing brine, channeling it downward under gravity flow into fractures in the floor.

Deal, D.E., J.B. Case, R.M. Deshler, P.E. Drez, J. Myers, and J.R. Tyburski. 1987. *Brine Sampling and Evaluation Program Phase II Report.* DOE-WIPP-87-010. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: Eighty-seven brine observations, between August 1986 and July 1987, update the data in the earlier phase I report for the Brine Sampling and Evaluation Program (BSEP).

Although Waste Isolation Pilot Plant (WIPP) underground workings are considered "dry", small amounts of brine are present. Some brine migrates in response to pressure gradients at essentially isothermal conditions. Brine seepages are manifested by salt efflorescences, moist areas, and fluid accumulations in drill holes.

Weep data acquired confirm previous observations that weeps are pervasive, they occur on exposed lithologic surfaces, and more brine seeps through the walls than through the roof of the workings. Weeps appear to develop more quickly on units containing clay, but clear halite

and clear polyhalitic halite units also produce weeps. However, more brine may actually seep from clear halite than from argillaceous (clayey) halite units in some locations over long periods of time.

In earlier reports, closely-spaced drill holes were observed to differ dramatically in brine accumulation. 'Averages' or 'typical occurrences' may be misleading.

The amount of brine accumulating within 34 downholes confirm general accumulation trends: 15 increasing, 5 steady, 12 decreasing, and 2 dry. Six downholes that were observed for more than 800 days had steady or increasing accumulation trends in August 1986 and now have slightly decreasing trends.

Upholes generally produce much less brine than the downholes. Data for 17 upholes show general accumulation trends: 3 increasing, 2 decreasing, and 12 dry. One location, monitored since November 1985, spontaneously seeps into a drift and moistens the floor, producing approximately 0.5 L. of brine per day.

A series of 12 nearly horizontal holes were drilled in the north wall of the S1950 drift at E100, documenting that brine seepage partly correlates with the stratigraphy of the Salado Formation. The most brine seeped from units near a slightly polyhalitic halite (orange band) used as a reference horizon during excavation.

A drill-hole video camera observed suspected damp areas or zones of salt encrustation on the sides of six downholes. Salt buildups were observed at MB-139 and anhydrite "c". Salt knobs and crusts were also seen at other stratigraphic horizons and, in one case, were fracture associated.

Samples collected for chemical analysis may not always represent formation brine. Fresh water, brines of other composition, and soluble materials have been both intentionally and unintentionally introduced. Ten samples from four locations appear to be uncontaminated. They are saturated, magnesium-rich sodium chloride brines with a specific gravity in excess of 1.2 g/cm³.

Moisture content was measured on an additional 101 samples from the stratigraphic units exposed in WIPP excavations and from drill holes. Moisture content distinctly correlates with stratigraphy. The "easily moved" moisture was driven off at 95°C. At 150°C only 0 to 20% additional moisture was driven off by dehydrating the clay minerals. Measured moisture content of halite samples was approximately 0.5% or less by weight. Electromagnetics, resistivity, radar, and nuclear source techniques were evaluated for ability to provide rapid and cost-effective estimations of in situ moisture content measurements. As variations in brine content within a rock strongly affect conductance, the electromagnetic (EM) method should have application to the WIPP brine studies. Although it was not possible to completely eliminate anthropogenic effects, the EM method gave promise as providing an index to relative moisture content of the rocks near the facility horizon. As brine reduces the resistivity of a material, it should be possible to determine relative variations in moisture content. Ground-penetrating radar and neutron-absorption techniques were found unsuitable for application to the BSEP at WIPP. Ground-penetrating radar could not delineate gradational variations, and neutron-absorption techniques produced large data errors. Electromagnetic or resistivity surveys are the most applicable geophysical techniques for the BSEP. These techniques provide data that is averaged over a volume of rock and can, in effect, "look" different distances into the surroundings. Geophysical techniques must be calibrated by in situ moisture content measurements and are not an adequate substitute for those measurements. For the immediate needs of the BSEP, moisture contents will be directly measured.

Preliminary, vertical drill hole data indicates that zones within the salt contain more moisture than anhydrite interbeds. In many places more moisture appears to seep from the anhydrite beds than from the salt. In this case, the most moist (greater porosity) and most productive (greater permeability) stratigraphic horizons are not the same.

The following BSEP activities continue: measure brine seepage accumulations and rates, analyze brine chemistry, measure moisture content of Salado rocks, and document with photographs the slow changes related to brine seepage at selected locations. DWP

Dennehy, K.F. 1982. *Results of Hydrologic Tests and Water-Chemistry Analyses, Wells H-6A, H-6B, and H-6C, at the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Water-Resources Investigations 82-8. Albuquerque, NM: US Geological Survey.

ABSTRACT: Hydrologic testing was conducted at wells H-6A, H-6B, and H-6C in the northwestern part of the proposed Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico to define hydraulic properties of three water-bearing zones. The zones tested were the Magenta and Culebra Dolomite Members of the Rustler Formation and the Rustler Formation-Salado Formation contact. The Magenta Dolomite and the Rustler/Salado contact yielded water to wells at rates less than 0.5 gal/min as determined from shut-in and slug tests. These test methods were not applicable for the hydrologic testing of the Culebra Dolomite Member of the Rustler Formation at well H-6B. Therefore, a transmissivity value for the Culebra Dolomite Member was obtained by conducting conventional pumping and recovery tests. Well H-6B was pumped at a rate of approximately 11 gal/min. Throughout the testing of the Magenta Dolomite Member and the Rustler-Salado contact, water-pressure response in the test zones was monitored by a pressure-transducer system. The calculated transmissivity values for the test zones were 0.3 ft²/day (estimated storage coefficient 10⁻⁵) for the Magenta Dolomite Member at well H-6A, 78 ft²/day for the Culebra Dolomite Member at well H-6B, and 0.003 ft²/day (estimated storage coefficient 10⁻⁶) for the Rustler Formation/Salado Formation contact at well H-6C.

Water samples from the Magenta Dolomite Member of the Rustler Formation had a dissolved-solids concentration of 5,760 mg/L. The major chemical constituents of water samples from this zone were sulfate, sodium, and chloride. Water samples from the Culebra Dolomite Member of the Rustler Formation had a dissolved-solids concentration of 52,600 mg/L, and samples from the Rustler Formation-Salado Formation contact had 316,000 mg/L; chloride and sodium were the major constituents in the water samples. Radium-266, a naturally occurring radioactive element, was present in samples from all three zones.

Dennehy, K.F., and P.A. Davis. 1981. "Hydrologic Testing of Tight Zones in Southeastern New Mexico," *Ground Water*. Vol. 19, no. 5, 482-489.

ABSTRACT: Increased attention is being directed toward the investigation of tight zones in relation to the storage and disposal of hazardous wastes. Shut-in tests, slug-tests, and pressure-slug tests are being used at the proposed Waste Isolation Pilot Plant (WIPP) Site, located in southeastern New Mexico, to evaluate the fluid-transmitting properties of several zones above the proposed repository zone. Apparatus used to conduct these tests includes a pressure-transducer system connected to a recording device at the land surface. All three testing methods were used in various combinations to obtain values for the hydraulic properties of the test zones. Multiple testing on the same zone produced similar results. Transmissivities determined by these tests range from 0.00001 to 10 ft²/day (.000001 to 1 m²/day).

Dennehy, K.F., and J.W. Mercer. 1982. *Results of Hydrologic Tests and Water-Chemistry Analyses, Wells H-5A, H-5B, and H-5C, at the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Water-Resources Investigations 82-19. Albuquerque, NM: US Geological Survey.

ABSTRACT: Data were collected during hydrologic testing at Wells H-5A, H-5B, and H-5C in the northeastern part of the proposed Waste Isolation Pilot Plant (WIPP) Site in southeastern

New Mexico. The three water-bearing zones tested, the Magenta and Culebra Dolomite Members of the Rustler Formation and the Rustler Formation-Salado Formation contact, yield water to wells at rates less than 0.6 gal/min. Throughout the testing, water-pressure response in the tested zone was monitored by a pressure-transducer system. Shut-in and slug tests were conducted to acquire data. The calculated transmissivity values for the test zones were 0.1 ft²/day (estimated storage coefficient 10⁻⁵) for the Magenta Dolomite Member at well H-5A, 0.2 ft²/day (estimated storage coefficient 10⁻⁵) for the Culebra Dolomite Member at Well H-5B, and 0.00003 ft²/day (estimated storage coefficient 10⁻³) for the Rustler Formation/Salado Formation contact at well H-5C.

Dissolved-solids concentrations in water samples were: Magenta Dolomite Member, 6,090 mg/L; Culebra Dolomite Member, 144,000 mg/L; and Rustler Formation-Salado Formation contact, 412,000 mg/L. The major chemical constituents of water samples from the Magenta Dolomite Member were sodium and sulfate; from the Culebra Dolomite Member, sodium and chloride; and from the Rustler Formation-Salado Formation contact, magnesium and chloride. Radium-226, a naturally occurring radioactive element, was present in samples from all three zones.

Dennis, A.W., J.A. Milloy, L.W. Scully, H.C. Shefelbine, R.E. Stinebaugh, and W.E. Wowak. 1978. *Revised Concept for the Waste Isolation Pilot Plant*. SAND78-1429. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The concept for the Waste Isolation Pilot Plant (WIPP) is revised because the quantities of remotely handled (RH) waste for the WIPP have been reduced from the estimates in the 1977 conceptual design report. The WIPP concept provides for the following: facilities for disposal of transuranic waste, facilities for research and development with other waste forms in salt, and a design that does not prevent a future decision to establish a high-level defense waste repository at this site. The RH waste capacity is changed from 250 x 10³ ft³/year to 10 x 10³ ft³/year. The underground storage area for RH waste is reduced and will be used for experiments without jeopardizing future use as a waste disposal area. Surface facilities and a shaft for RH waste have been eliminated. The revised concept has only two shafts instead of five. Several separate buildings for air filters, waste treatment, and hoists have been eliminated and their functions incorporated into the waste handling building. "It is unlikely that significant quantities of high-level waste in a form suitable for geologic disposal will be available until after 1990..." A high-level waste facility would not be needed before that time. DWP

Dobrin, M.B. 1979. *Consultant's Report on Seismic Survey of WIPP Site Conducted by Bechtel in 1979*. Document No. 22-V-510-03. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report supplements interpretations of seismic surveys of the Waste Isolation Pilot Plant (WIPP) Site conducted in June, 1979. The report addresses the suitability of evaporite layers in the area to locate the best site. Conclusions are based on data from this and earlier surveys.

The Salado reflector was more reliable in this survey than in earlier Sandia work. The field work and processing were done by the same contractor. Some lines still had poor quality shallow reflectors. The Cowden reflector was fair, though poorer than the Salado. The Castile reflector revealed a "tongue" of geological significance in the northern part of the 4 mi² area. The continuous Cherry Canyon reflector showed some structure under the Castile "tongue."

A velocity map for the Salado was constructed that increases reliability for mapping deeper reflections. In addition, the closer spacing of lines rule out most faults mapped with the

earlier data. Disruption of the Castile in the "tongue" area does not rule out the possibility of faults or suggest linear fault trends. With the exception of one small area in the "tongue", no evidence of faulting observed in the Salado or Castile was traced into underlying rocks. The area of disrupted evaporites should be avoided for siting because the effects of Castile deformation on the Salado are not precisely known.

Further data processing is recommended for areas where the top of Salado reflections deteriorate and to obtain a geological interpretation of the "tongue" in the Castile. High resolution data may be acquired in the field, but the costs are probably not justified for the WIPP Project. "The seismic data that have been obtained in the WIPP area indicate that any part of the area south of the 'tongue' ... should be free of disruptions in the Salado or Castile that would make these formations unsuitable for storage of radioactive wastes." DWP

ANNOTATION: The field data on which this report is mainly based are addressed in Bell and Murphy and Associates (1979). Sandia data referred to are described in Hern et al. (1979), Powers et al. (1978), and Barrows et al. (1980).

Dosch, R.G. 1979. "Radionuclide Migration Studies Associated With the WIPP Site in Southeastern New Mexico," *Scientific Basis for Nuclear Waste Management, Proceedings of the Symposium on 'Science Underlying Radioactive Waste Management,' Boston, MA, November 23-December 1, 1978.* Ed. G.J. McCarthy. SAND78-1178J. New York, NY: Plenum Press. Vol. 1, 395-398.

ABSTRACT: A survey of the potential of geological media (from the vicinity of the tentative site of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico) for retardation of radionuclide migration in an aqueous carrier has been completed. The survey included the measurement of sorption coefficients (K_d) for twelve radionuclides between three natural water simulants and ten rock or mineral samples associated with the site. The results and some parametric studies involving pH and trace organic constituents in the simulant solution are described in this paper.

Dosch, R.G. 1980. *Assessment of Potential Radionuclide Transport in Site-Specific Geologic Formations.* SAND79-2468. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Associated with the development of deep, geologic repositories for nuclear waste isolation is a need for safety assessments of the potential for nuclide migration. Frequently used in estimating migration rates is a parameter generally known as a distribution coefficient, K_d , which describes the distribution of a radionuclide between a solid (rock) and a liquid (groundwater) phase. This report is intended to emphasize that the use of K_d must be coupled with a knowledge of the geology and release scenarios applicable to a repository. Selected K_d values involving rock samples from and groundwater/brine simulants typical of two potential repository sites, the Waste Isolation Pilot Plant (WIPP) and the Nevada Test Site (NTS), are used to illustrate this concern. Experimental parameters used in K_d measurements including nuclide concentration, site sampling/rock composition, and liquid-to-solid ratios are discussed.

The solubility of U(VI) in WIPP brine/groundwater was addressed in order to assess the potential contribution of this phenomena to K_d values. The results showed a general decrease in solubility with increasing pH as well as a dependence on the total amount of U(VI) initially present in solution (1-50 ppm range). Also indicated was the formation of a U(VI) particulate that passed an 0.8 μm filter but was retained on a 0.2 μm filter. This behavior was observed in a simulant with a composition based on brine from a halite zone in the vicinity of WIPP.

Understanding mechanisms of sorption of radionuclides on rocks would lead to a better predictive capability. In most instances, these are not clearly defined and sorption is attributed

to the presence of trace constituents (often unidentified) in rocks, i.e., clay or hydrous oxide materials. An attempt was made to determine if this applied to WIPP dolomite rocks by comparing sorption behavior of the natural material with that of a synthetic dolomite prepared in the laboratory with reagent grade chemicals. The results were inconclusive as K_d values for Cs, Sr, Eu and Pu were comparable or higher on the synthetic material.

The results of a study of Tc sorption by an argillite sample from the Calico Hills Formation at NTS under ambient laboratory conditions were more conclusive. The Tc sorption was found to be associated with elemental carbon, which comprised approximately 1% by weight of the rock. Available evidence points to a reduction mechanism leading to the apparent sorption of Tc on the solid phase.

Dosch, R.G. 1981. *Solubility and Sorption Characteristics of Uranium (VI) Associated with Rock Samples and Brines/Groundwaters from WIPP and NTS*. SAND80-1595. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Solubility measurements for U(VI) in Waste Isolation Pilot Plant (WIPP)-related brines/groundwaters were made using initial U(VI) concentrations in the range of 1 to 50 $\mu\text{g/ml}$. Distribution coefficients (K_d) for U(VI) were determined for Culebra and Magenta Dolomites using four different brine/groundwater compositions and for argillaceous shale and hornfels samples from the Eleana and Calico Hills Formation on the Nevada Test Site (NTS) using a groundwater simulant typical of that area. The K_d 's were evaluated as functions of U(VI) concentration (1.4×10^{-4} to $1.4 \mu\text{g/ml}$); solution volume-to-rock mass ratios used in the measurements (5-100 ml/g), and for WIPP material only; water composition (0-100% brine in groundwater); and sample location in the Culebra and Magenta Dolomite Members of the Rustler Formation.

The results indicate that if groundwater intrudes into a repository and leaches a waste form, significant concentrations of dissolved or colloidal U(VI) could be maintained in the liquid phase. Should these solutions enter an aquifer system, there are reasonable sets of conditions that could lead to subsequent migration of U(VI) away from the repository site.

Dosch, R.G., and A.W. Lynch. 1978. *Interaction of Radionuclides With Geomedia Associated With the Waste Isolation Pilot Plant (WIPP) Site in New Mexico*. SAND78-0297. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A survey of the potential of geological media from the vicinity of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico for retardation of radionuclide migration in an aqueous carrier was conducted. The survey included the measurement of sorption coefficients (K_d) for twelve radionuclides between three natural water simulants and ten samples from various geological strata.

The nuclides included ^{137}Cs , ^{85}Sr , ^{131}I , ^{99}Tc , ^{125}Sb , ^{144}Ce , ^{152}Eu , ^{153}Gd , ^{106}Ru , ^{243}Am , ^{244}Cm , and ^{238}Pu . The compositions of the simulant solutions were those expected of water in contact with potash minerals or halite deposits in the area and in a typical groundwater found in the Delaware Basin. The geological samples were obtained from potential aquifers above and below the proposed repository horizons and from bedded salt deposits in the repository horizons. In brine solutions, Tc and I were not significantly adsorbed by any of the minerals and Cs and Sr showed minimal adsorption (K_d 's < 1). The lanthanide and actinide K_d 's were typically $> 10^3$ and Ru and Sb K_d 's varied in the range of 25 to $> 10^3$. In the groundwater simulant, Tc and I showed the same behavior, but the K_d 's of the other nuclides were generally higher.

Some initial parametric studies involving pH, trace organic constituents in the simulant solutions, and radionuclide concentrations were carried out. Significant differences in the observed K_d 's can result from varying one or more of these solution parameters.

Dosch, R.G., and A.W. Lynch. 1980. "Radionuclide Transport in a Dolomite Aquifer," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium, Boston, MA, November 27-30, 1979*. Ed. C.J.M. Northrup, Jr. SAND79-1016C. New York, NY: Plenum Press. Vol. 2, 617-624.

ABSTRACT: The most probable paths for radionuclide transport between the biosphere and the proposed bedded salt repository, the Waste Isolation Pilot Plant (WIPP), in southeastern New Mexico are through dolomite formations, which are the only currently water-bearing units overlying the repository horizon. This paper describes some of the experimental work performed to determine the potential for radionuclide migration in these formations. Included are the results of radionuclide sorption studies on natural dolomites (Magenta and Culebra) and on synthetic dolomite (proto-dolomite). Sorption on natural dolomites was evaluated with respect to core sample location, groundwater composition, nuclide concentration and water volume to rock mass ratios used in making the measurements. The results show that a discrete value such as a distribution coefficient (K_d) assigned to a given radionuclide does not accurately describe its interactions with site specific geological formation.

Drellack, S.L., Jr., and J.G. Wells. 1982a. *Geologic and Well-Construction Data for the H-7 Borehole Complex Near the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico*. Water-Resources Investigations 82-38. Albuquerque, NM: US Geological Survey.

ABSTRACT: The H-7 borehole complex, a group of three closely spaced bore holes, is located 2 mi southwest of the proposed Waste Isolation Pilot Plant (WIPP) Site in east-central Eddy County, NM. The holes were drilled during September and October 1979 to obtain geologic and hydrologic data to better define the regional groundwater flow system. The geologic data presented in this report are part of a site characterization study for the possible storage of defense-associated radioactive wastes within salt beds of the Salado Formation of Permian age. The geologic data include detailed descriptions of cores, cuttings, and geophysical logs.

Each bore hole was designed to penetrate a distinct water-bearing zone: H-7a (total depth 154 ft) was completed just below the Magenta dolomite member of the Rustler Formation of Permian age; H-7b (total depth 286 ft) was completed just below the Culebra Dolomite Member of the Rustler Formation; and H-7c (total depth 420 ft) was completed below the Rustler Formation/Salado Formation contact. The geologic units, penetrated in bore hole H-7c are surficial alluvium and dune sand of Holocene age (0-5 ft); the Gatuña Formation of Pleistocene age (5-57 ft); and the Dewey Lake Red Beds (57-87 ft), the Rustler Formation (87-283 ft), and part of the Salado Formation (283-420 ft), all of Permian age. The upper 122 feet of the Salado Formation penetrated by borehole H-7c is composed of residue from dissolution of halite and associated rocks, indicating that the eastward-moving dissolution front on top of the Salado, found just to the west of the WIPP Site, has reached the H-7 site.

Drellack, S.L., Jr., and J.G. Wells. 1982b. *Geologic and Well-Construction Data for the H-9 Borehole Complex Near the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico*. Water-Resources Investigations 82-4111. Albuquerque, NM: US Geological Survey.

ABSTRACT: The H-9 complex, a group of three closely spaced bore holes is located 5.5 mi south of the proposed Waste Isolation Pilot Plant (WIPP) Site in east-central Eddy County, NM. The holes were drilled during July, August, and September 1979 to obtain geologic and hydrologic data to better define the regional groundwater-flow system. The geologic data

presented in this report are part of a site-characterization study for the possible storage of defense-associated radioactive wastes within salt beds of the Salado Formation of Permian age. The geologic data include detailed descriptions of cores, cuttings, and geophysical logs.

Each bore hole was designed to penetrate a distinct water-bearing zone: H-9a (total depth 559 ft) was completed just below the Magenta Dolomite Member of the Rustler Formation; H-9 (total depth 708 ft) was completed just below the Culebra Dolomite Member of the Rustler Formation; H-9c (total depth 816 ft) was completed below the Rustler Formation/Salado Formation contact. The geologic units penetrated in borehole H-9c are eolian sand of Holocene age (0-5 ft); the Gatuña Formation of Pleistocene age (5-25 ft); and the Dewey Lake Red Beds (25-455 ft), the Rustler Formation (455-791 ft), and part of the Salado Formation (791-816 ft), all of Permian age. Three sections (484-501 ft, 615-625 ft, 692-712 ft) in the Rustler Formation penetrated by bore hole H-9c are composed of remnant anhydrite (locally altered to gypsum) and clay and silt residue from the dissolution of much thicker seams of argillaceous and silty halite. This residue indicates that the eastward-moving dissolution within the Rustler Formation, found west of the WIPP Site, is present at the H-9 site.

Duff, M., R. Carnes, J. Hart, and R. Hansen. 1990. "No-Migration Variance Petition for the Waste Isolation Pilot Plant," *Waste Management 90, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 25-March 1, 1990*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 1, 137-141.

ABSTRACT: The US Department of Energy (DOE) is petitioning the US Environmental Protection Agency (EPA) to allow the emplacement of hazardous wastes subject to the Resource Conservation and Recovery Act (RCRA) (1) land disposal restrictions in the Waste Isolation Pilot Plant (WIPP). The basis of the petition is that there will be no migration of hazardous constituents from the repository for as long as the wastes remain hazardous.

The EPA regulations in 40 CFR Section 268.6 identify specific criteria that must be addressed in making a demonstration of no migration. EPA's approval of this petition will allow the WIPP Facility to accept wastes otherwise prohibited or restricted from land disposal.

Duffey, T.A. 1980. *Final Report, The Salt Block I Test: Experimental Details and Comparison with Theory*. SAND79-7050. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A series of laboratory experiments has been completed at Sandia National Laboratories (SNL) to provide an understanding of the steady-state and transient thermal response of a large salt block containing an internal heat source. In this report, details of the experimental program are presented along with results of related efforts, such as thermal conductivity experiments, done in support of the heater experiments (Salt Block I). Finite element temperature field predictions, both transient and steady state, are performed utilizing the COYOTE nonlinear heat conduction program. Comparisons of experimental and theoretical results are generally quite good.

Dykhuisen, R.C., and W.H. Casey. 1989. *An Analysis of Solute Diffusion in the Culebra Dolomite*. SAND89-0750. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The diffusion of unreactive solutes through the Culebra Dolomite was studied experimentally and theoretically. The measured diffusive flux is less than that predicted from independent knowledge of the porosity and reasonable estimates of tortuosity. This low measured flux led to a review of the relationship between solute diffusion and pore geometry in rocks and sediments. Solute transport in hypothetical pore networks, where the effect of pore geometry on the solute flux is directly calculable, is examined. A conventional

interpretation of pore tortuosity, as a normalized length of diffusion through a pore, loses meaning for cases where pores intersect in networks. Some important variables affecting the tortuosity are: (i) the distribution of pore sizes, (ii) the distribution of pore lengths, (iii) the number of pores which intersect at a node, and (iv) the pore shape between nodes. Furthermore, in porous materials with a preferential distribution of pore sizes and orientation, tortuosity is a tensor. For the Culebra Dolomite, the wide range of pore sizes causes the diffusive flux to vary considerably from that predicted from conventional theory. These results indicate that diffusive fluxes from fractures into rock pores may be smaller than previously thought.

E

Earth Science & Engineering. 1981. *Field Data High Precision Gravity Survey W.I.P.P. Site.* Hemet, CA: Earth Science & Engineering. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Guides have been provided for the various field notes. The field notes include gravity data, leveling data, electronic distance measuring (EDM), and theodolite data. At the end of each section, a foldout map shows the date the data were collected and the direction of the survey.

The EDM and theodolite data were gathered with two Hewlett-Packard 3820A "Total Stations" that combined EDM and theodolite in one integrated instrument. The distance readings were always accurate, but the elevations obtained with the instrument in much of 1980 were not as accurate as required. Thus, the elevations of most of the stations were obtained by leveling.

Thirteen north-south lines were established with 79 stations on each line. Two smaller grids of detailed observations were established. DWP

Earth Technology Corporation. 1988. *Final Report for Time Domain Electromagnetic (TDEM) Surveys at the WIPP Site.* SAND87-7144. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A time domain electromagnetic (TDEM) survey was conducted at the Waste Isolation Pilot Plant (WIPP) Site to map the depth of occurrence of brine pockets and layers. Pressurized brine had been encountered in a drill hole (WIPP-12) about 1 mi north of the site center in the Castile Formation immediately underlying the bedded salts of the Salado Formation. TDEM is a geophysical technique that determines layering in the subsurface from surface electromagnetic measurements. Because brine layers and pockets have low resistivities compared to the bedded salts of the host rock, they are good targets for electrical exploration.

Most of the measurements (36 out of 38) were located in a 1.5 by 1 km grid directly over the waste storage panels. Single measurements next to drill holes WIPP-12 and DOE-1 validate the interpretation of the geophysical survey. One drill hole (ERDA-9) at the northern boundary of the survey grid was used for calibration.

The geoelectric sections derived from TDEM compare well with geologic and geophysical data of the three drill holes. At WIPP-12, the brine at about 800-m (2600-ft) depth is clearly seen in the TDEM data. The TDEM survey over the waste storage panels shows the first occurrence of brine at depths corresponding to the Castile Formation in portions of the area and to the Bell Canyon Formation in the rest of the area. The Bell Canyon is about 400 to 600 m below the level of waste storage panels. There is no evidence for brine pockets in the formations over the waste storage panels.

Only one sounding was made near Drillhole WIPP-12 for calibration. As the TDEM surveys correlate well with geologic data, it is recommended that the areal extent of the brine pocket encountered at WIPP-12 be mapped by surveying a grid centered on the well. DWP

ANNOTATION: This geophysical study culminated major investigations of pressurized brine reservoirs at and around the WIPP Site that were prompted by the discovery of brine in Drillhole ERDA-6 at the initial site investigated by Oak Ridge National Laboratories (ORNL) in 1974 and then by Sandia National Laboratories (SNL) in 1975. When Drillhole WIPP-12 (about 1 mi north of the site center) also encountered pressurized brine in the upper anhydrite of the Castile Formation, the concerns about such reservoirs under the WIPP intensified. Geophysical techniques were considered the most appropriate to explore the area, as it is preferable not to drill a bore hole through the intervening beds between the repository level and the probable reservoir horizons in the immediate site area.

Partly as a consequence of this study, it is generally accepted, though not proven, that pressurized brine exists within the Castile Formation under part of the central repository area. Failure scenarios for the WIPP involving bore holes into such pressurized brines have been considered since ERDA-6 encountered brine at the first site (now abandoned). The brine at WIPP-12 and this geophysical evidence demonstrate this scenario is much more realistic than initially believed.

Eaton, R.R. 1984. *Three-Dimensional Thermal Analysis for the WIPP In Situ Test Room A2 Heater Configuration*. SAND84-2220. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Two- and three-dimensional thermal analyses of the in situ Waste Isolation Pilot Plant (WIPP) heater experiments have been carried out using finite element heat conduction codes. Results for these simulations are presented and compared. Several modeling techniques for repository geometries are evaluated.

Eaton, R.R., and D.B. Hayes. 1981. *Analytical and Numerical Analyses of Hydrologic Well-Bore Experiments*. SAND80-1120. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: We have developed both an analytical approximate method and a finite-difference numerical model (based on the rate at which a bore hole fills with water) that have allowed us to estimate permeability of the Magenta Formation in southeastern New Mexico near the proposed Waste Isolation Pilot Project (WIPP) site. The analytical treatment applies to certain simple geometries with idealized boundary conditions whenever the geologic formation can be considered to have constant properties and when the groundwater compressibility is negligible. Permissible geometries include water-collecting cylinders with large, "needle-like" aspect ratios located beneath the water table. The analytical treatment clearly shows the sensitivity of inferences and conclusions to material properties and geometries. Much of the existing well-bore fill-rate data fall within the range of validity of this simplified analysis. Admission of compressibility effects into the generalized Darcy law, and a nondimensionalization of the equations identify the range of experimental conditions and material properties for which the approximations are invalid. We have developed a numerical capability to complement this analytical treatment. Numerous restrictions have been removed so that the code can treat complex geometries for a variety of boundary conditions and variable properties. The compressibility term that is excluded in the analytical treatment is maintained in these numerical solutions. The resulting equations are formally parabolic and can be solved by an implicit integrator with guaranteed stability. The two methods are applied to several different experimental situations and in each case produce results that agree with each other, lending confidence to each solution procedure.

Ehgartner, B. 1990. *Geomechanical Analyses in Support of the Waste Isolation Pilot Plant (WIPP)*. SAND90-0285. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A variety of geomechanical analyses are presented that support the Waste Isolation Pilot Plant (WIPP) Project. The scale of the analyses ranged through laboratory experiments, small-scale in situ tests, large-scale in situ tests, underground rooms, shafts and shaft keys, and multi-room panels. The structural behavior of underground rooms, shafts, and experiments was investigated using the finite element method. Both two- and three-dimensional analyses simulated the time-dependent behavior of the host rock salt. Two different constitutive models were used to represent the creeping motion of the salt. The investigations aided in experimental planning, code validation, and assessing excavation responses for safety and performance assessment.

Elliot, C.L. 1982. *Evaluation of the Suitability of Electrical Geophysical Techniques for the Detection and/or Mapping of Brine Reservoirs in the Castile Formation.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Numerous geophysical techniques were investigated leading to the following recommendations for the mapping of a brine reservoir at WIPP-12.

The CSAMT (controlled source audiomagnetotelluric) technique is known, and the equipment is available now. Some experimental data obtained by Bartel from the site area are helpful. A transmitter dipole position running north-south and west of WIPP-12 would emphasize a northerly striking structure lying to the west of WIPP-12 and thought to be connected to the brine reservoir. Specific line orientations and lengths are better derived in the field. After the specific tests are completed a compiled report should be published utilizing the previous experimental data. Expertise developed during this phase will be useful for other Waste Isolation Pilot Plant (WIPP) Site problems. This technique should be tested sufficiently to confirm applicability to site problems.

If the CSAMT technique fails, the *mise-a-la-masse* technique should be considered for the WIPP-12 problem but not for other site investigations. The initial complex electrode would consist of the WIPP-12 casing, brine filling, and brine reservoirs at depth. The remaining current electrode would be at one or more positions far from WIPP-12. Potentials can be measured in many patterns about WIPP-12. Generally, this approach is inexpensive, easy to apply, and available. Cultural features will affect the survey. However, implanting an electrode in the brine reservoir may, however, involve costly engineering designs.

A bore hole induction technique is an alternative if no results are obtained from the previous recommendations. "At this time I firmly believe that [the previous] steps ... will yield the desired information and therefore no consideration of the [b]orehole [i]nduction technique need be considered."
MM/DWP

Elliot Geophysical Company. 1976a. *An Experimental Detailed Gravity Survey of Known or Suspected Breccia Pipes at Weaver Hill, Hills A & B, and Hills C & D, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. Vols. 1-3. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Solution features known as breccia pipes in southeastern New Mexico are potential threats to the proposed disposal site. Five features, including known breccia pipes, have been surveyed for gravity anomalies to determine the effectiveness of the technique as a reconnaissance tool for these features at the Los Medanos site.

The gravity response at known breccia pipes (Weaver and Hill C) ranges from no measurable response to a suggested negative anomaly. Hill D shows no response. Hills A and B show more complicated gravity, but "there is no clear distinct gravity response that could be associated with breccia pipes. Further work with gravity as a reconnaissance tool does not appear warranted at this time."
DWP

Elliot Geophysical Company. 1976b. *An Experimental Detailed Resistivity Survey of Known or Suspected Breccia Pipes and Sinkholes, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Weaver Hill, Hills A and B, and Hills C and D are domal features northwest of the Waste Isolation Pilot Plant (WIPP) Site that are suspect or known breccia pipes. This

geophysical survey investigated domal features to determine associated resistivity anomalies. "Thus, it would be possible to determine if the resistivity geophysical technique might be utilized to search for and delineate any possible collapse structures or breccia pipes buried beneath the surface sand dunes that extensively cover the area surrounding the proposed Los Medaños waste disposal site. Such a geophysical study of these pipes would be in cooperation with other geophysical studies, particularly gravity studies conducted for this same ulterior purpose."

The resistivity contrast at Weaver Hill (section 12, T20S, R29E) suggests brecciated material at depth.

At Hill C (section 5, T21S, R30E), a gradient array was utilized to map the near-surface resistivities. A conventional array showed the broader resistivity response of this known breccia pipe. Both surveys showed a low resistivity response clearly indicating a breccia zone. Resistivity delineated a zone about 1,200 ft in diameter, which is comparable to the 1,000-ft diameter encountered underground.

Hill D (section 5, T21S, R30E) showed conflicting responses. One profile showed on contrasting response while the other showed a slight negative response. Hill D does not warrant further investigation.

Hills A and B (section 35, T20S, R30E and section 1 and 2, T21S, R29E, respectively) are adjacent features. The resistivity profile for Hill A gave a clear negative response while the response was unclear at Hill B. Because of the railroad track through Hill A, a shallow drill hole is recommended to verify the negative response indicative of a breccia pipe.

Another domal structure and a sinkhole were surveyed without obtaining negative resistivity profiles associated with breccia pipes.

A gradient array is more economical than resistivity profiling as a reconnaissance tool. Once this technique is verified at Hill A, C, and Weaver Hill, it could be used to locate suspected breccia pipes on a broader scale at the Los Medaños site. More detailed mapping of anomalies can then be performed by a pole-dipole or other suitable array, giving better depth and lateral control.

MM/DWP

ANNOTATION: This experimental resistivity field study, devised by Elliot and George Griswold, then at Sandia National Laboratories (SNL), and a later extension (Elliot Geophysical Company, 1977b) demonstrated that resistivity methods can identify these solution features. The technique also had the advantage of integrating an appropriate volume of rock in each measurement so that an effective grid could be established to survey the larger WIPP Site area (about 30 mi²) without missing features the size of known breccia pipes. For an intensive grid of measurements, the resistivity techniques would be relatively inexpensive. Other geophysical techniques appeared to be neither as effective in identifying breccia pipes nor as efficient for a reconnaissance study. As a consequence, then, of this study, the WIPP Site was mapped (Elliot Geophysical Company, 1977a) using this technique to survey for anomalies that might be investigated directly by drilling or seismic reflection techniques.

Elliot Geophysical Company. 1976c. *A Laboratory Investigation of the Density and Resistivity Physical Properties of Drill Core Samples from ERDA No. 9 Geologic Investigation Well, Section 20, T 22 S, R 31 E and USGS No. H-1 Hydrologic Investigation Well, Section 29, T 22 S, R 31 E.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Density and resistivity were measured on core samples from Drillholes ERDA-9 and H-1, located respectively in section 20 and section 29 of T22S, R31E. Samples are distributed through the Salado and from the bottom of the Rustler.

Only nondestructive density and resistivity measurements were conducted. Commercial grade kerosene was used to perform buoyancy tests on the water soluble evaporites to an accuracy of ± 0.01 g/cc. No water was added to the samples in order to simulate in situ resistivity readings. Measurements were made at 0.20 microamps/cm².

Laboratory resistivity sometimes does not adequately represent average resistivities, which may be influenced by fractures, seams, and faults containing mineralized or conductive solutions. Fractures filled with brine could greatly reduce true resistivities of compacted, fracture-free samples.

The density and resistivity measured agrees well with the Dresser Atlas geophysical logs. Well log data is superior to laboratory measurements.

The average physical properties from ERDA 9 and H-1 are:

Generalized Petrographic Description	Number of Typical samples	Density in gram/cc	Resistivity in ohm-meters	
clean salt	21	2.18	49000	
silty salt	14	2.16	5500	
anhydrite	12	2.80	6100	
polyhalite	10	2.70	9600	
siltstone	5	2.26	16	MM/DWP

Elliot Geophysical Company. 1976d. *A Laboratory Investigation of the Magnetic, Density and Resistivity Physical Properties of Drill Core Samples from A.E.C. No. 8 Well, Section 11, T 22 S, R 31 E.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A limited number of core samples from the Santa Rosa, Dewey Lake, Rustler, Salado, and Castile Formations in Drillhole AEC-8 were analyzed for physical properties. Density measurements agree well with geophysical log data. Resistivities may not be representative of the rocks in situ. Measurements depend on the tap water used and the amount absorbed by the rock. Geophysical logs or surface resistivity measurements better represent the true resistivity of the rocks. MM/DWP

Elliot Geophysical Company. 1976e. *A Laboratory Investigation of Magnetic Physical Properties of Igneous Dike Samples from Kerr-McGee Hobbs Plant, Section 31, T 20 S, R 32 E and Surface Outcrop, Section 31, T 26 S, R 25 E.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: An igneous dike, a significant structural feature, cuts across the northern Delaware Basin at approximately N50E. Samples were collected from an underground exposure at the Kerr McGee Hobbs plant (section 31, T20S, R32E) and a surface outcrop (section 31, T26S, R25E) for laboratory measurements of magnetic properties. Although separated by 50 mi, these features are apparently connected. Unoriented samples were collected from the poor exposures at T26S. Oriented samples were collected from underground.

The outcrop samples had an average magnetic susceptibility of 2690×10^{-6} cgs units, suggesting a magnetite content of 1% by volume. An average Koenigsberger ratio of 35 indicates that the magnetic intensity is controlled by the remanent magnetization of 5130

gammas. Underground samples yielded an average magnetic susceptibility of 2840×10^{-6} cgs units, indicating a magnetite content of 1% by volume. The Koenigsberger ratio of 7.2 shows a much lower remanent magnetization of 1044 gammas. The samples have comparable magnetite content but different magnetic properties.

The underground samples had an average declination of 35.1°E and an average inclination of 57° . No demagnetization techniques were used. As the outcrop samples were not oriented, no information is available about the inclination and declination. MM/DWP

Elliot Geophysical Company. 1976f. *A Preliminary Geophysical Study of a Trachyte Dike in Close Proximity to the Proposed Los Medanos Nuclear Waste Disposal Site, Eddy and Lea Counties, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A preliminary study was conducted to determine if geophysical methods could adequately define a trachyte dike in the vicinity of the Los Medanos area. This dike could be associated with a dike swarm and pose a significant hazard to the site. Geophysical methods must adequately identify, map, and determine the geometric configuration of the dike. The dike has been encountered in several wells (790-13,500 ft), apparently intruding upward in irregular pinnacles from the basement floor.

The dike rock has strong magnetic properties, and high-resolution airborne magnetic surveys could adequately map and differentiate closely spaced parallel dikes indicative of a dike swarm. Multi-level flight lines should be flown perpendicular to the strike of the dike, concentrating on the Los Medanos site and surrounding area. "The dike is a major structural feature and should not be discounted lightly" as a potential hazard to the proposed site of a nuclear repository. MM/DWP

Elliot Geophysical Company. 1977a. *Evaluation of the Proposed Los Medanos Nuclear Waste Disposal Site by Means of Electrical Resistivity Surveys, Eddy & Lea Counties, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Site area has been extensively surveyed using electrical resistivity methods during 1976 and 1977. These methods have been used to identify resistivity anomalies that may be associated with features, such as breccia pipes, that may present a threat to waste isolation at the WIPP. During 1977, gradient profiling arrays were obtained over an area of about 37 mi^2 with about 9880 measurements along 391 line mi of profiles. These data, along with 54 Schlumberger electrical soundings at 31 locations, have been analyzed to locate such anomalies for further investigation. The anomalies are classified into Zones I through IV, based on type of anomaly. Zone I anomalies occur to the northwest and southwest of the site and are apparently associated with dissolution front and water influx. Zone or anomaly II is a lobate area of low resistivity, oriented NW-SE, in the southeast part of the site area. It is not in an area of known dissolution, but it may reflect increased porosity that could later contribute to dissolution. The Zone or type III anomaly, located about 2 mi north of the site center, has the size, lateral extent, and decrease in resistivity comparable to profiles over known breccia pipes and should be further investigated. Zone IV anomalies have lesser resistivity decreases than do type III anomalies, but all nine of these should be investigated.

Schlumberger soundings for the area generally correlate well with the known geology. The Zone II anomalies demonstrated by the gradient profiles shows that the upper low-resistivity unit, normally associated with the Dewey Lake Formation in Schlumberger soundings, includes the entire Rustler Formation. This suggests "an increase in porosity or water-bearing

properties of perhaps the upper Salado, definitely the Rustler Formation and maybe even the lower part of the Dewey Lake Formation." DWP

ANNOTATION: The resistivity survey proved an effective and efficient way to screen the larger site area for possible anomalies, especially breccia pipes. As a consequence, several of the apparently anomalous areas were investigated further by drilling. None showed any evidence of a breccia pipe. With Bachman's later study (Bachman, 1980) detailing the origin of breccia pipes over the Capitan reef, the concern over these anomalies as a consequence of deep dissolution faded. While reviewing Elliot's maps for the bibliography, an area of low resistivity in the southern part of the WIPP Site was noted to correspond broadly to areas of increased transmissivity of the Culebra. The relationship will be further examined, though the areas certainly do not exactly correspond. A separate volume of maps is not included in the reference listing.

Elliot Geophysical Company, 1977b. *An Experimental Detailed Resistivity Survey of Hills C and D, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Resistivity profiling experiments were conducted at Hills C and D (section 5, T21S, R30E) northwest of the Waste Isolation Pilot Plant (WIPP) to determine if this method could delineate breccia pipes. Both hills have domal features at the surface. Mississippi Chemical Corporation encountered an estimated 1,000 ft diameter breccia pipe 1,300 ft below Hill C. No evidence of a breccia pipe has been substantiated at Hill D.

Resistivity profiles were obtained with an in-line pole-dipole array. Dipole length and separation distance were varied to produce the best configuration to define a breccia pipe below the effects of surface weathering. The resistivity profile over Hill C delineated a breccia pipe approximately 1,200 ft in diameter, comparable to the estimated underground diameter of 1,000 ft. The arrays at Hill D gave two different responses. One array showed a disturbed pattern while the other showed no negative anomaly. Further profiling to clarify the inconsistencies at Hill D are beyond the scope of this project.

Resistivity profiling provides an adequate method for delineating breccia pipes. Known or suspected breccia pipes gave a negative resistivity response while "...studies of features suspected to be mere sinkholes did not show a response." MM/DWP

ANNOTATION: This study extended the experimental field study (Elliot Geophysical Company, 1976a), which demonstrated the utility of resistivity methods for reconnaissance of the WIPP Site for breccia pipes or other sources of resistivity anomalies. The extensive survey of the WIPP Site (Elliot Geophysical Company, 1977a) was based on these experiments.

Elliot Geophysical Company, 1977c. *An Experimental Detailed Resistivity Survey of Suspected Breccia Pipes, Eddy County, New Mexico. An Addendum Report.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Profiles over known breccia pipes have shown these features have low resistivity. Based on these findings, resistivity profiles were obtained in 1977 over three additional sites located in sections 14, T23S, R30E; section 24 and 25 T23S, R29E; and section 29, T23S, R30E. "These suspected breccia pipes are southwest of the Los Medaños site and, ... do not present a geologic hazard to the proposed site in themselves."

A domal feature at section 14 was identified using aerial photographs. A linear array was set and a station southeast of the feature had a low resistivity response, but it was probably a measurement error. A station to the northwest had a slightly higher reading, but both measurements are not of sufficient contrast to indicate the presence of a breccia pipe.

A cross-centered resistivity array was placed near the top of the topographic hill in section 24 and 25. Variations encountered in one line were not found in the other. No low-resistivity zone indicative of a breccia pipe was found across the top of this hill.

A circular feature prominent on colored aerial photographs is not evident by surface observation in section 29. The surface revealed several major drainage areas with observable vertical displacement (tens of feet) associated with breccia pipes. A prominent resistivity low to the northwest of the feature is possibly caused by the vertical displacement, other structural disturbance, or the associated drainage system. "Underneath the circular feature there does not appear to be any prominent resistivity reflection of breccia material." Various changes in the resistivity profile are probably the result of lateral changes and not collapse features. These subtle variations are beyond the scope of this project.

"It is firmly concluded that no well-developed breccia pipes at or near the surface are evident at these locales."
MM/DWP

Elliot Geophysical Company. 1977d. *Experimental Resistivity Soundings Near a Known Breccia Pipe, Weaver Area, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Weaver Hill is located in section 12, T20S, R29E, northeast of Carlsbad, NM and about 21 mi from the Los Medaños site. An exploratory potash drillhole (GW-1) to 821 ft encountered breccia.

Schlumberger soundings were obtained to determine the levels of resistivity for each of the formations and their geometric relationships. The Salado Formation is much closer to the surface; it is possible resistivity information can be obtained about the underlying Castile Formation.

Three perpendicular arrays were set up to the north, west, and south of GW-1. The Schlumberger data from the three arrays around GW-1 agree with one another, but they are not in agreement with known lithologic boundaries. A resistivity profile may not show a lithologic boundary because it averages or obtains bulk properties, while well logs show detailed variations in resistivity.

Based on these results, Schlumberger soundings have limited application in the characterization of the Los Medaños site. An adequate number of drill holes at the site provide stricter lithologic controls without total reliance on the Schlumberger soundings.
MM/DWP

Elliot Geophysical Company. 1977e. *Resistivity and Gravity Survey Data, 1976 and 1977, Los Medaños Site Area and Experimental Surveys of the Surrounding Areas, Eddy and Lea Counties, New Mexico.* Tucson, AZ: Elliot Geophysical Company. Vol. 1. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Gravity and resistivity surveys were conducted to evaluate the site of the proposed Waste Isolation Pilot Plant (WIPP) Site and surrounding areas. Gravity and related digitized terrain data cover known or suspected breccia pipes at Hills A-D and Weaver pipe in the northern Nash Draw and Clayton Basin areas. Resistivity gradient arrays and

Schlumberger soundings covered the areas of suspected breccia pipes and the broader site area. Elliot Geophysical Company was responsible for planning, supervising, and data reduction, while the field work was performed by Mining Geophysical Surveys Inc., Tucson, AZ.

This report includes a printed version of the digital geophysical data obtained during the 1976 and 1977 gravity and resistivity survey. The data are also transmitted on a 1200-ft, 1/2-in. magnetic tape. DWP

Elliot Geophysical Company. 1977f. *Resistivity and Gravity Survey Data, 1976 and 1977, Los Medaños Site Area and Experimental Surveys of the Surrounding Areas, Eddy and Lea Counties, New Mexico. Volume II: Contents of Accompanying Magnetic Tape.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: These printed data from the 1976 and 1977 gravity and resistivity surveys of areas around the Waste Isolation Pilot Plant (WIPP) Site accompany a magnetic tape of data. DWP

Elliot Geophysical Company. 1979a. *A Detailed Resistivity Survey of a Suspected Breccia Pipe Anomaly in Section 17, T 22 S, R 31 E, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A resistivity anomaly with characteristics suggesting a breccia pipe or collapsed feature was identified in section 17 from the gradient profiles. Two perpendicular pole-dipole lines, centered over the gradient anomaly, clearly show a distinct low resistivity anomaly. A third line, parallel to one of the original lines, was set for shallower exploration and it revealed a lesser anomaly. The anomaly apparently does not reach near the surface. A position for Drillhole WIPP-13 was suggested based on the resistivity data.

The geophysical data for WIPP-13 reveals that a zone within the Dewey Lake Formation has a low resistivity, caused by a higher porosity and/or a higher intrinsic water content, and this zone appears to be the source of the anomaly. No brecciated or collapsed material was intersected in WIPP-13, which was drilled to 1020 ft. Other anomalies identified in the 1977 field program may still require evaluation. DWP

Elliot Geophysical Company. 1979b. *Evaluation of Schlumberger Resistivity Soundings in and Associated with Nash Draw, T21S, T22S, R30E, R31E, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Earlier Schlumberger soundings showed evidence of the dissolution front in the vicinity of Nash Draw. Locations have been chosen for drill holes in and around Nash Draw to investigate the evidence for salt dissolution and hydrology. These drill hole locations have been surveyed with Schlumberger soundings prior to drilling. The sites within Nash Draw all showed evidence of disturbed resistivity sections suggestive of salt dissolution and possible collapse. The site near the proposed location of WIPP-30, east of Nash Draw, showed consistent and generally normal resistivity, suggesting that salt is not being dissolved at this location. Drill hole information available between time of fieldwork and this report is consistent with these interpretations. DWP

Elliot Geophysical Company. 1979c. *Resistivity Survey Data, 1978, Los Medaños Site Area, Eddy County, New Mexico.* Tucson, AZ: Elliot Geophysical Company. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report transmits digital data obtained during the 1978 resistivity survey. These data include Schlumberger soundings and resistivity over a suspected breccia pipe location later drilled (WIPP 13). The Schlumberger files are organized by potential electrode spacing (NM/2) in ft, current electrode spacing (AB/2) in ft, and apparent resistivity value in ohm-meters. The pole-dipole data files were divided into two categories: center of potential electrode station in hundreds of feet with directions indicated, and apparent resistivity values in ohm-meters. A printed version of data on an accompanying 200-ft, 1/2-in. magnetic tape is included. MM/DWP

Environmental Evaluation Group. 1980. *Geotechnical Considerations for Radiological Hazard Assessment of WIPP: A Report of a Meeting Held on January 17-18, 1980.* EEG-6. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Environmental Evaluation Group (EEG) arranged a meeting in January, 1980, to ensure that all important radionuclide transport pathways are considered in quantitatively assessing radiological health risks to people from the proposed Waste Isolation Pilot Plant (WIPP).

Thirty-five geologists, hydrologists, geophysicists, and geochemists provided their views on the geologic and hydrologic mechanisms that might lead to the release of radionuclides from the WIPP repository. To help obtain a balance of views, the invitees included knowledgeable experts from Federal and State agencies, the National Academy of Science's WIPP Panel, the Governor's Advisory Committee on WIPP, several universities in the State, the mining industry, and the Natural Resources Defense Council.

Participants presented information and views on groundwater hydrology, deep dissolution, brine reservoirs, other features, and human intrusion. These presentations and subsequent discussion were summarized from notes and recordings.

The EEG also summarized major issues and provided recommendations. Principal uncertainties in groundwater hydrology concern fracture permeability, K_d values for radionuclides, and limited data on the Delaware Mountain Group. More field tests of recharge and geohydrology parameters are recommended. Deep dissolution issues range from the extent of dissolution to mechanisms. In order to resolve some of these issues, the EEG recommends the arguments against deep dissolution be provided in a reviewable form, that some features should be investigated, and that the consequences should be assessed and made available in a report. Brine reservoirs are still in question for their distribution, size, relationship to either deformation or dissolution, and connection to various sources of water. The EEG recommends that the Department of Energy (DOE) analyze the consequences of pressurized brine reservoirs in the Castile and water movement into a repository in the Salado. Human intrusion is considered related to resources at or in the vicinity of the WIPP. The EEG recommends that the DOE publish both plans and restrictions on resource production at the site and analyze several scenarios related to intrusion. Several scenarios have been added by the EEG to those proposed in the draft environmental impact statement. DWP

Environmental Evaluation Group. 1982. *Radionuclide Release, Transport and Consequence Modeling for WIPP. A Report of a Workshop Held on September 16-17, 1981.* EEG-16. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: A workshop was held to discuss potential mechanisms for the release of radionuclides from the Waste Isolation Pilot Plant (WIPP) and resultant radiological consequences years after waste emplacement and termination of institutional controls. Information was exchanged about release and transport models and the availability, reliability, and significance of data for those models. The Environmental Evaluation Group (EEG) provided additional breach scenarios for discussion. Based on the information, discussions, and field trip, the EEG summarizes its views as follows:

- (1) Liquid breach and transport scenarios in the *Final Environmental Impact Statement (FEIS)* reflect conservative assumptions and represent bounding consequences for breach and transport in Rustler aquifers. This assumes that fracture flow in the Rustler, now under study, will not substantially alter parameters being used.
- (2) The Culebra may be extensively fractured along the flow path to Malaga Bend. Until more definitive data are obtained, the models used include considerable uncertainty.
- (3) It does not appear likely that natural events involving a brine reservoir beneath the repository will transport radionuclides to the surface. A significant quantity of radionuclides might be brought to the surface if a breach involving human intrusion and a brine reservoir occurred within 500 years. Occupational hazards during construction and long-term threats from a large reservoir require more information on age, origin, size, and possible aquifer communication of brine reservoirs.
- (4) Available information and modeling indicate that the threat from breccia pipes is adequately bounded by the *FEIS* scenarios. Transport of radionuclides to the surface is unlikely because of the nature of the process.
- (5) Brine density flow is not believed to be adequate as a mechanism to explain salt dissolution in the Delaware Basin. The transport time through the Delaware Mountain Group is also too long to release radionuclides to the biosphere. Because of other possible transport pathways, EEG recommends obtaining additional information about the relationship of brine reservoirs to deep dissolution and about the zone of anomalous seismic reflections to determine if dissolution features are present.
- (6) *FEIS* scenarios appear to bound the radiological consequences of potash mining and hydrocarbon exploration. "In the unlikely event that solution mining for culinary salt should occur at WIPP, release of a fraction of the radioactivity and small doses to a large population could occur."

DWP

Environmental Evaluation Group. 1983. *EEG Review Comments on the Geotechnical Reports Provided by DOE to EEG Under the Stipulated Agreement Through March 1, 1983.* EEG-22. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Department of Energy (DOE) agreed to provide 14 reports to the State of New Mexico, as part of the stipulated agreement, to help the state evaluate the suitability of the Waste Isolation Pilot Plant (WIPP) Site. As of March 1, 1983, the Environmental Evaluation Group (EEG) had received draft reports on 9 of the 14 topics: deep dissolution, breccia pipes, Delaware Mountain Group hydrology, natural resources, plans for design validation for site preliminary design validation (SPDV), plans for simulated waste, brine reservoir report, disturbed zone exploration, and fracture flow in the Rustler aquifers. In this publication, the EEG has compiled written comments on these drafts by the EEG, and the DOE has written responses to these comments. EEG's conclusions on these issues will be provided in a later report.

DWP

Environmental Evaluation Group. 1989a. *Review of the Final Safety Analysis Report (Draft). DOE Waste Isolation Pilot Plant, December 1988.* EEG-40; DOE/AL/10752-40. Albuquerque, NM: Environmental Evaluation Group.

ABSTRACT: The Environmental Evaluation Group (EEG) has reviewed the December 1988 draft of the Department of Energy (DOE) *Final Safety Analysis Report (FSAR)* on the Waste

Isolation Pilot Plant (WIPP); comments have previously been provided on earlier drafts and amendments of the document. Many earlier comments are repeated because responses are inadequate or have not been received. Individual comments are provided on 12 chapters of the draft *FSAR*.

Seventeen of the more important concerns were summarized. As the *FSAR* does not include long-term risk assessment required by the Environmental Protection Agency (EPA), a supplement to the *FSAR* will be required before disposal begins. The hoist drop scenario should be included in the *FSAR*, and the low failure rate of the exhaust filtration system is unproven. The volumes and radioactivity of waste should be specified as much as possible. Methods of evaluating airborne radionuclide concentrations from routine operations are flawed; instruments for detecting these releases are unproven. Some analytical methods need to be modified. The radiation limit for waste containers is unacceptable. Potential doses to radiation workers from accidents are unreasonably low. Some safety aspects of nonradiological hazards need to be revised. EEG must be involved in peer review panels to take credit for assurance from such panels. Backfill is not addressed. Operational safety is not described sufficiently for review. A design basis accident should be assessed. The *FSAR* must include operations during the test phase and when it is complete.

EEG's comments from October 1988 are appended for comparison.

DWP

Environmental Evaluation Group. 1989b. *Review of the Draft Supplement Environmental Impact Statement, DOE/EIS-0026-DS, Volumes I and II, DOE Waste Isolation Pilot Plant, April 1989.* EEG-41; DOE/AL/10752-41. Albuquerque, NM: Environmental Evaluation Group.

ABSTRACT: The draft *Supplement Environmental Impact Statement (SEIS)* for the Waste Isolation Pilot Plant (WIPP) does not adequately justify shipping up to 620,000 ft³ of transuranic (TRU) waste to WIPP before demonstrating compliance with the Environmental Protection Agency's (EPA) *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes (40 CFR 191)*. The "alternative action" of not shipping waste to WIPP before demonstrating compliance with the EPA standards has been dismissed without sufficient discussion and justification. The document contains mistakes in calculations, reflects an erroneous knowledge of the history of the project, presents tables without units, and displays an indifference to the statistical precision of predictions. It does not adequately address the environmental impacts of failure to demonstrate compliance with the EPA standards by October 1993. The Department of Energy (DOE) plans to demonstrate compliance with the same standards before starting construction of the high-level waste repository in Nevada. These two diametrically opposed approaches for WIPP and for Yucca Mountain need to be addressed. The document appears hastily prepared and inadequately checked.

There is insufficient time for EEG to check all the calculations and to evaluate the public health and safety implications of the calculation errors. They may be substantial.

DWP

Ewing, R.I. 1981. *Preliminary Moisture Release Experiment in a Potash Mine in Southeastern New Mexico.* SAND81-1318. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: An "in situ" moisture release experiment was performed in the Mississippi Chemical Corporation Potash Mine near Carlsbad, NM. A radiant heater, used previously in another mine experiment, was used to internally heat a selected formation to about 200°C for a total operating time of 113 days. The moisture released by heating the walls of the 5-in.-diameter bore hole where the heater was inserted was measured using a moisture collection system employing commercial desiccant canisters. This system had also been used in the previous mine experiment.

The moisture yield for 113 days of operation was 188 ± 8 g. Of this amount 75 ± 4 g was released in an overtemperature spike lasting about 10 days, in which wall temperatures exceeded 250°C . The moisture release rate was 0.4 g/day during the last week of operation at a wall temperature of $180^{\circ} \pm 10^{\circ}\text{C}$. Elevated release rates up to 11 g/day were noted for short periods after the heater was turned on or off.

Ewing, R.I. 1982. *Environmental Gamma Ray Spectra From Selected Sites in Southeastern New Mexico*. SAND82-0738. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Environmental gamma ray spectra were obtained in 1978 and 1979 in the Carlsbad Caverns National Park and in a potash mine operated by the Mississippi Chemical Corporation near Carlsbad, NM, using a high-resolution germanium crystal detector. The spectra are analyzed for components from the uranium decay series, the thorium decay series, cesium¹³⁷, and potassium⁴⁰. Comparison spectra were obtained at the Avery Island Salt Dome in Louisiana, and from the naturally occurring activity in samples of uranium ore, thorium metal, and sylvite crystals.

Faith, S.[F.], P. Spiegler, and K.R. Rehfeldt. 1983. *The Geochemistry of Two Pressurized Brines From the Castile Formation in the Vicinity of the Waste Isolation Pilot Plant (WIPP) Site.* EEG-21. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Major and minor element data and isotopic data from ERDA-6 and WIPP-12 indicate that the brine reservoirs encountered in the upper Castile Formation are largely in equilibrium with their surrounding host rock environment. This contention is supported by thermodynamic and stable isotope data. It is not possible to assign an absolute age to the brine based on uranium disequilibrium considerations, but if the data is taken as an indicator of its age, then the brine has been a stagnant, chemically isolated body of fluid for no more than about two million years. It is likely that the brines encountered are predominantly, if not entirely, derived from a trapped seawater source subsequently modified by diagenesis. Major ion/bromide ratios indicate that halite dissolution has occurred to some extent subsequent to deposition of the Castile anhydrites and entrapment of the seawater brine. Additional halite might have been dissolved by dehydration of gypsum at depth, meteoric water introduced during the Permian when the Castile was exposed, Bell Canyon Formation groundwater transported through fractures that subsequently healed, or some combination of these mechanisms. Based on the degree of halite saturation, there is minimal potential for future dissolution of halite. It is recommended that the Harvie and Weare equilibrium model that was used be clarified with information on gas phases and how particular ions are incorporated into the model. Possible mechanisms for further halite dissolution should also be further evaluated.

DWP

Ferrall, C.C., and J.F. Gibbons. 1979. *Core Study of Rustler Formation Over the WIPP Site.* SAND79-71110; CSI 2055-03. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Core from the Rustler Formation was described to obtain data for thermomechanical modeling of the Rustler in response to heating. The Rustler units were characterized for physical properties, internal discontinuities, distribution, and boundary effects emphasizing the extent and nature of fractures.

Physical properties of the units (especially lateral variations within a given unit) require considerably more effort for definition. Further drilling would be helpful to provide additional views of the rock. This core study should be considered as an indicator of directions in which study can proceed.

Extensive open fractures, open solution channelways, and solution residues strongly imply that historic or recent flow through the Rustler Formation is not confined to the Culebra and Magenta Dolomites. Except where solution has extensively altered the rock, there is no interstitial permeability in the Rustler Formation. Most flow through that formation is through fractures or along bedding surfaces. The resulting channelways are roughly planar, but are extremely complex.

Small fractures and small interstitial spaces are generally filled with gypsum. Fractures, solution residues, and large solution channelways imply active intraformational solution. The evidence of penecontemporaneous solution and deposition suggests a nonequilibrium condition. Varying water availability may result in radical local differences in the solution of gypsum.

The layering and geometry of zones of deposition and diagenesis are sufficiently predictable that the Rustler Formation can be modeled as physical layers, separated by zones of decoupling. Individual layers are segmented by steeply dipping or vertical fractures.

The most important new source of permeability in the Rustler may be the growth of fractures caused by gypsum crystal growth. Griffith considerations imply that small stresses applied by

crystal growth are very effective. Such fractures are widely distributed in the Rustler anhydrites. Fibrous gypsum exhibits differential solubility, allowing fluids to circulate between stable or dissolving crystal faces while crystals grow against the fracture walls. Fluids near gypsum saturation probably can move freely through fibrous masses of gypsum. DWP

Fischer, N.T., ed. 1985. *Ecological Monitoring Program at the Waste Isolation Pilot Plant. Second Semiannual Report Covering Data Collected January to June 1985.* DOE/WIPP-85-002. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The ecological monitoring program (EMP) is designed to quantify and assess the effects of construction activities on the surrounding ecosystem. The effects predicted include altering the natural habitat, depositing salt and dust, and increasing human activity and noise. These data, analyses, and discussions cover the period from January through June 1985. The eight programs for the EMP are environmental photography, soil chemistry, soil microbiology, vegetation, wildlife, meteorology, air quality, and water quality. A new ecological study plot has been established where airborne particles may arrive from salt piles. In addition, wildlife censuses are no longer being conducted at near-field study plots, permitting more intense and more comparable censuses in other plots.

A new round of aerial photography supplements previous photography. Soil analyses show salt accumulating in soils adjacent to salt piles, but salt is not dispersed significantly beyond 200 m. The vegetation is not capturing airborne particles, but plant nutrient ions are more concentrated under vegetation. Soil microbial activity and decomposition rates are not inhibited by these soil ion concentrations. Vegetative cover, plant germination, and wildlife populations are generally greater than last year, probably because of high spring rainfall. Diversity of reptiles, amphibians, and small mammals is less. Habitat quality has been enhanced for some bird species by Waste Isolation Pilot Plant (WIPP) construction. A special study of raptors was begun in March 1985 with particular emphasis on Harris' hawk. Precipitation at the WIPP, airborne particulates, and groundwater chemistry are reported for the first time.

DWP

Fischer, N.T. 1986. "Statistical Considerations in the Design of a Baseline Radiological Surveillance Program at the Waste Isolation Pilot Plant," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 2-6, 1986.* Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 225-230.

ABSTRACT: Two contradictory factors must be considered in developing a sampling strategy for a preoperational environmental surveillance program. First is the stochastic nature of radiological data, which dictates large sample sizes to ensure validity and statistical confidence, especially when a large geographic area is being characterized. Second is an upper limit to the total sampling effort, imposed by practical constraints such as available time, manpower, and funding. These contradictory factors create a dilemma in program design with respect to the allocation of sampling effort among the various components of the program.

The Radiological Baseline Program (RBP) was initiated at the Waste Isolation Pilot Plant (WIPP) in July 1985 to establish a preoperational data base for the WIPP Operational Radiological Monitoring Program (ORMP). In the RBP, a partial resolution to this dilemma was achieved through the several design features.

Sampling was limited to those sites that would be used as sample locations during the ORMP, or that might be used during operations under special circumstances. These sites were strategically located to maximize the probability of detecting a release from the WIPP and to characterize radiation at sites of special concern. Thus, each sampling site in the ORMP will have its own preoperational data base.

Sampling locations were classified as either primary or secondary sites based upon their importance to the goals of the ORMP. The intensity with which each will be sampled during the RBP will be adjusted according to this classification.

Existing radiological data records from the area were used to predict the amount of spatial and temporal variability that can be expected for equivalent parameters being measured in the RBP and ORMP. These data enable predictions to be made of the number of samples required to achieve a designated degree of statistical confidence.

Where possible, existing data records were used to predict the type of statistical model that would be most likely to describe the behavior of equivalent parameters in the RBP. This information is useful in determining sample size and in prescribing methods of data transformation to facilitate statistical analysis.

Fischer, N.T. 1988. "Fitting Statistical Frequency Distributions to Baseline Environmental Monitoring Data for the Waste Isolation Pilot Plant," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. II, 677-682.

ABSTRACT: A preoperational environmental monitoring program has been active at the Waste Isolation Pilot Plant (WIPP) since July 1985 to determine the levels of radioactivity in various environmental media prior to the first receipt of waste. Ideally, statistical frequency distributions based on preoperational data can be found to accurately model the probability of obtaining a particular result during operations, assuming preoperational processes are intact. This paper presents a preliminary evaluation of four families of probability distribution functions (normal, lognormal, Weibull, and gamma) for their relative fit to 96 weeks of preoperational gross alpha and beta activity data from eight low-volume continuous air sampler locations. The results indicate that for gross beta counts, the lognormal gave the best fit to most data sets, with the gamma, normal, and Weibull following in that order. For gross alpha counts, the Weibull gave the best fits overall, with the gamma, normal and lognormal following. The final determination of the adequacy of these models will be made at the conclusion of the preoperational program.

Fossum, A.F. 1984. *Qualification of Spectrom-32 to Sandia/WIPP Benchmark II Specifications*. Topical Report RSI-0249. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report describes calculations made with the SPECTROM-32 structural finite element program for the second Waste Isolation Pilot Plant (WIPP) structural benchmark problem for the purpose of qualifying SPECTROM-32 to Benchmark II specifications. This problem involves 27 distinct geological layers including ten clay seams of which four are modeled as sliding interfaces. Heated and unheated drifts are considered at a depth of 650 m. A discussion is given of numerous aspects of the problem, including element choice, slip line modeling, creep law implementation, and thermal mechanical coupling. Also included are the computational results to ten years as specified in the benchmark problem formulation.

Foster, R.W. 1974. *Oil and Gas Potential of a Proposed Site for the Disposal of High-Level Radioactive Waste*. ORNL/SUB-4423/1. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology.

ABSTRACT: A four township area (T21-22S, R31-32E) centered on the Eddy and Lea County lines in southeastern New Mexico is being considered as a potential site for disposal of high-level radioactive waste. The oil and gas potential of this site has been evaluated based on geological evidence and statistical analysis. Because drilling in this site is quite limited, a regional study of 42 townships around the site has been used to develop the geologic base for evaluating the site. The total resources are reported without assessing the economics of extraction. In addition, the contour map of the Precambrian surface has been revised and published as required by contract.

Productive zones in the Delaware Basin include all rocks except those of the Ordovician and Mississippian systems. The Pennsylvanian and Silurian/Devonian rocks have the highest potential for gas and are at depths of 13,000 to 16,000 ft in the study area. The shallowest possible occurrence of oil is in the upper Bell Canyon Formation at a depth greater than 4,000 ft. The statistical potential for oil and gas in the rocks of Silurian/Devonian age is very good, but structural traps may be lacking. Pennsylvanian rocks have a very high potential for success for gas wells as well as moderate potential for oil. The Wolfcamp, Bone Spring Formation, and Delaware Mountain Group, all Permian in age, have potential for production. Oil accumulation is favored in the Ramsey zone of the Bell Canyon Formation.

The hydrocarbon potential has been projected per square mile (section) for the site area based on wildcat drilling (lower estimates) as well as production drilling (higher estimates) adjusted by a variety of factors. "The total projected reserves ... indicate a range of from 559,411 to 1,266,795 barrels of oil; 2,250,829 to 2,967,243 MCF [thousand cubic ft] of associated gas; 169,455 to 193,568 barrels of distillate; and 12,565,558 to 13,576,988 MCF of gas. At first these calculations might appear high, but it must be considered that an entire section is being included with a potential of 16 oil well locations and two to four gas well locations. The highest figures used in determining reserves based on wildcat success ratios were 1.44 oil wells and 2.0 gas wells per section. For comparison, 16 oil wells completed in the Ramsey would, based on average well production, recover over 1,000,000 barrels of oil, and two Silurian/Devonian gas wells over 15,000,000 MCF of gas. Where only part of a section might be withdrawn, potential reserves might be prorated, but it is important to be aware that most fields in the study area have stacked pay zones, and no particular stratigraphic unit could be eliminated from consideration." DWP

ANNOTATION: Hydrocarbon resources were evaluated by Foster using an approach different from that of Sipes, Williamson, and Aycock, Inc. (e.g., 1976a). Foster prepared a geological and statistical analysis of the resources, while later reports were more concerned with evaluating fair market values and production that could be expected given the various restrictions or conditions on drilling locations. Foster's approach tends to be a higher estimate of the hydrocarbons expected to be present, while the other estimates reflect industry standards for production and economic expectations for particular areas. Foster's estimates may provide an estimate of the overall effect of withdrawing land and resources for the Waste Isolation Pilot Plant (WIPP), while fair market estimates provide a basis for deciding compensation if leases are preempted for WIPP. Both approaches are important.

Foster, R.W. 1979. *Mineral Resources and the WIPP Site. Report of Member of the WIPP Review Committee (1975-1979), Socorro, NM.* (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Both short- and long-term integrity of a site are the most important criteria in selecting and accepting a site for radioactive waste disposal. Resources that could affect long-term integrity at the Waste Isolation Pilot Plant (WIPP) Site include potash, oil, gas, and salt. "It is not necessary and it is considered inadvisable to store Department of Energy (DOE) generated low- to intermediate-level transuranic (TRU) waste at the WIPP." Resources threaten the integrity of the site, and the thermal properties of salt are not required by these wastes. Mineral resources also represent a long-term risk for disposal of high-level waste and

spent fuel. Additional studies are required, as salt may prove to be the most suitable geologic media. Before developing the WIPP or any other site, the Federal Government must establish criteria for site selection and acceptance, develop regulations for mining and drilling within and around the site, and determine the type of waste to be stored, as well as the conditions under which the storage will be considered permanent. "In order to implement the above, the site must be licensed and at least one additional licensed site must be available before any waste is accepted."

DWP

Freeland, M.H. 1982. *Basic Data Report for Borehole DOE-1, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. TME 3159. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant.

ABSTRACT: Borehole DOE-1 is one of several exploratory bore holes drilled at the Waste Isolation Pilot Plant (WIPP) Site for the purpose of gathering stratigraphic, hydrologic, and structural data. DOE-1 is located in Section 28, T22S, R31E in Eddy County, NM. Within the WIPP Site proper, DOE-1 is located in Zone III about 1.25 mi southeast of the exploratory shaft location.

This project was undertaken to investigate the presence of an anticlinal structure in the Castile Formation indicated by seismic reflection surveys in the area; to gather data on the stratigraphy, structure, and lithology of the rocks that comprise the facility horizon in an area immediately southeast of the facility itself; to test for the presence of gas or fluids in the rocks associated with the anticlinal structure, if present, or in the flat-lying rocks; and to determine the nature of the Castile Formation near the site, but outside the "Disturbed Zone". Field operations were initiated July 12, 1982 and completed July 30, 1982. The bore hole was drilled to a depth of 4065.3 ft below kelly bushing, with approximately 420 ft of that interval cored. Where no core was taken, cutting samples were collected and described at ten-foot intervals, largely for stratigraphic control and estimation of coring points.

Data collected and observations made during drilling indicate that the lithology, stratigraphy and structure penetrated in DOE-1 are similar to that observed elsewhere in the WIPP vicinity. No brine or gas was noted, either by sensors at the wellhead or in trace amounts in the mud. Cored sections showed no structural disruption in the halite and anhydrite units of the Castile, other than minor, commonly observed folding and tilting of laminae in the anhydrites.

G

Geohydrology Associates, Inc. 1980. *Aquifer Tests in H-6b, H-4b, and WIPP-15 Wells Near Carlsbad, New Mexico.* Albuquerque, NM: Geohydrology Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: H-4b and H-6b are completed in the Culebra Dolomite Member of the Rustler Formation near the Waste Isolation Pilot Plant (WIPP) site. Initial pumping tests of H-4b demonstrated very low transmissivity values, and a modified bailer test provided an estimate (1.9×10^{-2} m² per day) of transmissivity. Water from H-6b was injected ("slug" test) in H-4b, and the transmissivity is calculated to be 6.1×10^{-2} m² per day. Average transmissivity at H-6b, determined from both drawdown and recovery curves of the pumping test, is 7.2 m² per day. "The ... recovery plot indicates lateral aquifer boundaries to be present near the well."

WIPP-15 was drilled in fill in the San Simon Sink collapse feature, about 23 mi east-southeast of the WIPP. Sand and silt were discharged for several hours during a pumping test. Because of the well development during pumping, the transmissivity obtained from the recovery plot (57 m² per day) is considered more representative than transmissivity from the drawdown plot (30 m² per day).

DWP

George, O.L., Jr. 1980a. *Predicted Temperature/Time Histories Resulting From the Burial of Nuclear Waste Canisters in Bedded Salt.* SAND79-1773. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report provides computed thermal mappings for bedded salt surrounding canisters containing nuclear waste. This information can be used to study the possible migration of fluids within bedded salt under the influence of thermal gradients created by the heat-generating nuclear waste. The results presented were obtained from CINDA thermal models. Three different drift/canister configurations were modeled. The thermal conductivity of the salt was assumed to be temperature dependent while both the density and specific heat were assumed to be constant. Thermal power densities of 30, 75, and 150 kW/acre were examined with canister powers of 0.581 kW (51.6 canisters/acre), 3.5 kW (21.4 canisters/acre), and 3.5 kW (42.9 canisters/acre) at emplacement, respectively. These three cases resulted in maximum salt temperatures of 55°C, 117°C, and 176°C, respectively; and maximum thermal gradients of -15°C/m, -63°C/m, and -101°C/m, respectively. Computer-generated plots of temperature versus distance in horizontal planes at the top, midpoint, and bottom of the canister were made for several times after emplacement. Logarithmic or linear equations (whichever provided the better fit) were used to describe these curves. Derivatives of temperature with respect to distance were then taken and results of the form $x(dT/dx)$ and dT/dx for the logarithmic and linear equations, respectively, were plotted against time. For the two cases where the waste thermal outputs decayed exponentially, it was found that $x(dT/dx)$ and dT/dx were linear functions of time over a large period of years.

George, O.L., Jr. 1980b. *Computer Thermal Modeling for the Salt Block II Experiment.* SAND79-2250. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Salt Block II experiment consisted of a cylindrical block of bedded salt that was heated from within by a cylindrical electric heater. It was an extensively instrumented laboratory experiment that served, among other things, as a touchstone against which to measure the validity of a computer thermal model. The thermal model consisted of 282 nodes joined by 572 conductors, and was constructed for use with the CINDA heat-transfer code. Both transient and steady-state temperature distributions within the salt were computed for

heater power levels of 200, 400, 600, 1000, and 1500 W. Temperature versus time plots are presented for 23 locations throughout the Block over a 58-day period. Comparisons of the model results and experimental results are shown for both transient and steady-state conditions. The computed steady-state results were used to develop equations describing both the temperature and the temperature derivative as functions of radial location.

Gera, F. 1972. "Review of Salt Tectonics in Relation to the Disposal of Radioactive Wastes in Salt Formations," *Geological Society of America Bulletin*. Vol. 83, no. 12, 3551-3574.

ABSTRACT: The plastic deformation of salt formations is reviewed to evaluate the possibility of diapiric processes affecting salt beds used for radioactive waste disposal. In a geological sense, rock salt is characterized by a marked mobility as a result of its ability to deform under relatively low stresses. Examples are known of salt formations deformed by tectonic forces, but the typical diapiric processes are essentially caused by gravitational forces. In the initial phase, salt deformation is caused by differential loading of the salt bed; only after salt flowage has resulted in thickening of the low pressure zones of the salt bed does the density difference between salt and sediment contribute to the deforming stress. Salt diapirs are usually large structures, and to furnish the necessary large volume of salt, a mother bed of great initial thickness must be presumed. No minimum depth seems to exist for the plastic deformation of salt; however, the plasticity of salt increases with depth as a result of the increasing temperature.

The rate of salt deformation is critical in relation to the required containment time for plutonium-contaminated waste. A few authors maintain that diapiric processes proceed at a catastrophic rate, but the geologic literature indicates that most geologists believe salt diapirism to be a relatively slow process and geologic evidence seems to support strongly the majority view. It can be concluded that, in the final stage of salt intrusion, rates of diapir growth as high as a few mm/year are possible, and in the initial phase of plastic deformation of the salt bed, flow rates should be markedly lower.

In relation to the safety of radioactive waste containment, the risk of excessive deformation can be kept acceptably low if the disposal formation meets the following requirements: bedded salt located in a geologically stable area; subhorizontal salt beds exposed to very limited differential loading; thickness of the salt beds of the order of 100 to 300 m; and depth of the salt beds between 300 and 700 m.

Gera, F. 1974. *On the Origin of the Small Hills in Nash Draw and Clayton Basin, Southeastern New Mexico*. CF-74-2-29. Oak Ridge, TN: Oak Ridge National Laboratory.

ABSTRACT: A magnetic and gravity survey has been performed on one of the small hills present in southeastern New Mexico, and at a 2 mi² possible site area for the radioactive waste repository. No significant variations of the intensity of the magnetic field have been identified.

The gravity data indicate the presence of sharp, small amplitude, negative anomalies both at the site and at the hill. The only acceptable interpretation of these anomalies is masses of low density materials in the first few hundred below the surface, which would seem to indicate the presence of small sinkholes full of wind-blown sand. The sinkholes could be caused by leaching in the Rustler Formation and collapse of the overlying materials.

On the other hand, the hills seem to be caused by differential subsidence as a result of dissolution of Salado salt. The mechanism capable of producing a positive relief on the Salado-Rustler contact, exactly under a sinkhole, is not clear. A tentative explanation is proposed, based on the confined conditions of the brine aquifer and the progressive saturation

of the brine while approaching the sinkholes, where discharge to the overlying aquifers takes place.

Gerstle, W.H., and A.K. Jones. 1986. *Mechanical Properties of Crushed Salt/Bentonite Blocks*. SAND86-0707. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A preliminary mechanical testing program has been conducted on crushed salt/bentonite blocks. These blocks are prototypes of blocks that may eventually be used to build engineered seals in drifts at the Waste Isolation Pilot Plant (WIPP) Site. Three types of blocks were tested: pure crushed salt, crushed salt with bentonite binder, and pure bentonite. Simple uniaxial compression tests were performed. Axial displacement and lateral displacements were measured as a function of applied axial load. The ultimate strength, initial elastic moduli, and mode of failure were determined from these tests. The ultimate uniaxial strength of the pure bentonite blocks was found to be about 6.8 MPa. The ultimate uniaxial strength of pure salt blocks was found to be about 3.2 MPa. The blocks composed of both salt and bentonite had a strength somewhere between these two values. Surprisingly, the bentonite blocks, while stronger than the pure salt blocks, were less stiff. The mode of failure in all cases was through longitudinal splitting/cracking. Also, ultrasonic velocities in the blocks were measured. The results of these tests indicate a high degree of anisotropy in the bentonite and salt/bentonite blocks, while the pure salt blocks appear to be isotropic.

Gibbons, J.F., C.C. Ferrall, and S.F. Faith. 1979. *Progress in Modelling the Mechanical, Hydrologic, and Geochemical Response of the Rustler Formation for the WIPP Project*. Albuquerque, NM: Civil Systems, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The mechanical, chemical, and hydrologic stability of the Rustler Formation can affect the Rustler's performance as a barrier to waste migration. Characteristics that affect stability have been summarized to help formulate further examination of the Rustler. The Rustler is a relatively thin-bedded and variable formation of interbedded evaporites, dolomite, and siltstone. Evaporites are soluble, and anhydrite is partially gypsified. Large-scale tectonic activity is not significant, and the processes of formation, the distribution, and possible solution of evaporites need study based on core examination. Groundwater may reach anhydrite units through fractures in dolomite and adjacent units affected by thermomechanical stress. Computer models, coupling equilibrium relationships of the minerals with dissolution based on kinetically controlled mass-transfer equations, can be used to predict stable mineral assemblages. The rate of mineral precipitation is difficult to predict because the gypsum/anhydrite system is poorly understood. Predicted temperature ranges for the Rustler are in the range of uncertainty about gypsum stability. Somewhat arbitrary parameters used in strain calculations indicate Rustler uplift with a domal shape and center uplift of 2 m. Maximum uplift occurs at about 2000 years, producing an integrated total strain of about 0.03%. Some bedding plane shear is expected to develop on uplift flanks. Anhydrite extension will probably occur by creep of gypsum fillings of old fractures. Hydraulic pressures over the uplifted area will vary depending on strain. Rustler cores need to be studied to define gypsum distribution, siltstone nature, fracture distribution, nature and extent of dissolution features, and other important features. A hydrologic model of permeability and porosity changes will be necessary to understand changes during both uplift and recovery of uplift. To continue the project, the following courses are recommended: 1) continue composite strain modelling, including both mechanical and geohydrologic models; 2) continue Rustler studies, including geology and gypsum/anhydrite stability, and 3) understand the influences of ambient and transient regional stresses, including seismic ground motion. DWP

Glass, R.S. 1981. *Effects of Radiation on the Chemical Environment Surrounding Waste Canisters in Proposed Repository Sites and Possible Effects on the Corrosion Process*. SAND81-1677. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report explores the interaction of ionizing radiation with various environments. In particular, worst-case (aqueous) environments for the proposed nuclear waste repository sites are considered. Emphasis is on the fundamental chemical and physical processes involved. The identities of possible radiolysis products (both transient and stable) have been sought through a literature search. The effect of radiation on corrosion processes is discussed.

The radiation-induced chemical environment in the worst case repository sites is not well defined. Attention should therefore be given to fundamental studies exploring the interaction of such environments with components of the nuclear waste package, including the canister materials and backfills. Identification and quantification of radiolysis products would be helpful in this regard.

Gnirk, P.S., W.B. Krause, and A.S. Fossum. 1981. *State-of-the-Art Review of Brine Migration Studies in Salt*. SAND81-7054; Technical Memorandum Report RSI-0075. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report provides a state of the art review of brine migration studies in rock salt and includes experimental work which has been conducted in the laboratory and in the field. Laboratory experiments are proposed to determine whether or not a relationship exists between brine migration and temperature, temperature gradient, and stress in rock salt. The results can be incorporated into analysis by finite element computer codes. Brine migration is studied primarily as a function of temperature and temperature gradients. The effects of stress fields on brine migration are planned for later study. Laboratory and field studies are combined with analytical methods to predict brine migration and determine its significance for radioactive waste disposal.

The theoretical model proposed by Bradshaw and Sanchez depends on a diffusion theory based on molecular-sized spherical particles with Stokes' creeping flow assumptions. More basic investigations are needed, as this can only be considered to be very simplistic for rock salt.

DWP

Goad, D. 1979. *A Compilation of Site Selection Criteria, Considerations and Concerns Appearing in the Literature on the Deep Geologic Disposal of Radioactive Wastes*. EEG-1. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Information was compiled from fifty-nine sources about the selection and evaluation of a site for the deep geologic disposal of radioactive wastes: the criteria that should be used, the factors that must be considered, and the concerns expressed by various authors on this issue. The criteria and factors cited here were neither analyzed nor judged. They are provided in a form for easy reference that delineates the degree of agreement and disagreement about waste repository site selection.

Parts I through IV of the report list criteria: Part I - general framework, Part II - host rock, Part III - waste form and canister, and Part IV - other criteria. Part V includes general considerations and concerns voiced in the sources. Criteria are grouped by subject; for example, statements about volcanic activity in the site region are listed under Geothermal Gradient/Volcanic Activity. To avoid repetition, statements in each chapter that summarize a given position are followed by the list of sources for the position. The criteria are organized in each chapter from general to specific.

DWP

Gonzales, M.M. 1989. *Compilation and Comparison of Test-Hole Location Surveys in the Vicinity of the Waste Isolation Pilot Plant Site*. SAND88-1065. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Between 1976 and 1988, many surveys were performed related to the Waste Isolation Pilot Plant (WIPP) and its geologic and hydrologic test holes, which are part of the hydrogeologic-characterization program. Among these surveys were two First-Order, Class I vertical surveys, a satellite survey, and a number of township-range surveys. An overview of the basic function, history, and methodology of each survey type is provided in this report along with a review and comparison of the two major test-hole surveys. Elevation and location data for 96 test holes and 4 shafts are also included. The comparison of the satellite survey to the township-range surveys showed that the latter have the following advantages: their data are more complete; their elevation data are more accurate; and their techniques can be used for surveying new wells, keeping the data set consistent. Therefore, the final township-range surveys were selected as the best source of elevation and location data to use in the WIPP hydrology program.

Gonzalez, D.D. 1983a. *Hydrogeochemical Parameters of Fluid-Bearing Zones in the Rustler and Bell Canyon Formations: Waste Isolation Pilot Plant (WIPP), Southeast New Mexico (SENM)*. SAND83-0210. Albuquerque, NM: Sandia National Laboratories

ABSTRACT: The data contained herein are a compilation of hydrogeochemical information collected by the US Geological Survey and Sandia National Laboratories in support of the proposed Waste Isolation Pilot Plant (WIPP) facility. These data have been collected as a result of field operations ongoing since 1976 and are a result of extensive observations made at 24 locations. Hydraulic testing, chemical analysis, and geophysical logging have been performed in the water-bearing zones of the Rustler and Bell Canyon Formations. Transmissivities in these zones vary within nine orders of magnitude, and total dissolved solids range from a few thousand to 400 000 mg/L throughout the study area. The hydraulic data, for the most part, represent confined water-bearing horizons that range from stratigraphic contacts to 30 ft in thickness. Due to the low productivity, these zones would not be classified as aquifers anywhere else in the world. Wells within a 2-mi radius of the site and in the general southeastern direction of flow of the dominant aquifer in the Rustler (the Culebra Dolomite) yield no more than 0.2 gal/min over an extended period of pumping.

Gonzalez, D.D. 1983b. *Groundwater Flow in the Rustler Formation, Waste Isolation Pilot Plant (WIPP), Southeast New Mexico (SENM): Interim Report*. SAND82-1012. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In hypothetical breach scenarios for the Waste Isolation Pilot Plant (WIPP), the Culebra Dolomite in the Rustler Formation has historically been considered the aquifer most likely to play a significant role in transporting radioisotopes to the biosphere. More recently, it was determined that breach scenarios involving connection of aquifers above and below the Salado Formation where waste emplacement is planned would not result in an upward flow of water into the Rustler aquifers. Nevertheless, considerable hydrologic investigation has focused on the Culebra, because some scenarios might result in contamination of this aquifer. In such events the Culebra would provide more rapid transport of radioisotopes from the WIPP than any of the other aquifers in the WIPP area. This report describes the hydrologic tests conducted in three-well arrays at four different locations near the WIPP. At two locations, tracer tests were run with nonsorbing tracers. Tracer tests at the H-6 wells northwest of the WIPP indicated an effective porosity of 0.007 in the principal direction of flow and a dispersivity of 33 ft. At the H-2 wells, 1-1/4 mi west-southwest of the center of the WIPP Site, the effective porosity in the principal flow direction (deduced from the tests) is 0.18 and the dispersivity is 17 ft. Anisotropy of transmissivity was determined from pumping tests at

the H-4, H-5, and H-6 wells. The principal direction of transmissivity is roughly northwest-southeast at all three locations. The ratio of the major-to-minor transmissivity components varies only from 2.1 to 2.7, even though the transmissivity itself varies three orders of magnitude among the three locations. This information, coupled with transmissivity and head potential data, indicates that flow patterns near the WIPP Site are toward the southeast. Present estimates for flow rates are ~ 1 to 10 ft/year. Values of transmissivity for the Culebra vary six orders of magnitude over the extent of the study area, decreasing monotonically from $\sim 10^3$ ft²/day in Nash Draw to $\sim 10^{-3}$ ft²/day on the east side of the WIPP Site. The high values in and near Nash Draw reflect the fracturing caused by subsidence after dissolution of evaporites in the Rustler and Upper Salado. Tracer test results imply that matrix diffusion plays an important role for flow in the Culebra. This effect would further reduce presently estimated flow rates. The results in this interim report will be supplemented by additional tracer tests and anisotropy determinations to expand the data base, to improve understanding of the actual flow mechanism, and to allow more deterministic modeling of the flow regime at the WIPP Site.

Gonzalez, D.D. 1983c. "The Criteria for Hydrogeologic Characterization of Radioactive Waste Repositories - The WIPP Example," *EOS Transactions, American Geophysical Union*. SAND83-2029A. Vol. 64, no. 45, 713. (Abstract Only).

ABSTRACT: Competent rock formations proposed for storage of radioactive waste at depth are always surrounded by heterogeneous hydrogeologic features capable of transporting waste to the biosphere in low-probability breach scenarios. These scenarios range from catastrophic tectonic events to encounters with highly improbable hydrogeologic phenomena. Human intrusion as the breach mechanism can never be ruled out. As is the case with most proposed facilities, absolute hydrogeologic characterization is impossible because of the remoteness and size of these sites and the corresponding lack of a complete data base. In order to satisfy the concerns of the public and technical reviewers, as well as the standards proposed by the Environmental Protection Agency (EPA), it is essential that adequate characterization be formulated consistent with the geologic setting and practical costs.

The proposed Waste Isolation Pilot Plant (WIPP) Facility in southeast New Mexico is under construction in bedded salts 2150 ft below land surface. Hydrogeologic characterization was initiated in 1976; in 1980 the formal program was begun to arrive at credible estimates for groundwater flow and solute transport. The results from drilling, field, and laboratory analyses form the basis for pad-scale modeling, leading to a foundation for, and refinement of, a regional-scale interpretation. Fracture orientation, matrix diffusion, anisotropy, effective porosity, dispersivity, transmissivity, static head, and water quality, including aquifer residence times, will form the basis for the final estimates of the hydraulics of the WIPP. Discrete flow in fractures will be analyzed in detail at eight locations surrounding the WIPP.

Gonzalez, D.D. 1985a. "Tracers: Recent Trends and Applications," *EOS Transactions, American Geophysical Union*. Vol. 66, no. 46, 894. (Abstract Only).

ABSTRACT: The use of tracers towards the quantification of solute transport in the groundwater is increasingly becoming a major consideration in characterizing sites where hazardous waste practices, past, present, and future, are an issue. The results of tracer tests are a major factor in justifying future hazardous waste sitings and evaluating the effects of past and present waste handling and storage facilities. Solute-transport rates included in risk assessments address standards enforced by federal, state, and local authorities.

Natural and artificial tracers are used in complex hydraulic tests to estimate areally large or localized hydraulic and sorptive parameters. Predictive numerical models utilizing these data and the geoscientific representation of the study area provide the guidance toward future site selection alternatives for handling and permanent storage of hazardous waste, and for remedial

action planning and implementation for present facilities that are of risk to the environment and the health and safety of the population.

Tracer techniques in testing and application of natural and artificial tracers to specific environments are presented with comment on applicability towards future trends in groundwater investigations in the hazardous waste environments.

Gonzalez, D.D. 1985b. "Hydraulic Studies in Low Permeability Evaporite Deposits, Southeastern New Mexico, (SENM)," *International Association of Hydrogeologists Memoires, Hydrogeology of Rocks of Low Permeability, Tucson, AZ, January 7-12, 1985.* Tucson, AZ: University of Arizona. Vol. 17, pt. 2, 795. (Abstract Only).

ABSTRACT: In support of the hydrogeologic characterization of the proposed Waste Isolation Pilot Plant (WIPP), in Southeastern New Mexico, hydraulic studies in Permian evaporites within the Delaware Basin have been on going since 1975 and were intensified and expanded in 1980.

The hydrologic program for the WIPP is designed to determine the parameters necessary to model the site area for mass transport considering the limitations imposed by the large areal extent of the study area and range in transmissivity ($10E2$ - $10E-3$ ft²/day), a double medium, fracture-filled system, water quality and density (1.001-1.260 g/cc) variation, and a limited number of test and observation wells. The principal components of the WIPP Hydrology Program are: (1) Regional hydrologic studies including recharge, discharge and infiltration investigations; (2) Drilling and completion designed for testing in low permeability rock; (3) Hydraulic testing that requires pumping at rates from several gal/min to 0.1 gal/min for periods lasting up to 30 days or more. Tests involve observation wells 3-4 mi from the pumping well and special downhole equipment suited to data acquisition in packed-off water-bearing units as much as 4,500 ft below land surface; (4) Aquifer anisotropy determination using data collected from three wells, the theory and technique adapted from techniques developed by Hantush Papadopoulos for application to the WIPP Hydrology Program; (5) A tracer test program where a suite of tracers best suited to the evaporites are used in the analysis of results obtained from two-well recirculation and convergent flow tests. Thiocyanate and five fluorinated derivatives of benzoic acid have been used successfully in tests lasting 20-600 days in wells spaced 100 ft and pumping rates of 10-0.10 gal/min. Effective porosity ranges from 0.1 [note: probably 0.1] to 18% in analyzed tests, and matrix diffusion is being evaluated by examining the tail portion of breakthrough curves under different pumping rates; (6) Water quality analysis and the use of environmental tracers to determine groundwater flow direction, source, age and velocity. Tracers include the halides, stable isotopes of mobile species of C, Cl, and S and the radioisotopes of H, C, Cl, and Kr; (7) Numerical groundwater flow and solute transport modeling. Several codes have been developed and/or modified to compliment the real double-porosity/fractured media for tracer tests, aquifer well interference tests and flow and solute transport modeling.

Gonzalez, D.D., and L.R. Hill. 1980. "Tracer Tests Performed in the Field for WIPP in Southeastern New Mexico," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium, Boston, MA, November 27-30, 1979.* Ed. C.J.M. Northrup, Jr. SAND79-0981C. New York, NY: Plenum Press. Vol. 2, 487-489.

ABSTRACT: A two-well recirculating tracer test began in October 1979 to define as accurately as possible the hydraulic character (natural groundwater velocities, aquifer porosity, and components of dispersivity) of a fractured carbonate aquifer, the Culebra Dolomite Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP) Site in Eddy and Lea Counties, NM. The Culebra Dolomite overlies a zone planned for isolation of transuranic (TRU) contaminated waste generated by US defense programs. The storage zone of the proposed facility is in nearly pure halite and about 1400 ft (427 m) below the Culebra

Dolomite, the most likely pathway for the migration of radionuclides to the biosphere in the event the repository is breached by groundwater. The aquifer thickness is 19 ft (5.8 m), with hydraulic conductivities estimated between 0.01 to 0.05 ft/day.

Injection flow rates initially will be low (0.2 gal/min) based on hydraulic conductivities. The proposed tracer test will use sodium benzoate and pentafluorobenzoic acid as tracers; fluorocarbons will be a backup. DWP

Grant Geophysical Corporation. 1978. *Reflection Seismograph Survey Operations Report. WIPP Project, Eddy County, New Mexico.* Grant Geophysical Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Between July and November 1978, Grant Geophysical Corporation conducted a seismic reflection survey for Bechtel National Inc. Data were collected on 22 lines totaling about 74 miles over the WIPP site area. "A fan geophone array of 36 geophones per station was used throughout the area." For most lines the array spread 110 ft from the center along each arm. For two lines the arrays spread 55 ft along each arm. DWP

ANNOTATION: The data acquired by Grant Geophysical Corp. are interpreted and presented in Bell and Murphy and Associates (1979) and Dobrin (1979), both included in this bibliography.

Gravity Meter Exploration Company. 1976. *Aeromagnetic Interpretation Delaware Basin Texas and New Mexico.* Houston, TX: Gravity Meter Exploration Company. Revised by Geophysical Exploration Corporation, May 1976. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report covers a speculative interpretation of a speculative survey by Aero Service Corporation. The report and its accompanying maps are the exclusive property of Sandia National Laboratories (SNL) and may not be sold, traded or in any way divulged except to employees of SNL without the written consent of Gravity Meter Exploration Company.

The field aeromagnetic data for the Delaware Basin were acquired during 1963-1964 by Fairchild Surveys. Maps were compiled at a scale of 1 mi : 8,000 ft with contour intervals of five gamma. This restricted work was purchased by SNL to examine basement structure and evidence for the dike trend northwest of the Waste Isolation Pilot Plant (WIPP) Site or other sites in the vicinity of the WIPP. DWP

Griswold, G.B., ed. 1977a. *Chemical Analyses of Potash-Bearing Horizons From 21 Exploratory Holes Drilled at a Tentative Site for the Waste Isolation Pilot Plant, Eddy County, New Mexico.* SAND77-1217. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Sandia Laboratories drilled 21 potash drill holes over an 18,960-acre site in east-central Eddy County, NM to evaluate potash resources as part of their Waste Isolation Pilot Plant (WIPP) Project. This report furnishes assay information on samples obtained from the drilling program.

Griswold, G.B. 1977b. *Site Selection and Evaluation Studies of the Waste Isolation Pilot Plant (WIPP), Los Medanos, Eddy County, NM.* SAND77-0946. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Bedded-salt deposits of the Salado Formation have been selected for evaluation for a proposed Waste Isolation Pilot Plant (WIPP) to be located in Eddy County, NM, ~26 mi east of Carlsbad, NM. Site selection and evaluation studies that included geologic mapping, geophysical surveys, drilling, and resource appraisal were conducted over and under the prospective location. The lower portion of the Salado meets essential criteria for waste isolation. Beds chosen for waste storage lie 2074-2730 ft below the surface. High-purity salt exists at these depths, and the geologic structure revealed by geophysical surveys indicates that these beds are essentially flat. Additional geophysical surveys are now under way. The initial interpretation of the new data indicates that more structure may exist in the salt beds in the northern portion of the site area. Full evaluation of potentially commercial deposits of potash and natural gas within the WIPP Site will be reported by separate studies, as will be the hydrologic details of the region.

ANNOTATION: The report by Griswold (1977b) provides considerable technical detail of the parameters used to select the present WIPP Site during late 1975 and early 1976 after the initial site (where ERDA-6 was drilled) was abandoned as unsuitable because of extreme deformation of the salt beds. Some parallel, but unpublished, study by the US Geological Survey (USGS) (especially C.L. Jones) gave similar results and selected the same primary area for the present site among alternatives.

The parameters for the preliminary site selection differed from implicit or explicit requirements for the original site. The most restrictive parameter added was to avoid the zone along the front of the Capitan Reef where the evaporites are generally deformed. The zone was considered to be about 6 mi wide. In addition, Oak Ridge National Laboratory (ORNL) selected the original site using a 2 mi buffer from any bore hole through the evaporites. This criterion was relaxed to 1 mi in view of further study of salt dissolution in bore holes. The known potash area was avoided, as were more favorable areas for hydrocarbons.

Griswold effectively covers the preliminary site selection process and the initial characterization through the drilling of the first bore hole and first seismic reflection data. The main site characterization phase which is considered to follow this stage, is covered by Powers et al. (1978) and Lappin (1988a).

Griswold, G.B. 1978. *Recommendations for Drilling a Geoscience Hole at the Pre-WIPP Designated Area Nash Draw Mine, Eddy County New Mexico.* Albuquerque, NM: Tecolote Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Sandia National Laboratories (SNL) is now negotiating with the Duval Corporation to excavate underground chambers in salt within the company's Nash Draw mine located about 5 mi southwest of the Waste Isolation Pilot Plant (WIPP) Site. Core and descriptive geologic logs from holes drilled near the proposed PWDA (Pre-WIPP Dedicated Area) indicate favorable conditions. However, available cores are incomplete for the interval above and below the selected salt horizon. No geophysical logs are available.

A coring program is recommended to verify stratigraphic details and chemical properties of the area selected for the PWDA. Geophysical logging is recommended to determine in situ physical properties and provide data for the comparison of those properties with the remotely handled (RH) and contact handled (CH) horizons selected at WIPP.

The drill hole can be used to test bore-hole plugging concepts. The hole is located in a pillar area such that reentry could be accomplished on two levels separated vertically by about 200 ft. The two level reentry has the advantages of testing continuity of the plugs plus allowing reentry at two different times of aging. DWP

Griswold, G.B. 1979. *Minimum Mining Development Plan PreWIPP Dedicated Area (PWDA), Nash Draw Mine, Eddy County, New Mexico.* Albuquerque, NM: Tecolote Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The PreWIPP Dedicated Area (PWDA) is an experimental facility to be located in the Duval Nash Draw mine. Experimental chambers can be developed through either of two plans differing mainly in having 51-ft long chambers and pillars in Plan I while Plan II will combine 51- and 123-ft lengths. Dimensions of the "heated room" experiment are not yet decided. Heated pillar and ambient pillar experiments are not compatible with stability requirements for Nash Draw mine, and experiments that induce gross movement should be sited in mines inducing continuous roof failure. Wiremesh and roofbolts will be required for the roof over the entire experimental area to protect experimenters and visitors. DWP

Griswold, G.B., and V.C. McWhirter. 1981. *Interpretation of Wireline Geophysical Logs ERDA No. 9 Stratigraphic Test Borehole DOE WIPP Site, Eddy County, New Mexico.* SAND80-7119. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: ERDA No. 9 was drilled at the approximate center of the Waste Isolation Pilot Plant (WIPP) Site to test the stratigraphy. The hole was continuously cored from 1090 to 2887 ft, the total depth of the hole. A suite of 20 wire line geophysical logs was recorded on analog strip charts under open hole conditions over the cored interval. The records were subsequently digitized at 0.5 ft intervals with the data placed on magnetic tape.

A simple computer program was devised to interpret rock type and calculate elastic properties based on the digital data. The analysis is in excellent agreement with physical examination of the core. Correlating the wireline geophysical logs with core provides a better basis for using wireline logs to describe rock conditions in future holes drilled by rotary methods or where core has been lost. DWP

Gulick, C.W. Jr. 1978. *Borehole Plugging-Materials Development Program.* SAND78-0715. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report discusses the background and first year's results of the grouting materials development program for plugging boreholes associated with the Nuclear Waste Isolation Pilot Plant (WIPP). The grouts are to be pumpable, impermeable, and durable for many thousands of years. The work was done at the Concrete Laboratory of the US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. The workability, strength, porosity, bonding, expansion, and permeability data are summarized and discussed. The work is continuing at WES.

Gulick, C.W., Jr. 1979. *Borehole Plugging Program Plugging of ERDA No. 10 Drill Hole.* SAND79-0789. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A requirement exists to plug exploratory drill holes located in the proposed Waste Isolation Pilot Plant (WIPP) area of southeastern New Mexico. Sandia National Laboratories (SNL), in cooperation with the US Army Corps of Engineers Waterways Experiment Station (WES) Concrete Laboratory developed pumpable and durable cement grouts. These grouts were successfully used to plug an existing drill hole in the area. Results of this project are presented, along with comments and conclusions.

Gulick, C.W., [Jr.], and L.D. Wakeley. 1989. *Reference Properties of Cement-Based Plugging and Sealing Materials for the Waste Isolation Pilot Plant (WIPP)*. Technical Report SL-89-17. Vicksburg, MS: Waterways Experiment Station.

ABSTRACT: The Structures Laboratory of the US Army Corps of Engineers Waterways Experiment Station (WES) has conducted research on cement-based composites for the Waste Isolation Pilot Project (WIPP) since 1977 in support of Sandia National Laboratories (SNL). Sealing shafts and plugging bore holes for closure of this geologic repository for radioactive wastes will require grouts and concretes. Salt-saturated grouts and concretes bond adequately to the bedded halite host rock. Freshwater mixtures will plug and seal penetrations through nonhalite strata.

This report gives reference values for such properties as unconfined compressive strength, static modulus, restrained expansion, and permeability of candidate grouts and concretes. Values tabulated here are not averages but are values that one could reasonably expect to attain with other candidate mixtures of similar composition. They are values that the authors consider reasonable targets for cement-based composites likely to be used in the closure phase of operation of the WIPP or other underground repositories.

Gulick, C.W., [Jr.], J.A. Boa, Jr., and A.D. Buck. 1980a. "Bell Canyon Test (BCT) - Cement Development Report," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980*. SAND80-0358C. Paris, France: Organisation for Economic Co-Operation and Development. 277-297.

ABSTRACT: The Borehole Plugging (BHP) materials development program, which has been underway at the US Army Corps of Engineers Waterways Experiment station (WES) under Sandia National Laboratories (SNL) sponsorship for about five years, is reviewed. Development testing data for candidate grout mixtures for the Bell Canyon Test (BCT) plug are presented. Field batching, mixing, and placement operations are discussed. Data from field samples molded during the two plug placements include strength, expansion, compressional wave velocity, dynamic modulus, density, and porosity. Microstructure and composition are compared for grout samples at ages of a few weeks and one year.

Gulick, C.W., Jr., J.A. Boa, Jr., and A.D. Buck. 1980b. *Bell Canyon Test (BCT) Cement Grout Development Report*. SAND80-1928. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The grout for the Bell Canyon Test (BCT) was developed and tested at the US Army Corps of Engineers Waterways Experiment Station (WES) and tested as well by Dowell Labs, Pennsylvania State University, and Oak Ridge National Laboratory (ORNL). A saltwater grout with Class H cement, fly ash, and an expansive additive developed unexpected permeability along the contact between grout and anhydrite. The space at the contact was caused when specimens dried. A freshwater grout and proper care to prevent drying alleviated the condition. The BCT-1FF freshwater grout was used in field operations.

"Physical property and expansivity data for the field samples through 90 days' age are in general agreement with laboratory development data." "The high-density, low water-cement ratio expansive grout (BCT-1FF) is considered to be an excellent candidate for plugging boreholes at most locations (except through halite sections). DWP

Gulick, C.W., Jr., J.A. Boa, [Jr.], and A.D. Buck. 1982. *Borehole Plugging Materials Development Program Report 3*. SAND81-0065. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report gives data for up to four years of durability studies of grout mixtures developed for the borehole plugging program of the Nuclear Waste Isolation Pilot Plant (WIPP). Samples from field plugging operations for the Bell Canyon Test and ERDA-10 drill hole are included in the durability studies. Specimens of all mixtures had phase compositions and microstructures that were considered normal for these mixtures at these ages. All of the specimens of the various grout mixtures (including fresh and salt water) have maintained acceptable physical properties as measured by compressive strength, compressional wave velocity, dynamic modulus of elasticity, and permeability to water. Porosity and expansion data under differing exposure conditions have been collected for continuing study evaluation. The work was performed and is continuing at the Structures Laboratory of the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

Gulick, C.W., Jr., J.A. Boa, Jr., D.M. Walley, and A.D. Buck. 1980. *Borehole Plugging Materials Development Program Report 2*. SAND79-1514. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The data for 2 years of grout mixtures durability studies developed for the borehole plugging program of the Nuclear Waste Isolation Pilot Plant (WIPP) are reported. In addition, data for 1 year of durability studies of grout mixture field samples used to plug the ERDA-10 exploratory drill hole near the WIPP Site are included. The grout samples and the data do not show any evidence of deterioration during the durability studies that include exposure to brine at both ambient and elevated temperatures. The data include strength, compressional wave velocity, dynamic modulus, expansion, weight change, porosity, permeability, bond strength, chemical analysis of cements, and petrographic examinations. The work was performed at the Concrete Division of the Structures Laboratory of the US Army Corps of Engineers Waterways Experiment Station (WES), Vicksburg, MS. The work is continuing at WES.

Guzowski, R.V. 1990. *Preliminary Identification of Scenarios That May Affect the Escape and Transport of Radionuclides From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-7149. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is being evaluated as a location for the disposal of defense-generated transuranic waste. One of the criteria to be used to determine the suitability of the disposal system is compliance with the Containment Requirements established by the US Environmental Protection Agency (EPA). One step in determining compliance is to identify the combinations of events and processes (scenarios) defining possible future states of the disposal system that may affect the escape of radionuclides from the repository and transport to the accessible environment.

A list of previously identified events and processes was adapted to a scenario-selection procedure that develops a comprehensive set of mutually exclusive scenarios through the use of a logic diagram. Four events resulted in the development of 16 scenarios. Preliminary analyses indicate that four scenarios result in no releases. Six scenarios consist of combinations of drilling into a room, drilling into a room and a brine reservoir, and emplacement of withdrawal wells downgradient from the repository. Six additional scenarios consist of these same six combinations with the addition of potash mining and the associated surface subsidence.

The 12 retained scenarios will be screened based on consequence and/or probability of occurrence. During the course of performance assessment, additional data and information will be used to revise and update these preliminary scenarios where appropriate.

H

Hadley, G.R. 1981. *Salt Block II: Brine Migration Modeling*. SAND81-0433. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A Darcy flow model of brine migration previously applied to a small-scale water loss experiment is used to model water loss from a large-scale experiment designated Salt Block II. Agreement with the data is found to be reasonably good provided some simplifying assumptions concerning the stress state of the salt are allowed. In general, agreement is better than that obtained using the inclusion migration model. However, post-test analysis of the salt block showed that inclusions did in fact move during the experiment so that the actual response is probably a combination of the two different effects.

Hadley, G.R., and G.W. Faris. 1981. *Revised Theory of Water Transport in Rock Salt*. SAND80-2398. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This paper presents a theoretical treatment of the water loss rate of a heated 1 kg sample of southeastern New Mexico rock salt. The analysis presented here represents a refinement of a previously published model in which the water loss was assumed to be the Darcy flow of water vapor from a receding evaporation front. The refinement consists of a more careful and detailed modeling of the vapor region, including the effects of Knudsen diffusion and binary gaseous diffusion of water vapor through air. The results of the analysis are found to provide improved agreement with experiment during the room temperature drying stage.

Hansen, F.D. 1979. *Triaxial Quasi-Static Compression and Creep Behavior of Bedded Salt from Southeastern New Mexico*. SAND79-7045. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Ten samples of bedded salt from Drillhole AEC-7 were tested by triaxial quasi-static compression and triaxial creep tests. The program was developed to determine deformation characteristics as well as to test and refine procedural details. Samples 2 in. in diameter were recovered from original 4-in. cores from depths of 1935-1954 and 2711-2722 ft. Confining pressures were 500 and 2000 psi; differential axial stresses were 1500, 3000, and 4500 psi; temperatures were 23 and 100°C; and the tests continued from several hours to ten days.

Axial and lateral strain was determined as a function of time for a constant load. For times of more than one hour, power laws fit the axial and lateral strain data well. Creep behavior was transient for these tests. Steady-state creep was not definable for these tests, and creep rupture did not occur even for samples with more than 25% axial strain. At lower differential stress, creep yielded principal strain ratios less than 0.5 while at higher differential stresses the ratios were about 0.5 to 0.55. No dilatation was observed. DWP

Hansen, F.D., and K.D. Mellegard. 1979. *Creep Behavior of Bedded Salt From Southeastern New Mexico at Elevated Temperature*. SAND79-7030; Technical Memorandum Report RSI-0062. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Seventeen triaxial creep experiments were conducted on 2 in. diameter core specimens from depths of 2605 to 2679 ft in Drillhole ERDA-9 to determine time-dependent deformation characteristics. The tests were conducted under differential axial stress ranging

from 1500 to 6000 psi, confining pressures from zero to 3000 psi, and temperatures of 24, 70, and 100°C. Experiments ranged from 15 minutes to 20 days in length.

"All tests exhibited transient creep to various degrees; two experiments resulted in rupture..." For a few experiments, creep accelerated prior to termination. Data do not justify comprehensive creep analysis. Regression analysis yielded an equation that fits axial creep data to a function of time, differential stress, and temperature. Lateral strain was not treated by regression analysis, though lateral strain is qualitatively similar to axial strain. DWP

Hansen, F.D., and K.D. Mellegard. 1980. *Further Creep Behavior of Bedded Salt From Southeastern New Mexico at Elevated Temperature*. SAND80-7114. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Seventeen tests were conducted on halite samples removed from depths of about 2440 and 2500 ft in borehole ERDA-9. Two-inch diameter specimens were recored from original cores from the bore hole. Triaxial compression creep experiments were conducted at differential stresses ranging from 800 to 3000 psi, confining pressures from 0 to 3000 psi, and temperatures to 200°C over periods up to 60 days. Test parameters and most procedures in these tests were similar to those for earlier series.

All samples initially deformed transiently while a few reached steady state. Tertiary creep was observed once. Transient data were fit well with a simple power law. The power law for these tests predicts strains considerably smaller than does the power law for each of the previous series of tests. An undetermined error may exist, though no experimental error has been found. "... an empirical power law was fit to all of the existing transient data by ... multiple regression. A hand calculation yielded a steady-state equation. A comparison of the strain predictions based on these two fits shows a reasonable estimate for transition from transient to steady-state deformation." DWP

Hansen, F.D., D.E. Munson, and A.F. Fossum. 1988. "Substructures of Salt from the WIPP Site," *EOS Transactions, American Geophysical Union*, SAND88-2444A. Vol. 69, no. 44, 1446. (Abstract Only).

ABSTRACT: Substructures of untested salt from a horizontal borehole within Room D at the Waste Isolation Pilot Plant (WIPP) Site have been examined using optical microscopy of etched cleavage chips. The borehole samples were extracted from six locations between 0.3 and 14.3 m deep into a relatively clean salt layer. Subgrain size and free dislocation densities of the samples in the proximity of the WIPP opening were compared to those of four salt samples taken from the ERDA 9 surface drillhole at the same horizon depth, 653 m, as Room D. A uniform subgrain size of 300 μm found in all samples compared very well to data of Carter and coworkers. Free dislocation density varies monotonically as a function of horizontal depth into the rib, ranging from 5.4 to 2.4 (10^7) cm^{-2} between 0.3 and 14.3 m depth, respectively. Density of the laterally equivalent ERDA 9 salt is 1.7(10^7) cm^{-2} . Increase in free dislocation density ($\Delta\rho$) is attributed to creep deformation around the WIPP underground opening. A relationship between $\Delta\rho$ and a state parameter (ξ) has been calculated from finite element simulations of Room D using a Munson-Dawson creep law. The state parameter (ξ) is a measure of the transient strain. A linear fit ($r = 0.97$) between $\Delta\rho$ and ξ suggests that each percent increase in the state parameter can be equated to an increase in free dislocation density of 2.3(10^7) cm^{-2} .

Harrington, T.J. 1979. *TSC Single Room Stability Analysis*. WTSD-TME-2971. Pittsburgh, PA: Westinghouse Electric Corporation.

ABSTRACT: The single-room concept was derived by using the same overall lateral area with the four room yield pillar design. The room is 32 ft wide, 12 ft high, and the rooms are separated by pillars 112 ft wide. The model has four clay seams in the roof of the room; the first is 16 ft above the roof. The floor of the model has a 3-ft-thick anhydrite layer 4 ft below the floor and 3 clay seams below the anhydrite.

The ANSYS computer code used to perform the time-dependent closure analysis is publicly available. The code was able to model the creep of the rock salt, the elastic nature of the anhydrite, and the slipping nature of the clay seams. The material properties for the creep response of the rock salt were taken from the work by Munson and Dawson. The creep response of the rock salt is an empirical power law curve based on creep data collected from samples of rock salt from the 2150-ft horizon in the ERDA-9 bore hole. The elastic properties of both rock salt and anhydrite were compiled from Waste Isolation Pilot Plant (WIPP) sources. Properties of the clay discontinuities were not determined in any testing program; therefore, the clay seams were assigned properties based on typical clay material properties.

The analysis shows total vertical and horizontal room closures, respectively, of 1.83 in. and 0.82 in. from the initial elastic response to mining. The ultimate closures at ten years time are 9.82 in. in the vertical and 10.41 in. in the horizontal directions. The closure rate decreases markedly over the first year, after which the closure rate becomes approximately constant at 0.76 in./year in the horizontal direction and 0.65 in. in the vertical direction. The anhydrite layer acts to isolate the rock salt below the room from the effects of mining the room. The lack of high deviator stress under the anhydrite layer prevents creep of the rock salt under the anhydrite layer. The clay seams affect the vertical closure of the roof, and the effect of the anhydrite layers is demonstrated by the minimal floor heave. DWP

Harrington, T.J., C.R. Chabannes, and D.K. Shukla. 1984. "Rock Mechanics Considerations in the WIPP Room Design," *The Mechanical Behavior of Salt: Proceedings of the First Conference, Pennsylvania State University, University Park, PA, November 9-11, 1981*, Eds. H.R. Hardy, Jr. and M. Langer. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 681-696.

ABSTRACT: An analysis of the Waste Isolation Pilot Plant (WIPP) room geometry at about 650 m (2100 ft) under isothermal conditions was performed. The analysis evaluated the stability of the room design over a ten-year period. The presence of stiff anhydrite layers and clay seams, as determined from field investigations, was evaluated. The clay seams were treated as joints in the model with the influence of the joint properties evaluated parametrically.

The results indicate that the behavior of the room is governed by the locations and properties of the clay seams and stiff anhydrite layers. Hence, for the design of actual mine rooms that are required to remain open for a number of years, the determination of the exact local geology and the properties of the clay seams or joints and other interbeds is of prime importance.

Hart, J.S., and J.K. Register. 1982. *A Description of the Site and Preliminary Design Validation Program for the WIPP Site*. TME 3063, Rev. 1. Albuquerque, NM: US Department of Energy.

ABSTRACT: As of October, 1982, two shafts had been blind-bored to the facility horizon at 2150-ft depth and were connected by a drift. A shaft station was established near the bottom of the 12-ft diameter exploratory shaft. Instruments in the exploratory shaft monitor rock response and water pressure.

Underground areas north of the shafts will be developed to test disposal room designs. An exploratory drift will extend 3264 ft south of the ventilation shaft centerline. Surface facilities are developed for temporary service and minimum cost. Site and Preliminary Design Validation (SPDV) construction work should be complete by August, 1983. If the site proves unacceptable, site restoration plans include filling shaft, removing surface facilities, regrading the site and spreading stockpiled topsoil, mulching disturbed areas, and monitoring restoration.

Site validation programs include geologic mapping of shafts and underground excavations, drilling and logging core from vertical holes in the roof of underground workings, laboratory analyses of core and fluid samples, measuring fluid inflow and pressure in the shafts, obtaining high-resolution gravity data over much of the site, and correlating drill-hole logs. DWP

ANNOTATION: The original TME 3063 is cited as Little et al. (1980).

Haug, A. 1987. "A Modeling Study of the Culebra Dolomite," *Proceedings of the Solving Ground Water Problems With Models Conference and Exposition*, Denver, CO, February 10-12, 1987, Dublin, OH: National Water Well Association, Vol. 2, 827-852. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A modeling study has been performed as part of the regional hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) Site in New Mexico. The study resulted in an estimation of the transmissivity distribution, the hydraulic potentials, the flow field, and the fluid densities in the Culebra Dolomite Member of the Rustler Formation at the WIPP Site.

The work performed consisted of modeling the hydrogeology in the Culebra using two different approaches: steady-state modeling of the best estimate of the undisturbed situation, and transient modeling of the hydrogeologic conditions resulting from excavating three shafts at the center of the WIPP Site as well as from various well tests.

The three-dimensional finite-difference code SWIFT II with variable fluid density formulation was employed. The size of the model area was 12.24 km x 11.70 km. The boundary conditions (prescribed pressures and fluid densities) were estimated using the hydraulic head and fluid density data obtained from 40 wells at the WIPP Site. The initial spatial transmissivity distribution in the Culebra Dolomite was estimated using kriging techniques.

The steady-state model was calibrated against the observed formation pressures and fluid densities. The calibration parameters were the transmissivities and the boundary conditions. The transmissivities were modified during the calibration process using kriging techniques, thus maintaining the statistical properties of the observed transmissivity data.

The calibrated steady-state model was used as initial conditions for simulating transient processes in the Culebra at the WIPP Site. The examples presented include the shaft history beginning in 1981 and a long-term pumping test (denoted the H-3 multipad pumping test) conducted in 1985.

Haug, A., V.A. Kelley, A.M. LaVenue, and J.F. Pickens. 1987. *Modeling of Ground-Water Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site: Interim Report*, SAND86-7167, Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The hydrogeology of the Culebra Dolomite Member was modeled with the numerical code SWIFT II, using two approaches: steady state modeling to estimate the undisturbed head and fluid-density distribution prior to sinking Waste Isolation Pilot Plant

(WIPP) shafts in 1981, and modeling of local, transient hydrologic responses to excavation of the three shafts at WIPP as well as to well tests. The distribution of transmissivity, hydraulic potentials, flow field, and fluid densities were estimated by this modeling.

The distribution of initial spatial transmissivities were obtained using kriging techniques, and the steady-state model was calibrated against observed pressures and densities. A zone of high transmissivity (as much as $2 \times 10^{-4} \text{ m}^2/\text{sec}$) extends south from H-11 to the model boundary outside the control zone. A relatively large area near the center of the site has low transmissivities ($< \text{about } 10^{-6} \text{ m}^2/\text{sec}$).

After calibrating the steady-state model against best estimates of undisturbed freshwater heads, the difference between observed and calculated head is less than 1.1 m for all wells. The model was not completely calibrated against observed fluid densities ranging from 1.00 to more than 1.10 g/cm^3 . The differences may result from a flux of water from various sources or may be caused by transient boundary conditions. An upward flux of highly saline water may be possible around P-17. An alternative may be problems with the well completion at P-17. In the western part of the model area, it is possible that slightly saline water flows downward from the Magenta.

After the steady-state model was calibrated, drilling and testing activities for shafts and several hydrologic holes were superimposed on the model. The model and observations of long-term freshwater head histories agreed well at shafts and hydrologic holes, indicating the distribution of transmissivities is realistic. The transient head responses to the H-3 test were not reproduced without assuming additional leakage from the Culebra into the waste handling shaft.

The effects of dual porosity models were assessed using SWIFT II. The results did not significantly differ from those obtained using single porosity.

This study is based on transmissivity data available as of April 1986, and hydraulic head data as of August 1986. The study area will be enlarged and additional test results included in further modeling. DWP

Hayes, P.T., and G.O. Bachman. [1979]. *Examination and Reevaluation of Evidence for the Barrera Fault, Guadalupe Mountains, New Mexico*. Open-File Report 79-1520. Denver, CO: US Geological Survey.

ABSTRACT: In southeastern New Mexico a prominent escarpment marks the southeastern boundary of the Guadalupe Mountains and the massive Capitan limestone of Permian age is well exposed along the mountain front. Vincent Kelley described faults that he named the Barrera and Carlsbad Faults along the escarpment. As part of the earth-science investigations for the Waste Isolation Pilot Plant (WIPP) Site, we examined the evidence for those faults in the field and concluded that the faults are nonexistent, and that Kelley's conclusions were based on misinterpretation of exposures of fan gravel, jointing, and shrub alignment.

ANNOTATION: The work by Kelley cited by Hayes and Bachman refers to publications of the New Mexico Bureau of Mines and Mineral Resources dated 1971 and 1972. These alleged faults would be the closest probable active faults to the WIPP if verified. Seismic analysis of the WIPP Facilities would have been affected. In personal comments to L.R. Hill and D.W. Powers at about the time Hayes and Bachman reexamined these lineaments, Kelley indicated he was doubtful these were faults. His analysis was based mainly on photo interpretation. The closest known recent fault scarps to the site are still along the West Texas salt flat graben between Carlsbad and El Paso. These faults are part of a system related to the Valentine, TX, earthquake of 1931, the largest known historical earthquake in West Texas.

Hern, J.L. 1977. *Waste Isolation Pilot Plant (WIPP) Site Characterization Report - Los Medanos Area, New Mexico*. Houston, TX: G.J. Long & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A total of 47 line mi of new Vibroseis seismic data was acquired in 1977 to examine specific phenomena earlier identified from industry and Waste Isolation Pilot Plant (WIPP) seismic data. Data quality is generally of good to very good quality, with data quality degraded over areas of complex geology. Higher frequency data enable better and more consistent mapping of reflector horizons within the evaporite section. Structure maps were prepared for top of Salado, top of Castile, and a Delaware sand marker. An isochron map was prepared of the Castile-Delaware interval. These preliminary maps show an anomalous zone north of the site as well as around borehole ERDA 6. Limited velocity data are available to evaluate a velocity problem in upper units. Changing lithology within the Rustler Formation may explain velocity changes in the section. A program to collect 61 additional line mi of seismic data is recommended. DWP

Hern, J.L. 1979. "Geophysical Investigations for Pilot Plant for Nuclear-Waste Isolation in Southeastern New Mexico," *AAPG Bulletin*, Vol. 63, no. 3, 465-466. (Abstract Only).

ABSTRACT: A thick salt bed, the Salado Formation, is present in the northwestern part of the Delaware Basin. In an area about 30 mi east of Carlsbad, Eddy County, NM, this salt bed is being investigated as a possible site for a pilot plant for radioactive waste isolation. Geophysical investigations have been carried out at the proposed site since 1976. This work was performed under the direction of Sandia National Laboratories (SNL), Albuquerque, under contract to the Department of Energy (DOE). The purpose of these geophysical investigations was to study the geologic conditions of the bedded salt deposit, including the evaporite section and overlying and underlying formations as part of site evaluation and characterization.

Both nonseismic and seismic geophysical techniques were employed. Seismic investigations were used to map from the top of the Salado Formation downward to Precambrian basement in order to locate and delineate salt breccia pipes or collapse features that penetrate into and possibly through the Salado Formation, an igneous dike that cuts the Salado Formation, salt-dissolution fronts within or above the evaporite section, and slump, faulting, or other structural disturbances above, below, or within the evaporite section.

The seismic site-evaluation studies included two Vibroseis programs plus a review of all the petroleum industry data available in the area of interest. The 1977 seismic program was for the semidetained analysis of anomalies located during all earlier data studies. Any indications of slumping, faulting, and dissolution within the evaporite zones or any other structural departure from a "stable" condition in the post-Delaware deposits on the first review were subjected to additional seismic study. Forty-eight miles of extended frequency Vibroseis data were gathered over the anomalies in 1977. Sweeps to 110 Hz were utilized.

The results of the 1977 program indicated that in some areas the Castile and lower Salado Formations are deformed, a fact supported by a follow-up series of drill holes. Examples of the early interpreted anomalies with the normal petroleum industry field-recording parameters clearly show the need to modify the parameters to obtain shallow information. The latest Vibroseis data indicate the enhancement obtained by shortening the geophone and source intervals and by raising the sweep range to 100 Hz. The earlier observed anomalies are compared with later examples and, in all cases, the detailed studies give excellent definition as to salt deformation, timing of movement, and extent of structural effect on the salt beds.

Hern, J.L., D.W. Powers, and L.J. Barrows. 1979. *Seismic Reflection Data Report Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico*. SAND79-0264. Albuquerque, NM: Sandia National Laboratories. Vols. 1-2.

ABSTRACT: This report describes three seismic reflection (Vibroseis) surveys conducted from 1976 through 1978 by Sandia Laboratories to support investigations for the Waste Isolation Pilot Plant (WIPP). Volume I describes the purpose, field parameters, and data processing parameters. Volume II contains uninterpreted processed lines and shotpoint maps. Data interpretations will be the subject of the subsequent reports.

The data collected during these three surveys totals 77 line mi; 72 line mi of this are on or very near the WIPP Site. The first of the surveys (1976 SAN) covered 25 line mi and was conducted similarly to previous petroleum industry surveys in the area. 1976 SAN supplemented existing petroleum industry data. The two subsequent surveys (1977 X and 1978 Y) used shorter geophone spacings (110 ft), higher signal frequencies (up to 100 Hz), and higher data sampling rates (2 ms.) to better define the shallow zone (less than 4000 ft) of primary interest. 1977 X contained 47 line mi on or near the WIPP Site and over several structural features northwest of the site. 1978 Y contains 5 line mi over a one square mi area near the center of the WIPP Site. These data show increasing discrimination of shallow reflectors as data collection parameters were modified. Data tables of recording and processing parameters are included.

A fourth Vibroseis survey was conducted at the WIPP Site in 1978 by Grant Geophysical Company for Bechtel; the data are not in final form and are not included. Petroleum industry data and an inconclusive weight-drop survey, conducted in 1976, are also not included in this report.

Herrmann, W., and H.S. Lauson. 1981a. *Review and Comparison of Transient Creep Laws Used for Natural Rock Salt*. SAND81-0738. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A number of creep laws are reviewed that have been proposed to describe the transient creep of rock salt for use in design calculations of nuclear waste isolation and strategic petroleum reserve repositories. It is shown that they all have the same general form, and their ability to fit creep data for rock salt is tested. Four creep laws are found to fit the data for individual creep tests about equally well. Three of these include steady-state as well as transient creep, while the fourth, equivalent to power-law time hardening in the case of a creep test, does not. Extrapolations at constant stress and temperature of the three creep laws with steady-state creep essentially coincide for times longer than a few months, since the transient creep becomes negligible for such times. Power-law hardening, on the other hand, since it depends on time through a power less than one, predicts much smaller creep strains at very long times.

Herrmann, W., and H.S. Lauson. 1981b. *Analysis of Stress Drop in Multistage Creep Experiments: Predictions of Exponential Creep Law*. SAND81-1612. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Multistage creep experiments in which the stress or temperature are increased stepwise have been successfully analyzed previously using an exponential transient creep law. The analysis is generalized and implemented for an arbitrary number of stages including stress and temperature drops. Under certain conditions, the simple exponential creep law, evaluated from data for stages following increases in stress and temperature, predicts inverted transients for stages following decreases in stress or temperature. Comparisons of predictions with limited experimental data suggest that the simple exponential creep law is inadequate, and that

separate hardening and recovery processes need to be modelled to handle stress or temperature drops.

Herrmann, W., and H.S. Lauson. 1981c. *Analysis of Creep Data for Various Natural Rock Salts*. SAND81-2567. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Data from creep tests conducted on natural rock salt from Lyons, KS; Jefferson Island, LA; and Avery Island, LA are analyzed using an exponential transient creep law. Steady-state creep rates are fitted to a thermally activated stress-power law, while transient creep parameters are fitted to a model that relates them to steady-state creep rates. The results are compared with previous results for salt from the Salado Formation in the WIPP study area in southeastern New Mexico.

Herrmann, W., W.R. Wawersik, and H.S. Lauson. 1980a. *Creep Curves and Fitting Parameters for Southeastern New Mexico Bedded Salt*. SAND80-0087. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Existing experimental data for 68 separate creep tests on rock salt from the Salado Formation of southeastern New Mexico have been analyzed. The experimental conditions covered an intermediate temperature range from 22 to 200°C, and shear stresses from 1000 psi (7 MPa) to 6000 psi (31 MPa). Most tests exhibited both transient and steady-state creep. Data for individual tests have been fitted both to an exponential transient creep law expected to hold at high temperatures (> 200°C) and to a logarithmic transient creep law expected to hold at low temperatures (< 50°C). A few tests also exhibited accelerating creep, and these were fitted with an exponential creep law that included an accelerating term. The exponential and logarithmic fits yielded steady-state creep rates that were in good agreement with each other. Low temperature and low stress tests were fitted much better by the logarithmic creep law. At higher temperatures, both logarithmic and exponential creep laws were found to fit equally well. Tabulations of fitting parameters and plots of the experimental data and fitted creep curves are presented for each experiment, for use in further analysis.

Herrmann, W., W.R. Wawersik, and H.S. Lauson. 1980b. *Analysis of Steady State Creep of Southeastern New Mexico Bedded Salt*. SAND80-0558. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Steady-state creep rates have been obtained from a large suite of existing experimental creep data relating to bedded rock salt from the Salado Formation of southeastern New Mexico. Experimental conditions covered an intermediate temperature range from 22 to 200°C, and shear stresses from 1000 psi (7 MPa) to 6000 psi (31 MPa). An expression, based on a single diffusion controlled dislocation climb mechanism, has been found to fit the observed dependence of steady-state creep rate on shear stress and temperature, yielding an activation energy of 12 kcal/mole (50 kJ/mole) and a stress exponent of 4.9. Multiple regression analysis revealed a dependence on stratigraphy, but no statistically significant dependence on pressure or specimen size. No consistent dilatancy or compaction associated with steady-state creep was found, although some individual specimens dilated or compacted during creep. The steady-state creep data were found to agree very well with creep data for both bedded and dome salt from a variety of other locations.

Herrmann, W., W.R. Wawersik, and H.S. Lauson. 1980c. *A Model for Transient Creep of Southeastern New Mexico Salt*. SAND80-2172. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In a previous analysis, existing experimental data pertaining to creep tests on rock salt from the Salado Formation of southeastern New Mexico were fitted to an exponential transient creep law. While very early time portions of creep-strain histories were not fitted very well for tests at low temperatures and stresses, initial creep rates in particular generally being underestimated, the exponential creep law has the property that the transient creep strain approaches a finite limit with time, and is therefore desirable from a creep modeling point of view. In this report, an analysis of transient creep is made. It is found that exponential transient creep can be related to steady-state creep through a universal creep curve. The resultant description is convenient for creep analyses where very early time behavior is not important.

Herrmann, W., W.R. Wawersik, and S.T. Montgomery. 1984. "Review of Creep Modelling for Rock Salt," *Mechanics of Engineering Materials, International Conference on Constitutive Laws for Engineering Materials: Theory and Application, Tucson, AZ, January 10-14, 1983*. SAND82-2178C. New York, NY: John Wiley and Sons. 297-317.

ABSTRACT: Finite-element analyses are being used to help design mines or caverns in salt deposits for waste repositories and petroleum reserves. As these facilities differ greatly from previous mining, engineering design by finite element computer modeling is emphasized. Adequate constitutive models of salt creep are essential for these models. Several empirical creep laws (e.g., exponential, logarithmic, time-hardening) fit laboratory creep data well except for very early data (i.e., from the first few hours). The exponential creep law has a convenient mathematical form. The creep law, constructed from test data at constant stress and temperature, is assumed valid for changing stresses and temperatures. This assumption is partially confirmed by successive tests on the same specimen, though the dependence on stress history is more complicated than that included in the exponential law. The creep law also fits directly, or with some parameter changes, data from bedded and domal salt from other locations. The fit does not extend to temperatures or stresses above those normally encountered in repository designs. To incorporate the creep law into constitutive equations for arbitrary stress states, several sweeping assumptions are made that have not been checked in detail. The constitutive theories of a non-Newtonian viscous incompressible fluid and an elastic-viscous response give different results. Room closure data are reasonably modeled by either constitutive theory, but the elastic-viscous model fits better. These calculations are based on simple, highly idealized geologic conditions. Though these results are useful, it is still possible the fits are fortuitous. A variety of laboratory and in situ data are needed to refine the model. DWP

Higgins, K.L., and C.L. Stein. 1986. "Micro-Raman Spectroscopy of Fluid Inclusions in a Hopper Crystal in Halite," *Microbeam Analysis, 22nd Annual Meeting of the Microbeam Analysis Society, Albuquerque, NM, August 10-15, 1986*. SAND86-0237C. Vol. 21, 31-34.

ABSTRACT: Raman microscopy was used to analyze dissolved sulfate in fluid inclusions in a halite crystal from the Salado Formation, southeastern New Mexico. Sulfate waste determined along a cross-section of the crystal displayed primary fluid inclusion bands of a hopper crystal and large inclusions in recrystallized halite. Solutions of Na_2SO_4 in NaCl-saturated brine as a standard were analyzed, and data were fit with an equation by linear regression ($r = 0.97$). Repeated analysis of a natural fluid inclusion yielded an estimated standard deviation of $\pm 14\%$ relative.

Sulfate values ranged from about 13.5 parts per thousand (ppt) in the most recent (outside) band to about 2-3 ppt near the center of the halite hopper crystal. Within one band, values range from 3.1 to 6.3 ppt. The trends suggest primary growth and fluid entrapments rather than water diffusing along crystal growth planes. These hopper crystals must have grown in very shallow water, with periodic influxes of fresh seawater. This would explain continuous

precipitation of halite from a solution that is saturated with NaCl but with normal seawater sulfate concentrations.

Sulfate concentrations of the large inclusions adjacent to the hopper crystals are in the range of sulfate analyses of the hopper crystal inclusions. This supports explaining large fluid inclusions in recrystallized halite as the result of coalescing hopper crystal fluid inclusions. It is unnecessary to add freshwater to dissolve and precipitate the recrystallized halite.

The micro-Raman technique yields in situ and nondestructive measurements of the concentration of sulfate in fluid inclusions in optically transparent crystals. The results can be used to interpret mineral growth. These data were previously very difficult to obtain because of the extremely small size of the fluid inclusions in hopper crystals. DWP

Hill, L.R. 1980. "Characterization of a Site in Bedded Salt for Isolation of Radioactive Wastes," *Underground Disposal of Radioactive Wastes*. IAEA-SM-243/38. Vienna, Austria: International Atomic Energy Agency. Vol. 1, 269-287. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The first radioactive waste repository in the USA is scheduled to begin operation in the 1980s. Plans are to locate this facility, the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico as a repository for transuranic (TRU) waste from past and current US defense programs. In addition, the WIPP would provide a research facility to examine, on a large scale, the interactions between bedded salt and high-level radioactive waste. The US Department of Energy (DOE) has recommended that WIPP also be used to demonstrate surface and subsurface methods of handling, storing, and disposing of up to 1000 canisters of spent reactor fuel; however, a decision to implement this recommendation has not been made. The proposed underground storage facilities are to be placed near the middle of a 3600-ft-thick sequence of relatively pure evaporite strata containing primarily rock salt. Within this sequence, the formation richest in rock salt is nearly 2000 ft thick and contains the two proposed underground storage levels at depths near 2100 ft and 2650 ft. In the past four years, many techniques have been used to characterize the WIPP Site. Geophysical surveys include about 140 line mi of new seismic reflection data and over 9000 resistivity measurements. More than 50 bore holes have been drilled. Hydrologic studies of the proposed site and adjacent area have been directed toward a quantitative evaluation of the salt-dissolution process, the hydrogeologic parameters affecting groundwater movement, and the major elements of surface and groundwater quality as related to water-resource use. Potash salt and natural gas are two potential resources of economic significance under the WIPP Site. Potassium salts occur in a variety of mineral types, but only sylvite and langbeinite are currently economic. It is believed that a langbeinite deposit located in the northeast quadrant of the WIPP Site could be profitably mined using today's technology. Several deposits of sylvite are present in the WIPP Site, but none would be developed under today's economic conditions. Natural gas is estimated to be economically recoverable from the site area; however, its value is insignificant compared to total US reserves. Laboratory and in situ experimental programs are to be performed before the WIPP Facility is operational and will address such issues as brine migration, corrosion, hole plugging, and structural deformations. These programs are aimed at refining and supplementing information gathered to increase confidence in the use of this site. The information gathered will also support repository design and long-term safety assessment.

Hinkebein, T.E., and P.F. Hlava. 1978. *Microstructural Interactions of Geologic Media with Waste Radionuclides*. SAND78-0108. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A preliminary investigation of the microstructure of four geologic media was undertaken to examine the interaction of Cs, Sr, Gd, and U with those media. Since K_D measurements often vary by more than an order of magnitude on rocks of the same strata

separated by several feet, it was probable that minor rock components play an important role in radionuclide sorption. A qualitative analysis of the rock surfaces after equilibration with solutions of Cs^+ , Sr^{++} , Gd^{+++} and UO_2^{++} revealed that clay minerals are responsible for all important sorption that takes place on the rocks studied (Magenta Dolomite, Bell Canyon silt stone, Eleana shale, and clay-bearing halite). Thus it is concluded that a relatively small portion of these rocks is actively responsible for sorption characteristics. Gd was bound on all samples, probably as Fe bearing chlorites. Cs was strongly held on the Eleana shale, probably by an illite. Although uranium was associated with an unidentified clay in the halite sample, uranium sorption probably occurred as UO_2CO_3 , which would not significantly retard uranium movement at trace concentrations. Similarly Sr was retained only as SrSO_4 on Magenta and this mechanism is not significant at trace levels. These analyses were performed by correlating electron microprobe elemental distribution photomicrographs with x-ray analyses of the four rocks.

Hinkebein, T.E., and P.F. Hlava. 1979. "Interactions of Simulated Waste Radionuclides and Rocks," *Scientific Basis for Nuclear Waste Management, Proceedings of the Symposium on 'Science Underlying Radioactive Waste Management,' Materials Research Society Annual Meeting, Boston, MA, November 28-December 1, 1978.* Ed. G.J. McCarthy. New York, NY: Plenum Press. Vol. 1, 419-422.

ABSTRACT: Samples from three cores of rocks in southeastern New Mexico and a core of argillite from the Eleana Formation, Nevada Test Site (NTS), were tested with solutions containing Cs, Sr, Gd, and U to simulate waste radionuclides sorbing on minerals in these rocks. The elements were mapped on surfaces by electron microprobe to establish and photograph the relationship to mineral phases. Cs was detectable only on Eleana samples. Gd sorbed on all samples, probably on chamosite or chlorite. Sr was sorbed by samples from the Magenta Dolomite Member (Rustler Formation), sandstone from the Bell Canyon Formation, and dirty salt from the Salado Formation. U sorbed on the Magenta and salt samples. Solutions were highly concentrated, leading to unlikely compounds at levels of tracer studies. At tracer level studies, microprobe methods and autoradiography should help show active sorptive minerals and mechanics. DWP

Hohlfelder, J.J. 1979. *Measurement of Water Lost From Heated Geologic Salt.* SAND79-0462. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report describes three methods used to measure the rate at which water is lost from heated geologic salt. The three methods were employed in each of a series of "proof" tests that were performed to evaluate instrumentation designed to measure the water-loss rate. We found that the water lost from heated, 1-kg salt specimens that were measured according to these three methods was consistent to within an average 9%.

Hohlfelder, J.J. 1980. *Salt Block II: Description and Results.* SAND79-2226. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A description of and results from the Salt Block II experiment, which involved the heating of and measurement of water transport within a large sample of rock salt, are presented. These results include the measurement of water released into a heated bore hole in the sample as well as measured temperatures within the salt. Measured temperatures are compared with the results of a mathematical model of the experiment.

Hohlfelder, J.J. 1981. *Volatile Content of Rock Salt.* SAND79-2349. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Measurements of the volatile content of rock salt are described. Results from these measurements are presented and compared with results from earlier measurements made on smaller samples of similar material. Possible sources of the volatile matter are discussed.

Hohlfelder, J.J., and G.R. Hadley. 1979. "Laboratory Studies of Water Transport in Rock Salt," *Letters in Heat and Mass Transfer*. SAND79-1044J. Vol. 6, no. 4, 271-279.

ABSTRACT: The transport of water through rock salt as a result of heating is examined experimentally and a new model is proposed to explain the data. The experiment consists of the measurement of water loss rate as a function of time for three 1 kg blocks of southeastern New Mexico rock salt. Each block was heated for approximately three days with maximum temperature ranging from 165 to 250°C. The resulting data is qualitatively explained by a continuum model of Darcian flow of water vapor from a receding evaporation front. The model includes the prediction of thermal stresses that are calculated to crack the specimens during heater shutdown giving an anomalously high water loss spike in agreement with the data.

Hohlfelder, J.J., and W.M. McMurtry. 1983. *Water Sources in Southeast New Mexico (SENM) Rock Salt*. SAND82-0530. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In this report the two principal components of water in southeast New Mexico rock salt are determined. The water in this material that is caused by fluid inclusions is shown to be $0.30 \pm 0.03\%$. The total water content of this material, $0.65 \pm 0.05\%$, is consistent with earlier measurements of similar material.

Hohlfelder, J.J., A.G. Beattie, and H.C. Shefelbine. 1982. *Water Release and Mechanical Failure in Heated Geologic Salt*. SAND81-1488. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The rate of water release and the acoustic emission rate were measured in heated specimens of geologic salt. These measurements show that changes in thermal power applied to the salt cause increased acoustic emission from the salt. The acoustic emission is caused by the salt's cracking. The salt's cracking enhances its prompt release of water.

Holcomb, D.J. 1982. "Consolidation of Crushed Salt Backfill for Conditions Appropriate to the WIPP Facility," *EOS Transactions, American Geophysical Union*. SAND82-2088A. Vol. 63, no. 45, 1111. (Abstract Only).

ABSTRACT: Mechanical properties of granulated rock salt are of interest to the Waste Isolation Pilot Plant (WIPP) Project because native salt from the excavations will probably be used as backfill around the waste packages and as void filler in storage rooms, shafts, and other openings. Backfill properties will be an important factor in controlling room closure rates and local permeability. To fill the need for data on time dependent compaction of crushed salt, a series of tests has been done to measure the compaction as a function of time, temperature, and pressure. Tests were done for a range of temperatures from 21 to 100°C and pressures from 1.72 to ≥ 1 MPa, under quasistatic and creep conditions. All tests were done under pure hydrostatic conditions. The crushed salt, with a maximum particle size of 1 cm, was produced by a rock crusher. All tests were done under nominally dry conditions, which means the only water present was the $\approx .5\%$ water content of the salt. The first major conclusion is that creep consolidation under hydrostatic stresses proceeds at a rate of approximately $.01/t$, where t is the time in seconds (t must be greater than 100 seconds). Total

creep consolidation is a function of $\log(t)$ and is very slow. The second major conclusion is that consolidation is not very temperature dependent in the range 21 to 100°C. The final major conclusion is that on the basis of the present data, the mechanical response of crushed salt backfill can be modeled primarily using quasistatic results because time and temperature effects are small. These conclusions are tested only for times up to 3×10^5 seconds. The major question is whether the creep consolidation rate will continue to decelerate so rapidly. If it does, then creep may be significant.

Holcomb, D.J. 1987. "Consolidation of Crushed Salt With Added Water," *EOS Transactions, American Geophysical Union*. Vol. 68, no. 44, 1479. (Abstract Only).

ABSTRACT: Long-term mechanical and hydrological properties of reemplaced crushed salt will be important in determining the effectiveness of sealing the openings at the Waste Isolation Pilot Plant (WIPP), a nuclear waste disposal facility being constructed near Carlsbad, NM. Seals at WIPP are intended to prevent circulation of intruding groundwater or fluids introduced by accidentally drilling into the repository at some future date. For short-term seals, various cementitious materials will be used, but there is no way to guarantee survival of the seals in contact with salt and brine for the long term. It has been hypothesized that reemplaced crushed salt would be consolidated by the creep closure of the drifts to a state where permeability was comparable to the surrounding unmined salt. If that were shown, then the crushed salt would form an ideal seal for the waste panels and drifts, being compatible with the intact salt and highly redundant.

A program was designed to measure the time-dependent consolidation rates and permeability under conditions expected to be encountered in WIPP. Since it is known that creep on intact salt is sensitive to small amounts of water, it was decided to examine the effects of adding a few %, by mass, of water. The completed testing program confirms the effectiveness of small amounts of water in accelerating the consolidation process. At pressures from 5 to 40% of the in situ stress at WIPP (17 MPa), the extrapolated results show that with the added water, consolidation rates are sufficiently rapid and that the backfilled salt will form an effective seal within times on the order of decades. Consolidation time is not determined by the properties of the crushed salt, but by how long it takes the drifts to creep sufficiently to remove the initial void space in the crushed salt.

These results demonstrate that under conditions of temperature and stress relevant to the WIPP the permeability of reemplaced crushed salt with added water will be reduced to values comparable to the unmined salt within a few decades, allowing the salt to function as a seal.

Holcomb, D.J. 1988. "Cross-Hole Measurements of Velocity and Attenuation to Detect a Disturbed Zone in Salt at the Waste Isolation Pilot Plant," *Key Questions in Rock Mechanics: Proceedings of the 29th US Symposium, University of Minnesota, Minneapolis, MN, June 13-15, 1988*. Eds. P.A. Cundall, R.L. Sterling, and A.M. Starfield. SAND87-3016C. Brookfield, VT: A.A. Balkema. 633-640.

ABSTRACT: Cross-hole ultrasonic measurements were made at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM to delineate the disturbed zone around drifts and rooms. Using compressional mode waves it was found that there was a small decrease in velocity and a large increase in attenuation immediately after the test room was mined. Disturbances extended at least 3 m from a room with a width of 5.5 m. The results are interpreted as resulting from the introduction of about 0.5% crack-like, pore space.

Holcomb, D.J., and D.W. Hannum. 1982. *Consolidation of Crushed Salt Backfill Under Conditions Appropriate to the WIPP Facility*. SAND82-0630. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Mechanical properties of granulated rock salt are of interest to the Waste Isolation Pilot Plant (WIPP) Project because native salt from the excavations will probably be used as backfill around the waste packages and as void filler in storage rooms, shafts, and other openings. Backfill properties will be an important factor in controlling room closure rates and local permeability. To fill the need for data on time-dependent compaction of crushed salt, we have done a series of tests to measure the compaction as a function of time, temperature, and pressure. Tests were done for a range of temperatures from 21 to 100°C and pressures from 1.72 MPa, under quasistatic and creep conditions. All tests were done under pure hydrostatic conditions. A rock crusher was used to produce crushed salt with a maximum particle size of 1 cm. All tests were done under nominally dry conditions, which means the only water present was the ~5% water content of the salt. Creep consolidation under hydrostatic stresses proceeds at a rate of approximately .01/t, where t is the time in seconds. Total creep consolidation is a function of log(t) and is very slow. Consolidation is not very temperature dependent in the range 21 to 100°C. The conclusions are tested only for times up to 3×10^5 sec. The major question is whether the creep consolidation rate will continue to decelerate rapidly. If rapid deceleration continues, then for the time periods of interest, creep consolidation will be small compared to the consolidation produced by quasistatic pressurization.

Holcomb, D.J., and M. Shields. 1987. *Hydrostatic Creep Consolidation of Crushed Salt With Added Water*. SAND87-1990. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Mined salt from the WIPP repository is a candidate material for use as backfill and for sealing at the WIPP, if it can be demonstrated that, in response to time-dependent room, drift and shaft closure, the salt will reconsolidate sufficiently to serve as an effective seal component. Small quantities of brine are present at the WIPP, and water is known to increase the rate of consolidation of salt under pressure. In this study, the effects of addition of small amounts of water (0.5 to 3 wt percent) on the consolidation rate of crushed WIPP salt were investigated in the laboratory. Fourteen experiments were conducted at room temperature, and hydrostatic pressures of either 1.72 or 3.44 MPa. In addition, one multistage experiment was carried out at pressures ranging from 0.34 to 6.9 MPa. Gas permeability measurements were performed on the multistage specimen at various points in the experiment, and similarly on two of the single-stage consolidation specimens.

Relative to nominally dry salt, water was found to increase consolidation rates under all conditions. Within the range of water contents investigated, no lower threshold for the accelerating effect of water was detected. At a fractional density of about 0.91, the multistage consolidation specimen exhibited a gas permeability of about 10^{-20}m^2 , which approaches that of the intact salt formation, 10^{-21}m^2 . The mechanism by which water accelerates the consolidation of crushed salt is unknown, but may be related to the general phenomenon of pressure solution. DWP

ANNOTATION: The abstract for Holcomb and Shields was written by D. Zeuch (Sandia National Laboratories) for inclusion in this bibliography.

Holcomb, D.J., and D.H. Zeuch. 1988. *Consolidation of Crushed Rock Salt, Part I: Experimental Results for Dry Salt Analyzed Using a Hot-Pressing Model*. SAND88-1469. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Mechanical properties of granulated rock salt are of interest in the underground disposal of nuclear waste because native salt from the excavations will be used as part of the backfill around the waste packages and in storage rooms, shafts, and other openings. Backfill properties will be important in controlling room closure rates and local permeability. To obtain data on instantaneous and time-dependent compaction of crushed salt, we have done tests to measure the compaction as a function of time, temperature, and pressure. Tests were done for a range of temperatures from 21 to 100°C and pressures from 1.72 to 21 MPa, under quasistatic and creep conditions. All tests were done under hydrostatic loading, and also under nominally dry conditions, which means the only water present was the ~0.2% water content of the salt. We found that volumetric creep consolidation under hydrostatic stress proceeds at a rate of approximately 0.01 t^{-1} , where t is the time in seconds. Creep consolidation is a function of $\log(t)$ and is slow. Consolidation is not very temperature dependent in the range 21 to 100°C. Results can be fit reasonably well by a model developed to describe isostatic hot-pressing.

Holt, R.M. 1988. *The Depositional Environments of the Late Permian Rustler Formation, in the Vicinity of the Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* MS Thesis. El Paso, TX: University of Texas at El Paso.

ABSTRACT: The Late Permian Rustler Formation is the youngest of three evaporite-bearing formations in the Delaware Basin. The depositional environments that formed the Rustler have never been investigated in a detailed, systematic way. The purpose of this study is to describe the detailed sedimentology and interpret the depositional environments of the Rustler. The Rustler was examined in detail in two shafts at and in many cores from the vicinity of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico.

The Rustler consists of sulfate, carbonate, halite, and clastic rocks. The Rustler exhibits abundant primary depositional textures and fabrics, and shows the effects of several post-depositional alterations. Rustler sulfates and carbonates are areally extensive and vary little. Major lateral changes occur in those zones containing halite and mudstone. The Rustler thickens considerably in the direction of a depocenter southeast of the WIPP Site. Variations in Rustler thickness are attributed to those stratigraphic intervals containing halite.

The depositional environments of the various units within the Rustler were reconstructed using a sedimentological approach. Carbonate and sulfate units within the Rustler were nearly all deposited subaqueously following a transgression or freshening event. Halite and mudstone units accumulated slowly because of repeated solution and reprecipitation of halite in salt pan and marginal mudflat environments. For this reason, the halite and mudstone accumulation was controlled by subsidence in the depocenter. Syndepositional dissolution was common during the deposition of halite and mudstone units. Small scale dissolution, often reported in halite from both modern and ancient evaporite environments, was common, and on a larger scale, syndepositional dissolution drastically modified the sedimentary sequence.

Rustler deposition was characterized by rapid transgressions of fresher water over very low topography, deposition of nonhalite sediment from a fresher fluid accompanied by rapid desiccation and a salinity increase, and slower subsidence-controlled deposition of clastics and halite within the depocenter, abruptly terminated by another freshening event. This style of deposition repeats itself several times throughout the Rustler sequence and begins with the initial marine transgression over the Salado.

Holt, R.M., and R.L. Beauheim. 1990. "Depositional and Diagenetic Controls on Transmissivity Variations in the Culebra Dolomite Near the WIPP Site," *EOS Transactions, American Geophysical Union*, Vol. 71, no. 17, 511. (Abstract Only).

ABSTRACT: The Culebra Dolomite Member of the Late Permian Rustler Formation is the most transmissive hydrologic unit overlying the Waste Isolation Pilot Plant (WIPP) Site, an underground repository constructed in bedded evaporites for defense-related transuranic (TRU) waste. Culebra transmissivities vary over seven orders of magnitude across the WIPP Site area. Higher transmissivities are related to fracturing.

Examination of core, outcrops, and shaft exposure have led to the following interpretation of the geologic history of the Culebra. The Culebra was deposited in a shallow lagoon following a rapid marine transgression over saltpan deposits. In the lower part of the Culebra, abundant sulfate nodules grew displacively within the pelletal muds immediately following deposition. Circulation of groundwater through the Culebra was restricted until the Cenozoic. In the Cenozoic, progressive west to east unloading caused stress-relief fracturing, allowing improved circulation of groundwater through the Culebra. Progressive west to east dissolution of the sulfate nodules and other porefilling sulfate followed and increased permeability. Large vugs resulted from the dissolution of these nodules. These vugs collapsed, further increasing permeability. Disruption and collapse following dissolution of evaporites underlying the Culebra west of the WIPP Site further increased permeability in that region.

Based upon these relationships, a conceptual hydrogeologic model for the Culebra was developed, and six hydrogeologic zones were identified and their spatial distributions interpreted. These interpretations provide the basis for assigning hydraulic properties for future numerical modeling of groundwater flow within the Culebra.

Holt, R.M., and D.W. Powers. 1984. *Geotechnical Activities in the Waste Handling Shaft, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. WTSD-TME 038. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant.

ABSTRACT: The Waste Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site is an enlargement of the drilled, Site and Preliminary Design Validation (SPDV) ventilation shaft. Geotechnical activities in the waste shaft were designed to confirm the SPDV ventilation shaft mapping results and to provide additional information about identified zones of interest. The activities included identification of instrument locations, geologic inspections of the exposed shaft surface during sinking operations, reconnaissance geologic mapping of the waste shaft sump, and detailed geologic mapping in identified zones of interest. These activities were carried out concurrently with construction.

The results of the geologic inspections in the waste shaft and the reconnaissance geologic mapping in the waste shaft sump correlate well with previous characterizations. However, the detailed 360° geologic mapping performed in several zones of interest did not reveal post-depositional dissolution features thought to occur at several stratigraphic horizons in the Rustler Formation at the WIPP Site. At the waste shaft, zones previously identified as dissolution residues in nearby bore holes contained pronounced primary sedimentary features.

Holt, R.M., and D.W. Powers. 1986a. "Rustler Formation: Evaporite End Stages of a Continental Basin," *Sediments Down-Under, 12th International Sedimentological Congress, Canberra, Australia, August 24-31, 1986*. 141-142. (Abstract Only).

ABSTRACT: The Late Permian Rustler Formation records the closing evaporitic stages in the development of a North American cratonic basin. The Rustler is the youngest of three evaporite formations and culminates a 1500-m sequence of bedded evaporites in the Delaware Basin of New Mexico and Texas. The Rustler consists of interbedded sulfates, halite, carbonates, and clastics.

The lower part of the Rustler consists primarily of clastic rock and minor chemical precipitates. Invertebrate fossils near the base and locally intense bioturbation suggest a

significant rise in sea level and an accompanying decrease in salinity from the underlying evaporites (Salado Formation). These rocks are the result of the vertical succession of a slightly saline lagoon, saline mudflat/salt pan, and a saline lagoon.

The upper Rustler consists of carbonate, sulfate, and minor amounts of clastics locally associated with significant volumes of halite. The vertical and lateral associations of these rocks and their features are interpreted as forming by the interaction of sabkha environments with saline lagoons and saline mudflats/salt pans. The margins of saline mudflats/salt pans show syndepositional erosion and dissolution caused by freshwater influxes and local base level changes.

The ending stages of deposition in the Delaware Basin record both an environmentally variable sequence (characterized by rapidly prograding and retrograding environments) and areally less variable environments similar to those of the underlying Salado Formation. Basin subsidence was episodic and local, creating marginal effects including syndepositional dissolution and erosion. Pre-Rustler evaporites display consistent bedding and rock types over the extent of the Delaware Basin, reflecting relatively constant conditions.

Holt, R.M., and D.W. Powers. 1986b. *Geotechnical Activities in the Exhaust Shaft*. DOE-WIPP 86-008. Carlsbad, NM: US Department of Energy.

ABSTRACT: The Exhaust Shaft at the Waste Isolation Pilot Plant (WIPP) Site was a conventional mining-slashing enlargement of an upreamed shaft. Geotechnical activities provided additional confirmation of the stratigraphic details of the strata overlying the WIPP underground facility, provided details about identified zones of interest, confirmed the geology of planned instrument levels and locations, and provided a basis for field adjustment and modification of key and aquifer seal design. The activities were concurrent with construction during the period from July 16, 1984, through January 18, 1985.

The Exhaust Shaft penetrates thin surficial deposits and five stratigraphic units: the Quaternary Gatuña Formation, the Triassic Santa Rosa sandstone, and Permian age Dewey Lake Redbeds, Rustler Formation, and Salado Formation. The entire shaft section from the surface to the facility level was geologically mapped. Ten preselected zones of special interest were mapped in detail. Gypsum-filled fracture systems in the Dewey Lake were mapped in detail in three zones: 195.0 to 210.0 ft, 269.0 to 280.5 ft, and 353.5 to 375.0 ft.

Seven zones, in or adjacent to the Rustler Formation, were mapped in detail: the Dewey Lake/Rustler contact (546.5 ft), the Forty-niner member claystone (575.5 to 586.5 ft), the Magenta Dolomite Member (602.5 to 627.0 ft), the Tamarisk member claystone (689.0 to 695.5 ft), the Culebra Dolomite Member (713.5 to 736.0 ft), the upper portion of the unnamed lower member (736.0 to 800 ft), and the Rustler/Salado Formation contact and the keyway (845.0 to 912.0 ft). The stratigraphy in the Exhaust Shaft correlates well with that in the Waste Handling Shaft.

Minor fluid-producing zones were observed within the Magenta and Culebra Dolomite Members. The shaft key and aquifer seals were adjusted downward between seven and nine feet as a result of the observed geology.

DWP

Holt, R.M., and D.W. Powers. 1987a. "Rustler Formation in the Waste Handling and Exhaust Shafts, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico," *The Rustler Formation at the WIPP Site, Report of a Workshop on the Geology and Hydrology of the Rustler Formation as it Relates to the WIPP Project*. Ed. L. Chaturvedi. EEG-34; DOE/AL/10752-34. Santa Fe, NM: Environmental Evaluation Group. 26-35.

ABSTRACT: The Permian Rustler Formation has been mapped in considerable detail in the waste and exhaust shafts at the WIPP site. Various bedding and sedimentary features have been described from all members of the formation in these shafts. In particular, the claystone bed within the Forty-niner Member displays bedding and depositional features that contrast sharply with previous interpretations of this unit as a dissolution residue. The Rustler is being completely re-evaluated, based on the revised interpretation of its dispositional environments, to ascertain the extent of dissolution of the Rustler in the vicinity of the WIPP. DWP

ANNOTATION: The background reports for this paper are found in Holt and Powers (1984, 1986b); the followup study is reported in Holt and Powers (1988).

Holt, R.M., and D.W. Powers. 1987b. "The Permian Rustler Formation at the WIPP Site, Southeastern New Mexico," *Geology of the Western Delaware Basin, West Texas and Southeastern New Mexico*, Eds. D.W. Powers and W.C. James. El Paso Geological Society Guidebook 18. El Paso, TX: El Paso Geological Society. 140-148.

ABSTRACT: The Permian Rustler Formation has long been interpreted as having undergone extensive dissolution at depth as well as at the surface. The Rustler has been examined in detail in two shafts for the Waste Isolation Pilot Plant (WIPP) Project east of Carlsbad, NM. Bedding and primary sedimentary structures are abundant through the formation. Invertebrate fossils, mainly pelecypods, were found in the basal member. The formation was deposited in near-normal marine to saline mudpan environments. The Rustler was considered in this location to be composed partly of the residues from dissolution halite in the formation. At the shafts, no collapse structures, chaotic bedding, breccias, or other features are directly attributed to late dissolution. Well-preserved primary sedimentary structures and lack of dissolution features indicate that halite was never present in some zones in the Rustler. Lateral change of thickness of beds and the absence of halite have been used as criteria for the interpretation of dissolution of evaporites. These may be necessary, but not sufficient, criteria.

Holt, R.M., and D.W. Powers. 1988. *Facies Variability and Post-Depositional Alteration Within the Rustler Formation in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico*. DOE/WIPP 88-004. Carlsbad, NM: US Department of Energy.

ABSTRACT: The Late Permian Rustler Formation is the youngest of three evaporite-bearing formations in the Delaware Basin. The depositional environments that formed the Rustler and the post-depositional events that subsequently modified the Rustler have never before been investigated in a detailed, systematic way. The purpose of this study is to describe the detailed sedimentology and to interpret the depositional environments of the Rustler. Another objective of this study is to reassess the extent of Rustler dissolution. The reconstructed depositional environments help to bound the extent and relative timing of dissolution. Existing literature was surveyed to distill criteria by which dissolution can be recognized. Microscopic examination of diagenetic alteration of the Rustler rounds out the evidence.

The Rustler was examined in detail in two shafts and many cores from the vicinity of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. Nearly 600 geophysical logs from bore holes in southeastern New Mexico were interpreted, and the stratigraphy and lithology over a larger study area were related to units observed in cores and shafts from the WIPP Site.

The Rustler consists of sulfates, carbonates, halite, and clastic rocks. Rustler sulfates and carbonates are areally extensive and vary little. Those zones containing halite and mudstone laterally change greatly in thickness and lithology. The Rustler thickens considerably toward a depocenter east and southeast of the WIPP Site. Most of the variation in Rustler thickness is attributed to those stratigraphic intervals containing halite.

The depositional environments of the various units within the Rustler were reconstructed using a sedimentological approach. Carbonate and sulfate units were deposited subaqueously following a transgression or freshening event. Among the diagnostic features for subaqueous deposition are algal beds and laminations, bioturbation, fossils, gypsum growth textures, and cross-bedding sequences. Halite and mudstone units accumulated slowly because of repeated solution and reprecipitation of halite in salt pan and marginal mudflat environments. Subsidence in the depocenter allowed halite to accumulate and be preserved. Halite commonly was dissolved syndepositionally from parts of the halite and mudstone units. Small scale dissolution, often reported in halite from both modern and ancient evaporite environments, was common, and, on a larger scale, syndepositional dissolution drastically modified the sedimentary sequence. Diagnostic features include pedogenic clay skins, incorporative gypsum, incorporative and displacive halite in various stages of growth and solution, and bedding. Smeared intraclast textures are a newly described feature formed by repeated solution of halite in mudflat environments.

Several times during Rustler deposition, relatively fresh water transgressed rapidly over very low topography. Carbonate or sulfate formed subaqueously as evaporation proceeded. Salinity increased and the brine margins retracted as desiccation continued. Marginal clastics and a halite lens in the depocenter accumulated relatively slowly and were controlled by subsidence and cannibalism of soluble minerals at the margins. Deposition of these saline facies was abruptly ended by another freshening event. This style of deposition began with an initial marine transgression over the Salado and was repeated several times.

The Rustler in, and adjacent to, Nash Draw has been brecciated because of solution of the Salado. Breccias were superimposed on Rustler rocks, including clastic rocks exhibiting smeared intraclasts that are caused by syndepositional dissolution. These breccias have a stratiform base, and the degree of brecciation diminishes upwards. These features are consistent with post-depositional dissolution of a bed at depth as described in the literature. Some of these areas are now also being affected by karst processes (as at WIPP-33).

Most of the immediate site area is unaffected by large-scale post-depositional dissolution. Halite was removed from parts of the lower unnamed member, Tamarisk Member, and Forty-niner Member before overlying units were deposited. Minor brecciation at boreholes H-3 and H-11 indicates some dissolution and collapse after the Rustler was deposited. These bore holes are in marginal areas of the depositional environments where some halite precipitated in mudstone units. Part of the Tamarisk Member is brecciated in WIPP-13. Partial core from WIPP-13 limits interpretation of this anomaly. Halite is not predicted for the Tamarisk Member at this location, but the brecciation may have begun below the Tamarisk.

The Rustler has been altered extensively at the microscopic scale. Petrographic evidence demonstrates mainly volume-for-volume replacement of minerals, especially sulfates. Overgrowths on some clastic gypsum grains preserve shapes, suggesting the gypsum may never have inverted to anhydrite. These phenomena help limit hypotheses of the effects of the volume changes associated with sulfate mineral inversion.

Holt, R.M., D.W. Powers, R.L. Beauheim, and M.E. Crawley. 1988. "Origin of Transmissivity Variations in the Culebra Dolomite Near the Waste Isolation Pilot Plant Site, Southeastern New Mexico," *Ground Water*. Vol. 26, no. 6, 790. (Abstract Only).

ABSTRACT: The Culebra Dolomite Member of the Rustler Formation is the most transmissive hydrologic unit overlying the Waste Isolation Pilot Plant (WIPP) repository horizon. The WIPP is a Department of Energy (DOE) facility constructed in bedded salt for the purpose of isolating defense-generated transuranic (TRU) waste. The Culebra is considered a potential pathway for the transport of radionuclides should a repository breach ever occur.

The Culebra is a thin (10 m), areally extensive dolomite unit underlain and overlain by evaporites. It crops out west and southwest of the WIPP in a karst valley. The Culebra was

last actively recharged during the Pleistocene from areas south and west of WIPP. Both gypsum-filled and open intercrystalline, vuggy, and fracture porosity are present. Permeability is primarily along fractures.

The ratio of open to gypsum-filled porosity increases progressively from east of the WIPP toward the west and southwest. High transmissivities generally occur where there is less gypsum-filled porosity. Transmissivities vary from about $1 \times 10^{-3} \text{ m}^2/\text{sec}$ in the karst valley and south of the WIPP to $2 \times 10^{-9} \text{ m}^2/\text{sec}$ 5 km east of the WIPP. These variations probably reflect the progressive dissolution of gypsum fracture fillings away from paleorecharge areas. Local variations in transmissivity are attributed to dissolution of soluble rocks above and below the Culebra. In the vicinity of the karst valley and along the course of the ancestral Pecos River, subsidence following dissolution of halite from the underlying Salado Formation has increased Culebra transmissivity.

Hunter, R.L. 1985a. "A Preliminary Regional Water Balance for the WIPP Site and Surrounding Area," *EOS Transactions, American Geophysical Union*. Vol. 66, no. 18, 263. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) water-balance study area defined here comprises about 2,000 mi^2 in Eddy and Lea Counties, southeastern New Mexico. Inflows to the study area are precipitation ($\sim 1.4 \times 10^6$ acre-ft/year), surface water ($\sim 1.1 \times 10^5$ acre-ft/year), water imported by municipalities and industries ($\sim 3 \times 10^4$ acre-ft/year), and groundwater (volume not estimated). Outflows from the area are evapotranspiration ($\sim 1.5 \times 10^6$ acre-ft/year), surface water ($\sim 6.5 \times 10^4$ acre-ft/year), and possibly some groundwater. The volume of surface and groundwater stored in Nash Draw has increased since the beginning of potash refining. Regional groundwater flow in aquifers above the Salado Formation is from the northeast to the southwest, although this pattern is interrupted by Clayton Basin, Nash Draw, and San Simon Swale. The Pecos River is the only important perennial stream. Most of the area has no integrated surface-water drainage.

The sparsity of precipitation data gives rise to an uncertainty in precipitation of 6%, $\sim 70,000$ acre-ft/year. This volume is greater than most factors in the water balance. The uncertainty in evapotranspiration is similar. Much larger uncertainties in smaller factors are of lesser importance. Poorly located groundwater divides, inadequate geohydrologic data, and lack of preindustrial baseline data contribute uncertainty to the water balance.

It seems from the available data that approximately 1,600 mi^2 of the study area are hydrologically separate from Nash Draw and the WIPP Site. Groundwater north of Highway 180 apparently discharges into Clayton Basin and evaporates. Water in the San Simon Swale apparently percolates downward and flows to the southeast. This preliminary water budget, although based on limited data, can provide guidance for further study.

Hunter, R.L. 1985b. *A Regional Water Balance for the Waste Isolation Pilot Plant (WIPP) Site and Surrounding Area*. SAND84-2233. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) water-balance study area defined here comprises $\sim 2000 \text{ mi}^2$ in Eddy and Lea Counties, southeastern New Mexico. Inflows to the study area are precipitation (about 1.47×10^6 acre-ft/year), surface water (about 1.1×10^5 acre-ft/year), water imported by municipalities and industries (about 3×10^4 acre-ft/year), and groundwater (volume not estimated). Outflows from the area are evapotranspiration (about 1.5×10^6 acre-ft/year), surface water (about 1.2×10^5 acre-ft/year), and possibly some groundwater. The volume of surface and groundwater in storage in Nash Draw has increased since the beginning of potash refining. Regional groundwater flow in aquifers above the Salado Formation is from the northeast to the southwest, although this pattern is interrupted by Clayton Basin, Nash Draw, and San Simon Swale. The Pecos River is the only important perennial stream. Most of the area has no integrated surface-water drainage.

The available data suggest that ~1600 mi² of the study area are hydrologically separate from Nash Draw and the WIPP Site. Groundwater north of Highway 180 apparently discharges into Clayton Basin and evaporates. Water in San Simon Swale apparently percolates downward and flows to the southeast. Data are inadequate to create a water budget for the Nash Draw-WIPP Site hydrologic system alone, although an attempt to do so can provide guidance for further study.

Hunter, R.L. 1987. "A Regional Water Balance for the WIPP Site and Surrounding Area," *The Rustler Formation at the WIPP Site. Report of a Workshop on the Geology and Hydrology of the Rustler Formation as it Relates to the WIPP Project*. Ed. L. Chaturvedi. EEG-34; SAND84-2233C. Santa Fe, NM: Environmental Evaluation Group. 58-70.

ABSTRACT: A water-balance study around the Waste Isolation Pilot Plant (WIPP) covers about 2000 mi² in Eddy and Lea Counties of southeastern New Mexico. Inflows include precipitation (about 1.47×10^6 acre-ft/year), surface water (about 1.1×10^6 acre-ft/year), water imported by municipalities and industries (about 3×10^4 acre-ft/year), and groundwater (not estimated). Outflows are evapotranspiration (about 1.5×10^6 acre-ft/year), surface water (about 1.2×10^6 acre-ft/year), and possibly some groundwater. Surface and groundwater stored in Nash Draw has increased since potash refining began. Regional groundwater flow in most aquifers above the Salado Formation is from northeast to southwest; this pattern is interrupted by Clayton Basin, Nash Draw, and San Simon Swale. The Pecos River is the only important perennial stream, and most of the area has no integrated surface water drainage.

About 1600 mi² of the study area are apparently hydrologically separate from Nash Draw and the WIPP Site. North of US Highway 180, groundwater apparently discharges into Clayton Basin and evaporates. Water in San Simon Swale apparently percolates downward and flows to the southeast.

DWP

Hunter, R.L. 1989. *Events and Processes for Constructing Scenarios for the Release of Transuranic Waste From the Waste Isolation Pilot Plant, Southeastern New Mexico*. SAND89-2546. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, is a research and development facility to demonstrate safe disposal of defense-generated transuranic (TRU) waste. The US Department of Energy (DOE) will designate the WIPP as a disposal facility only if it meets the US Environmental Protection Agency's (EPA's) standard for the disposal of such waste, which includes a requirement for a performance assessment. Performance assessment comprises scenario development and screening and probability assignment; consequence analysis; sensitivity and uncertainty analysis; and comparison with a standard. This report examines events and processes that might give rise to scenarios for the long-term release of waste from the WIPP and begins to screen and assign probabilities to them. The events and processes retained here will be used to develop scenarios during the WIPP performance assessment; the consequences of scenarios that survive screening will be calculated and compared with the standard.

The events and processes retained for scenario development are the normal flow of groundwater, climatic change, drilling of exploratory bore holes, solution mining, seal performance, the effects of drilling into a brine pocket beneath the repository, leaching of the solid waste, nuclear criticality, waste/rock interaction, and waste effects. Numerous other events and processes considered by earlier workers are dismissed from further analysis during the WIPP performance assessment on the basis of physical unreasonableness, low probability, negligible consequence, or regulatory guidelines.

Hunter, T.O. 1979a. "Waste Isolation Pilot Plant (WIPP) Experimental Program," *Waste Isolation Performance Assessment and In-Situ Testing, Proceedings of the US/FRG Bilateral Workshop, Berlin, Germany, October 1-5, 1979*. ONWI-88; SAND79-1950C. Springfield, VA: National Technical Information Service. 340-345. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) provides a location for generic experiments on the interaction of defense wastes and bedded salt. These experiments will include waste forms that produce heat and radiation commensurate with defense high-level wastes (DHLW). Enhanced temperature and radiation will accelerate the interactions of interest. All experiments on DHLW will be removed after they are complete.

The WIPP experimental program is based on nine basic program areas, each representing technical concerns based on an issue. These program areas may consist of several phases: modeling, laboratory analyses, bench scale experiments, pre-WIPP experiments, and WIPP experiments. WIPP experimental programs are summarized on brine migration, studies of canister materials, and studies of mine environments. Laboratory studies of brine migration, including a 1-m-diameter cylindrical block, have been partially completed, and the data are still being analyzed. The fundamental mechanisms are still open to question. Further testing is planned, though fluid migration may be of no practical consequence. Canister materials continue to be tested with different brines and a variety of environmental parameters. Candidate alloys for canister materials were selected for further corrosion studies. Mine environments have been monitored to establish air particulates, temperature, and relative humidity. Radiation background has been measured, but the data have not been analyzed.

DWP

Hunter, T.O. 1979b. "Technical Issues of Nuclear Waste Isolation in the Waste Isolation Pilot Plant (WIPP)," *87th National Meeting, American Institute of Chemical Engineers, Boston, MA, August 19-22, 1979*. SAND79-1117C. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The development of the Waste Isolation Pilot Plant (WIPP) is supported by a research and development program that addresses various technical issues for geologic isolation of nuclear waste in bedded salt. These issues include waste interaction with the host material, structural response of the rock, repository sealing, and methods for repository design and operation. This paper discusses the status of various laboratory and field investigations in this program, and presents a summary of recent results for selected issues. In addition, an overview of all activities and the relations of each to plans for implementation of WIPP is presented. These plans include full-scale experimentation with various waste forms in 1986.

Hunter, T.O. 1980a. "Role of Borehole Plugging in the Evaluation of the Waste Isolation Pilot Plant," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980*. SAND80-0502C. Paris, France: Organisation for Economic Co-Operation and Development. 199-221. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Research on bore-hole plugging (BHP) is part of an integrated strategy to develop technology that can assure successful nuclear waste isolation. The application of this strategy to the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico has included an assessment of the role BHP plays in the development of a repository at that site. This paper presents a description of the WIPP Site, repository design, and the current research and development program. The status of drill holes--those drilled for petroleum and potash exploration and those drilled for site characterization--within the proposed site boundaries is

presented. Sixty-six holes are present on the 7700 hectare (19,000 acre) site, yet only 8 penetrate as deep as the proposed repository location. The assumptions made about shaft and bore-hole sealing in consequence assessment studies are presented. The results of these studies indicate that bore-hole seals with effective permeabilities greater than tens of darcies would result in doses to maximally exposed individuals of less than 0.01% of natural background.

Hunter, T.O. 1980b. "The Perspective of Waste Isolation Research Issues and Assessment of Consequences for Radionuclide Release," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium, Boston, MA, November 27-30, 1979*. Ed. C.J.M. Northrup, Jr. SAND79-1076C. New York, NY: Plenum Press. Vol. 2, 61-68.

ABSTRACT: Issues proliferate around the problem of radioactive waste management, and initial consequence assessments provide a basis, to separate key issues from inconsequential ones, allowing appropriate resources to be allocated. One of the scenarios examined for the Waste Isolation Pilot Plant (WIPP) - a drill hole intercepts a high concentration of radioactive waste - highlights the issues of waste form stability, brine migration, radionuclide migration, and bore-hole plugging. In the analysis of WIPP scenarios, no credit was taken for several parameters, and the sensitivity of releases to variations were little examined. The waste form, and its effects as a barrier to delay release, are not considered. Technology should increase confidence in isolation through choice of waste form and canister material. Brine migration studies will help resolve the issue of brine influx around heat-producing wastes. The influx from these mechanisms is much less than is assumed for consequence analysis. Sensitivity analysis of changes in radionuclide sorption shows that reasonably small sorption coefficients dramatically reduce already inconsequential doses; ranges of certain parameters are not important to overall system performance. Likewise, bore hole and shaft sealing is required, though consequence assessments, which indicate inconsequential releases, assumed penetrations were totally unsealed. These issues, which will be refined by further investigation, should clearly be distinguished from critical issues. DWP

Hunter, T.O. 1980c. "Borehole Plugging Test Activities in Southeastern New Mexico," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980*. ONWI-212; SAND80-2462C. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 173-174.

ABSTRACT: Test activities in southeastern New Mexico directed at sealing bore holes and shafts for the Waste Isolation Pilot Plant (WIPP) are in progress. The objectives are to assess the effects of leakage through man-made penetrations on repository system performance, develop candidate plugging materials for the WIPP rocks, develop methods to assess long-term geochemical stability, develop laboratory and field-testing techniques, evaluate emplacement techniques and plug performance, and provide design information for plugs and emplacement techniques. The program includes performance assessment, material development, instrument development, and field testing. Breaching scenarios related to performance assessment indicate that bore hole seals with effective permeabilities of tens of darcies would result in exposures of less than 0.01% natural background. Grout materials have been developed, tested for laboratory behavior, and compared with in situ performance. Grouts plugging potash holes for 17 years have been examined for long-term stability. Specific systems of packer and testing equipment have been developed for in situ testing of plug performance; downhole TV has been successfully used in support of plugging. A grout plug has been successfully placed and tested in the field, indicating a permeability of about 50 microdarcies. Additional field testing is planned. DWP

Hunter, T.O. 1982a. "Borehole and Facility Sealing Activities for the Waste Isolation Pilot Plant," *The Technology of High-Level Nuclear Waste Disposal, Advances in the Science and Engineering of the Management of High-Level Nuclear Wastes*. Ed. P.L. Hofmann.

DOE/TIC-4621; SAND81-2034. Oak Ridge, TN: Technical Information Center, Office of Scientific and Technical Information. Vol. 2, 228-242.

ABSTRACT: The design of the Waste Isolation Pilot Plant (WIPP) proposed for a site in southeastern New Mexico, includes a working level at 2150 ft with four shafts to the surface. About 70 holes have been drilled for site and mineral exploration in the 19,000 acre area considered. Of these, however, only eight penetrate below the repository level and only four penetrate into underlying aquifers and these are greater than 1 mi from the underground workings. A development program is in progress at Sandia National Laboratories (SNL) to provide adequate seals for these penetrations. Performance assessments have indicated that effective permeabilities as high as ten darcies do not result in doses to maximally exposed individuals greater than 0.01% of natural background. Materials, emphasizing cementitious grouts, have been developed to match the WIPP lithologies. These grouts have been evaluated in the laboratory, both alone and in contact with rock specimens, and in field tests. Results indicate that effective permeabilities of plugs measured in field tests (about 50 microdarcies), while still small, can be 100 times greater than the basic grout and ten times greater than observed in samples with the same rocks in the laboratory. Two major field tests, ERDA-10 and the Bell Canyon Test, have been performed and a test series is planned that includes removal of an existing plug emplaced in 1976, a 26-in.-diameter hole plugged but with a central tubing for diagnosing seal performance, and numerous tests in the experimental facility within the WIPP.

Hunter, T.O. 1982b. "Nuclear Waste Disposal: Technical Issues and Status," *Institute for Nuclear Materials Management Seminar on Spent Fuel Management and Waste Disposal, Washington, DC, October 20-22, 1982*. SAND82-2238C. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The nuclear waste from the defense programs of the United States and the commercial nuclear fuel cycle are planned for disposal in mined geologic repositories. High-level waste (HLW) will require the development of one to three repositories. A number of technical issues are associated with the selection and characterization of a suitable site, the design of surface and underground facilities, development of an appropriate waste package, and methods to assess the performance of the system relative to regulatory requirements. These issues are being addressed by four major projects to evaluate salt, basalt, volcanic tuff, and other crystalline rocks such as granite. The key technical issues and the status of activities to resolve those issues are reviewed.

Hunter, T.O. 1983. "The WIPP Research and Development Program: Providing the Technical Basis for Defense Waste Disposal," *Management 83, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, February 27-March 3, 1983*. Ed. R.G. Post. SAND83-0178C. Tucson, AZ: University of Arizona. Vol. 2, 367-371.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, is being developed by the US Department of Energy (DOE) as a research and development facility to demonstrate the safe disposal of radioactive wastes from the defense programs of the United States. Underground workings are at a depth of 660 m in a bedded-salt formation. Site investigations began in the early 1970s and are culminating with the completion of the Site and Preliminary Design Validation (SPDV) Program in 1983 in which two shafts and several thousand feet of underground drifts are being constructed.

The underground facility will be used for in situ tests and demonstrations that address technical issues associated with the disposal of transuranic (TRU) and defense high-level wastes (DHLW) in bedded salt. These tests are based on several years of laboratory tests, field

tests in mines, and analytical modeling studies. They primarily address repository development in bedded salt, including thermal-structural interactions, plugging and sealing, and facility operations; and waste package interactions, including the effects of the waste on local rock salt and the evaluation of waste package materials.

In situ testing began in the WIPP with the initiation of the SPDV Program in 1981. In 1983, a major series of tests will begin to investigate the response of the rock salt without the use of any radioactivity. These tests will include underground rooms simulating the configuration of a representative DHLW repository with an extraction ratio of about 25% and a heat loading of 12 W/m². Other tests will include overtests in which heat loadings are increased to bound the possible effects and to determine design margins. In the late 1980s, radioactive experiments will be performed with actual TRU and DHLW waste forms from the US defense programs. Then together, these experiments, the associated performance-assessment modeling, and the design and operation demonstrations will establish the technical basis for a defense waste repository in bedded salt.

Hunter, T.O. 1984. "Disposal of United States Defense Wastes in the Waste Isolation Pilot Plant," *Radioactive Waste Management, Proceedings of an International Conference on Radioactive Waste Management, Seattle, WA, May 6-20, 1983*. SAND82-2313C; IAEA-CN-43/463. Vienna, Austria: International Atomic Energy Agency. Vol. 3, 205-219.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a research and development (R&D) facility, located in bedded rock salt in southeastern New Mexico, to demonstrate the safe disposal of nuclear wastes from the US defense programmes. Excavation is now in progress for the underground rooms in which in situ experiments will be performed. These experiments are a follow-on to site selection and characterization studies that began as early as 1972, and are based on an extensive amount of laboratory testing, analytical modelling, and field tests in boreholes and nearby mines. Results of experimental activities to date and the plans for remaining tests are presented, with emphasis on those to be completed in 1984 and 1985. The first phase of the experiments is performed without using radioactive material. These experiments began with the Site Preliminary Design Validation (SPDV) program, which consisted of (1) two shafts, 3.66 m and 1.83 m in diameter, drilled to 659 m; and (2) underground drifts and rooms monitored to determine the response of the rock salt under ambient conditions. The SPDV program will be followed by experiments in a series of underground rooms in which the response of the rock to heat emplacements with an areal loading of 12 W/m² will be determined. Other experiments in rooms include overtest configurations that will generate about four times that heat loading, and other well-defined geometric configurations to evaluate predictive models. Also planned are experiments concerning waste package interactions with rock salt and tests in other technical areas, such as repository sealing and operational considerations. In about 1989, a series of experiments and demonstrations will be performed with radioactive wastes. These include a full-scale storage demonstration using about 6 million ft³ of transuranic (TRU) wastes and tests using up to 40 canisters of defense high-level waste (HLW).

Hunter, T.O., C.L. Christensen, R.V. Matalucci, W.R. Wawersik, and M.A. Molecke. 1981. "Summary of Research and Development Activities Related to the US/FRG Cooperative Program on Nuclear Waste Management," *US/FRG Bilateral Meeting, Bonn, Germany, June 8-12, 1981*. SAND81-1204C. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Sandia research and development program was established to investigate nuclear waste repository development in rock salt, based on the Waste Isolation Pilot Plant (WIPP) Project but with applications to the National Waste Terminal Storage system. The program and current results are summarized for fluid migration experiments, waste package

materials testing, benchmark calculations for thermomechanical codes, and the development of rock mechanics constitutive models.

Fluid migration experiments include water loss tests, constant temperature heating of small samples, Salt Block II bench scale experiments, a heated borehole in a southeast New Mexico (SENM) mine, and a heated borehole in dome salt at Avery Island. The results indicate: 1) mass losses consistently range between 0.1-0.5 weight % for bedded salt; 2) changes in fluid production from heater holes related to power level changes are not expected in a repository; 3) surface salt encrustations suggest migrations as a liquid rather than as vapor, and 4) the region influenced by the heater is limited.

Waste package materials testing evaluates potential alloys for use as canisters or overpacks for high-level waste. The canister materials protect the waste during transport and emplacement and resist lithostatic and hydrostatic pressures. Overpacks are designed to resist corrosion. Screening tests led to selecting TiCode-12 as a prime overpack candidate, with alternates also being considered. Effects being examined include general corrosion, stress corrosion cracking, hydrogen embrittlement, and physical and mechanical metallurgy. A first phase of testing waste package interaction is complete with an apparent deterioration of the TiCode-12. Further tests will be conducted before a final material is chosen.

Benchmark I and II problems were developed to examine the characteristics of various thermomechanical codes applied to the closure rates of WIPP storage rooms. Benchmark II included stratigraphy, two room configurations with differing thermal conditions, and several assumptions regarding plane strain, symmetry, and slip power. Two codes that included known discrepancies show disparate results. Other codes show similar closure trends for a 10-year calculation. The results are still being compared to resolve variations before selecting a code to make reference calculations.

A cooperative effort between US and Federal Republic of Germany investigators focuses on two areas: 1) developing a consistent, well documented data base on salt being considered for nuclear waste isolation and 2) evaluating fundamental uncertainties in variations of rock salt creep and extrapolating creep data to low stresses. To determine or choose representative constitutive equations, general activities have been agreed to that include data compilations and evaluations. Two sets of experiments are proposed: 1) "reference experiments" to permit intercomparison of test results and existing data, and 2) "SNLA/BGR Creep Test Program" using Asse and WIPP samples to develop data about deformation mechanisms over a range of conditions, secondary creep, creep during unloading, and creep rupture. DWP

Hydro Geo Chem, Inc. 1985. *WIPP Hydrology Program Waste Isolation Pilot Plant, SENM, Hydrologic Data Report #1*. SAND85-7206. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This is the first in a series of reports of the basic data from field investigations to characterize the hydrologic properties of the water-bearing units in the Rustler and overlying formations near the Waste Isolation Pilot Plant (WIPP), southeastern New Mexico. The field activities have included drilling new wells and recompletion of existing hydrologic test wells, hydraulic aquifer tests, groundwater tracer tests, and various studies to characterize the regional groundwater flow system.

Test wells have been completed at twelve sites termed hydropads and designated H-1 through H-12. The hydropads include 34 wells. Ten of the wells have been drilled since 1983.

Hydraulic aquifer tests have been conducted on four units, the Dewey Lake Redbeds, the Magenta and Culebra Dolomite Members of the Rustler Formation, and the Rustler/Salado Formation contact zone. Tests include single-well pump, slug, and pressure-pulse tests and multiple-well pump and slug-interference tests. Interference tests at H-4, H-5, H-6, and H-9

hydropads evaluate hydraulic anisotropy for the Culebra. Pumping interference tests on the Culebra at H-4, H-5, H-6, and DOE-1 are reported.

Groundwater tracer tests describe the solute transport properties of the Culebra. Conservative (nonsorbing) tracers have been used at H-2, H-3, H-4, and H-6 hydropads to measure effective (kinematic) porosity and describe hydrodynamic dispersion along flow paths in the Culebra. Convergent flow tracer tests were conducted at H-3, H-4, and H-6. Recirculating tracer tests were performed at the H-2 and H-6 hydropads.

Regional hydrologic studies include resurvey of hydropad elevations, water-level monitoring, and groundwater sampling. The procedures are described for collecting water samples for chemical and isotopic analysis. The resurvey of well elevations using satellite positioning is reported, as is basic water level data throughout the study area. DWP

Hydro Geo Chem, Inc. 1986. *Two-Well Recirculation Tracer Tests at the H-2 Hydropad, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico*. SAND86-7092. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Two recirculation tracer tests were performed on the Culebra Dolomite Member of the Rustler Formation at the H-2 hydropad at the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. The first test, which used pentafluorobenzoate (PFB), sodium benzoate, and a suite of halocarbons for tracers, was terminated before breakthrough at the pumping well because of equipment failure. The second test, which used sodium thiocyanate (SCN) and difluorochlorobromomethane (BCF) as tracers, proceeded normally and lasted 270 days. During the second test, the tracer injected during the first test was recovered.

Tracer test analyses for the two tests were performed only for the PFB tracer injected during the first test and recovered during the second, and for SCN. Analysis of the PFB recovery was crudely modeled as a one-dimensional pulse-injection test. The SCN tracer used in the second test was analyzed with the homogeneous, isotropic Grove and Beetem one-dimensional porous-medium recirculating flow test model. In general, model predictions are in poor agreement with the field measurements. Discrepancies could be produced by the combined effects of local nonhomogeneities, matrix diffusion, and possible sorption or degradation of the tracer during the test. The best overall match between the SCN breakthrough curve predicted by the semianalytical model and that observed in measurements was achieved using a porosity that ranged from 17 to 19% and a dispersivity of 16 to 18 ft. A match based only on the early part of the breakthrough curve, however, yielded a porosity of 11.5% and a dispersivity of 8 ft. The latter porosity might more closely represent the effective porosity of the Culebra, if the SCN degraded during the test.

The work described in this report was performed in 1980 by Hydro Geo Chem, Inc. of Tucson, AZ, under contract to Sandia National Laboratories (SNL). Modeling of test results on the assumption that the Culebra dolomite behaves as an isotropic porous medium is described.

Intera Environmental Consultants, Inc. 1980a. *Compilation of Long-Term Waste Isolation Assessment Studies (1978-1980)*. 651A-01G-05. Houston, TX: Intera Environmental Consultants, Inc. (Copy on file at the US Department of Energy Public Reading Room, National Atomic Museum, Albuquerque, NM).

ABSTRACT: Data and modeling studies of geosphere transport modeling through stages of the WIPP project have been coalesced into a comprehensive report. The phases of consequence assessment that make up geosphere transport are: 1) modeling the regional hydrology of a square area 36 mi on a side, 2) modeling of six scenarios that combine breach events and transport mechanisms, and 3) modeling radionuclide migration in one or two dimensions. The work is based principally on data collected before 1978, and is checked for consistency against some later data.

The regional hydrology is considered to consist of three main units: the Rustler Aquifer, combining Culebra and Magenta Dolomite Members; the brine aquifer along the top of Salado west and southwest of WIPP; and the Delaware Mountain Group aquifers. The Rustler Aquifer is emphasized because of its role in breach events and transport. Hydraulic conductivities for this and other units were adjusted iteratively to match the model satisfactorily to the regional geology.

Scenario events are assumed to begin 1000 years after repository closure, with fluids assumed to be saturated brine. Five waste transport mechanisms have been classified: 1) forced convection driven by a pressure gradient, 2) molecular diffusion through connections to an aquifer, 3) dissolution of salt between the repository and aquifer, 4) direct access to the surface, such as a fault or drillhole, and 5) natural convection in a fluid driven by temperature or salinity (density) gradients. Forced convection has been divided into scenarios involving one aquifer and two aquifers. Only scenarios involving forced convection and diffusion have been considered.

The repository was assumed to contain both transuranic and remote-handled waste, and radionuclides are assumed to be released as salt backfill is dissolved. The "Rustler Aquifer" is the most significant pathway, and the anticipated discharge point is Malaga Bend on the Pecos River, about 15 miles downgradient from the WIPP. Discharge was also examined at a hypothetical well for domestic purposes three miles downgradient.

The hydrologic modeling shows that: 1) aquifers above and below Salado and Castile do not communicate hydrologically with each other, 2) calculated transmissivities differ significantly from many reported values, 3) calculated water velocities in the Rustler range from 0.015 to 14 ft/yr with 5000 to 100,000 yr travel time to Malaga bend, 4) calculated Delaware Mountain Group velocities are less than 0.1 ft/yr with at least 500,000 yr travel time to the Capitan, 5) calculated waste leach times are 1/2 million to 3 billion years, 6) simulations of discharge at Malaga Bend indicate that radionuclide discharge rates increase logarithmically for the first million years, that discharge rate is controlled by both scenario release mechanisms and aquifer characteristics, and that after one million years discharge is controlled by regeneration decay effects, and 7) simulations of discharge to a domestic well indicate that leach time changes discharge rates at 800,000 years, that radionuclide concentrations strongly correlate with salinity, and that radionuclides are released through the well 4 times sooner at 1/15 the activity predicted at Malaga Bend.

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Intera Environmental Consultants, Inc. 1980b. *Hydrogeological Analysis (1979) in Support of the Waste Isolation Pilot Plant (WIPP) Program*. Houston, TX: Intera Environmental Consultants, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Hydrogeological calculations in support of the WIPP program involved nuclide transport calculations in support of environmental impact statements and the safety assessment report and scenario modeling calculations. Hydrological parameters available January 1, 1978 were not modified for further hydrogeological interpretation. A two-well tracer test of the Culebra Dolomite Member of the Rustler Formation has been simulated numerically to assist in designing the test. Consequences of borehole plug designs and failures have also been calculated for two base cases including both single and multiple well scenarios. In addition, a program was begun to validate the numerical nuclide transport model being used, and various data, calculations, and models have been discussed with Pacific Northwest Laboratories as they demonstrate their capabilities for modeling salt repositories.

Safety assessment calculations used both one- and two-level repository designs (both contact- and remote-handled waste), regional Rustler hydrology that results in a travel time to Malaga Bend of 5400 years, and breach events or scenarios previously reported for WIPP and summarized in six conceptual models. Spent fuel discharges occur early, dominated by Tc and I, and result in discharges of < 0.1 curie/year ending before about 200,000 years after closure. Discharges at Malaga from transuranic nuclides begin at nearly 1 million years after closure and peak at about 1.1 million years from uranium isotopes with a total discharge < 0.01 curies/year.

Five tests, slug or recovery, of the Magenta or Culebra in the H-2 hydro well complex were modeled, obtaining matrix transmissivities the same as the USGS analytical solutions and adding fracture transmissivities for three tests. The fracture transmissivity of the Magenta in H-2A is calculated at 0.05 ft²/day; fracture transmissivity of the Culebra in H-2B is 1.17 ft²/day. H-2C Culebra test showed no fracture component. Hydrologic potentials for the Culebra indicate a more southerly initial path that will affect the path and modeling of nuclide transport to Malaga Bend.

Tracer test design modeling indicates a closed system may be preferred. A pumping test before the tracer test is recommended to permit selection of pumping-injection rates that will maximize the gradient between wells. Sampling will likely be at least daily, and the injection period is recommended to be at least as long as the flow time for the centerline streamline between wells. Several tracers may be used, permitting both slug and continuous injection.

The sensitivity of discharge of plutonium to adsorption coefficients was examined, indicating that nuclide discharge is very insensitive to adsorption coefficients for plutonium above 10 mL/g. Lower coefficients can affect discharge significantly. As the preliminary estimate of plutonium adsorption is 2100 mL/g, the error in adsorption would have to be at least a factor of 200 to have any affect on discharges. Changes in porosity, adsorption, and solubility of Tc-99 were analyzed as well. Reductions in porosity caused little change in cumulative dose and maximum discharge activity, though travel time to Malaga Bend was dramatically reduced. Adsorption changes from 0 to 1 mL/g to 10 mL/g increased travel times a factor of about 20 or more while the discharge activity and dose decreased to 74% and 5%, respectively, of the base case. Reducing the solubility also reduced discharges almost proportionately because the radionuclides are retained longer within the repository. DWP

Intera Environmental Consultants, Inc. 1981a. *Hydrogeological Analysis (1980) in Support of the Waste Isolation Pilot Plant (WIPP) Program*. Houston, TX: Intera Environmental Consultants, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Geohydrological analyses supported six areas: geosphere transport, aquifer tracer tests, refining a scenario model, regional hydrology, near-field models of dissolution, and experimental activities in the near-field system.

The geosphere transport calculations supporting the environmental impact statement and safety assessment report simulated transport in the Rustler for a period of 1.5 million years. Radionuclide discharge at Malaga Bend on the Pecos River indicates differences between

scenarios. "A maximum discharge rate for all radionuclides of 8.5×10^{-3} curies per year is calculated for the forced-convection, two-aquifer connection scenario." The peak occurs about 1 million years after repository closure. Source rates based on solubility show greater calculated discharge concentration than for rates based on leaching.

Injection tracer tests in the Culebra were analyzed numerically to evaluate dispersivity and duration of the tracer injection pulse. New analytical solutions for tracer tests are presented, as field tests with short injection periods and large dispersivities that deviate from existing analytical solutions.

Salt creep and dissolution compete in scenarios of bore-hole plugging. Effective stress in salt is more important than temperature or dynamic pressure gradients. "Bore-hole plugs in the Salado [F]ormation will probably be safely installed with an initial annulus substantially less than the 'critical initial annulus' (on the order of fractions of an inch) that leads to plug failure."

Static well potential measurements are calculated as equivalent freshwater heads. "Potential for flow in the Magenta, Culebra, and Rustler/Salado contact is predominantly west, south-southeast, and south, respectively." There is potential for downward interaquifer flow. Density measurements are recommended.

Three models of salt dissolution were reviewed. Of these, the SWIFT model is most versatile, but it has been only recently developed.

Reviewed technical reports summarize experiments of brine migration, canister corrosion, and gas generation. A conceptual model linking resaturation and corrosion should include air invasion, two-phase fluid flow for air invasion, and system geochemistry. DWP

Intera Environmental Consultants, Inc. 1981b. *Consequence Assessment of Hydrological Communications Through Borehole Plugs*. SAND81-7164. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report describes the effect of bore-hole plug integrity on consequence assessments performed for the Waste Isolation Pilot Plant (WIPP). The study is based on scenarios described in the *Final Environmental Impact Statement (FEIS)*, Appendix K, for the WIPP; US Department of Energy (DOE), October 1980. The flow rates through a bore hole, assumed to penetrate the waste storage location and to connect underlying and overlying aquifers, are determined as a function of the hydraulic conductance of the plugs. Similar calculations are performed for multiple bore holes communicating with the aquifers. It is concluded that low permeability plugs (less than 1 millidarcy) are not essential to satisfy public health and safety requirements at the WIPP, but rather that such plugs act as a redundant barrier in the multiple barrier isolation concept.

Intera Technologies, Inc. 1986. *WIPP Hydrology Program. Waste Isolation Pilot Plant, Southeastern New Mexico, Hydrologic Data Report #3*. SAND86-7109. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #3* includes basic hydrologic data for aquifer tests and water-level measurements at the Waste Isolation Pilot Plant (WIPP) Site over the period of 1984 through 1986. Part A reports hydrologic data obtained during the H-3 multipad pumping test of the Culebra from October 1985 through April 1986. During the 62 day pumping period, fluid-pressure data were collected at the H-3 hydropad and observation wells DOE-1, H-11b3, H-2c, and H-4b. Water level was frequently measured at 18 other observation wells in the Culebra and Magenta dolomite members. Appendices tabulate fluid-pressure, pumping-rate,

and barometric-pressure data collected during the test. Water levels and transducer responses during the drawdown and recovery periods are plotted.

Part B is an account of anisotropy and convergent-flow tracer testing conducted from April to June 1984, at the H-3 hydropad. The test equipment, a short history of the testing, and plots of the data are described. Appendices present tabulated pressure, water-quality, and observation-well data.

Part C describes a six-day aquifer test conducted in the Culebra at the H-8 hydropad in December 1985. The test consisted of 72 hours of pumping at approximately 6 gal/min, followed by a 72-hour recovery period. The test equipment and test history are described. Appendices present tabulated fluid-pressure, water-quality, and observation-well data.

Part D describes a six-day aquifer test of the Culebra at the H-7 hydropad in February, 1986. The test consisted of 72 hours of pumping at approximately 81.5 gal/min, followed by a 72-hour recovery period. The test equipment and test history are described. Appendices present tabulated water-quality and observation-well data.

Part E reports basic data from open-hole testing during the drilling of well DOE-2 from August 1984 through July 1985. Drillstem, pulse, and slug tests were conducted on the Rustler, Salado, and Bell Canyon Formations. The Culebra was tested by pumping. Downhole equipment is described, and the testing history is recapitulated. Appendices include tabulated fluid-pressure data collected during all testing phases.

Part F presents water-level data from November 1985 through April 1986. The water-level data for the Magenta, the Culebra, the Rustler/Salado contact zone, the Bell Canyon Formation, and the Salado/Castile Formations are plotted. Water-level data are presented in an appendix.

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Intera Technologies, Inc., and Hydro Geo Chem, Inc. 1985. *WIPP Hydrology Program, Waste Isolation Pilot Plant, Southeastern New Mexico, Hydrologic Data Report #2*. SAND85-7263. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #2* contains basic hydrologic data for aquifer tests and water-level measurements conducted at the Waste Isolation Pilot Plant (WIPP) Site from 1983 through November 1985. Part A summarizes data collected pumping and slug tests conducted during 1983 and 1984 in wells at the H-2 and H-9 hydropads and in well H-12. Water-level data collected in 1983 and 1984 at the H-2 hydropad are revised. Appendices tabulate water-level, drawdown, millivolt, and pressure data collected during the aquifer tests for both the test wells and the observation wells and water-level data collected with electric water-level sounders.

Part B presents details of pumping tests at the H-11 hydropad during May and June 1985. The automated data acquisition system (DAS), water-level measurement devices, the discharge measurement system, and the well and equipment configurations are described. Pressure or water-level response in both the pumping and observation wells are plotted. Appendices include pressure data, depth to water in observation wells, and measured pumping-rate data.

Part C presents water-level data collected from January through November, 1985, near the WIPP Site. Water-levels are plotted for the Magenta, the Culebra, the Rustler/Salado contact zone, the Bell Canyon Formation, and the Salado/Castile Formations.

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Jarollmek, L., M.J. Timmer, and R.F. McKinney. 1983. *Geotechnical Activities in the Exploratory Shaft--Selection of the Facility Interval, Waste Isolation Pilot Plant (WIPP) Project Southeastern New Mexico*. TME 3178. Albuquerque, NM: US Department of Energy.

ABSTRACT: This report on geotechnical activities in the exploratory shaft was prepared as part of the Site Validation Field Program for the US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. The report summarizes basic data on shaft drilling and construction; presents the geologic mapping results which essentially correspond to the conditions predicted from previous investigations; and discusses the optimization process based on the geologic conditions encountered and its results for the adjustment and modification of the shaft key design, selection of the facility interval, and selection of the geotechnical instrument locations.

Jarollmek, L., M.J. Timmer, and D.W. Powers. 1983. *Correlation of Drillhole and Shaft Logs Waste Isolation Pilot Plant (WIPP) Project Southeastern New Mexico*. WTSD-TME-3179. Albuquerque, NM: US Department of Energy.

ABSTRACT: This report on stratigraphic correlations from drill-hole and shaft data along a generally north-south section across the potential extent of underground excavations of the Waste Isolation Pilot Plant (WIPP) Facility was prepared as part of the *Site Validation Field Program Plan*. The results provide input for the report entitled *Results of Site Validation Experiments*; input for other WIPP-related investigations, including the Design Validation Program; and a framework for further underground activities at WIPP.

In general, this correlation study confirmed previous findings, including: a relatively high consistency of thickness and lateral continuity of all beds within the Salado Formation, especially in the host rock interval; gentle, generally south and southeastward dips/slopes of the host rock interval strata; close correspondence between stratigraphic data obtained from the present underground excavations and data derived from the previous investigative drill holes and shafts; and depositional origin of the undulations on the top of Marker Bed (MB) 139 and relatively small variation in its thickness (1.2 to 4.1 ft).

John, C.B., R.J. Cheeseman, J.C. Lorenz, and M.L. Millgate. 1976. *Potash Ore Reserves In The Proposed Waste Isolation Pilot Plant Area, Eddy County, Southeastern New Mexico*. Open-File Report 78-828. Denver, CO: US Geological Survey.

ABSTRACT: The proposed Waste Isolation Pilot Plant (WIPP) area includes about 18,960 acres in Tps. 22 and 23S, Rs. 30 and 31E., New Mexico Principal Meridian Eddy County, southeastern New Mexico. It is located within the Carlsbad Mining District about 25 mi east of Carlsbad.

The WIPP area is immediately south of the Capitan Limestone subcrop, which formed the northern margin of the Delaware Basin in Permian time. During Late Permian (Ochoan) time, gypsum, anhydrite, and halite were deposited in the seas of the Delaware Basin to form the Castile Formation. These deposits have a maximum thickness of about 2,000 ft and grade upward into the more argillaceous beds of the Salado Formation. The Salado Formation contains abundant sulfate minerals, notably anhydrite and polyhalite. The potash ore minerals, langbeinite and sylvite, occur in the upper part of the Salado Formation in the McNutt potash zone, a local name applied to a potassium-rich zone.

Structurally, the WIPP area is situated within a broad syncline (mapped on top of the Salado) plunging gently to the southeast. Drill holes and surface geology analyses indicate no faulting in the area; and the only structural anomalies found are a local high and a small depression located in the southwest corner and north-central part of the WIPP area, respectively.

The minimum US Geological Survey (USGS) standards for leasable potash ore are 4 ft of 10% K_2O as sylvite, 4 ft of 4% K_2O as langbeinite, or 4 ft of equivalent mixed ore as defined by a minimum of three data points in any one ore zone. Seven ore zones -- the 10th, 9th, 8th, 5th, 4th, 3rd, and 2nd -- maintain at least this thickness and grade in parts of the WIPP area. The WIPP area overlies an estimated 353.3 million t (USGS lease grade) of measured and indicated sylvite and langbeinite potash ore reserves. Approximately two-thirds of this ore occurs in intervals in the 10th and 4th ore zones; the rest is distributed among the five other ore zones.

Jones, C.L. 1974. *Salt Deposits of the Mescalero Plains Area, Chaves County, New Mexico*. Open-File Report 74-190. Denver, CO: US Geological Survey.

ABSTRACT: Salt deposits in the Mescalero Plains area of Chaves County, NM, belong to the Guadalupian and Ochoan Series of Late Permian age. The Guadalupian deposits are part of a complex succession of red beds and evaporite deposits known as the Artesia Group. The Artesia is 1,200-1,800 ft (365-550 m) thick and is about one-half rock salt and anhydrite and one-half dolomite and red beds composed of sandstone, siltstone, and shale. Much of its rock salt is clayey and is intercalated between beds of sandstone and siltstone. The thickest and most clay-free seams of rock salt are in the Salado Formation of the Ochoan Series. The Salado is as much as 820 ft (250 m) thick; it is dominantly rock salt that contains minor amounts of anhydrite, polyhalite, and clay, and traces of sylvite and carnallite. The salt in the Salado underlies an eastwardly thickening wedge of overburden as much as 1,580 ft (480 m) thick, and it has undergone partial or complete solution beneath large sections of the overburden.

Oil and gas are produced at more than 50 fields in and near the area. Their presence elsewhere is a geologic possibility. Occurrences of potassium salts have been prospected, but there are no significant potash resources.

Jones, C.L. 1975a. "An Evaluation of a Potential Site for Emplacement of Nuclear Waste in Rock Salt of Southeastern New Mexico," *New Mexico Academy of Science Bulletin*. Vol. 16, no. 2, 16. (Abstract Only).

ABSTRACT: The US Geological Survey (USGS) recently completed a series of site evaluation studies for the US Energy Research and Development Administration. The studies indicated that the general area straddling the Eddy-Lea County line at the latitude of, and about 50 km east of, Carlsbad meets the hydrogeologic criteria for nuclear waste emplacement in rock salt. The Salado Formation, the main salt-bearing unit of the area, ranges in thickness from 580 to 605 m. The formation consists of thick, persistent units of rock salt alternating with thinner units of anhydrite, polyhalite, and potash-bearing rocks that contain sylvite and langbeinite. The Salado lies at a depth of 300m, and it has a substantial sedimentary mantle of well-consolidated evaporites and red beds that have very low hydraulic transmissivity. The formation is slightly deformed in places by monoclinial flexures having low relief and broad, gentle, southeastwardly plunging troughs and ridges. Evidence of deformation involving tectonic stresses of appreciable regional or local importance has not been found. Hydrogeologic and logistic factors favorable to the possible emplacement of nuclear waste in the rock salt of the area include a demonstrated geologic stability during the past 225×10^6 years, a predicted probability projection from exhumation by erosion and/or invasion by groundwater during a time span of a few hundred thousand years, availability of public lands isolated from populated areas, and ready access to rail and utility services.

Jones, C.L. 1975b. *Potash Resources in Part of Los Medanos Area of Eddy and Lea Counties, New Mexico*. Open-File Report 75-407. Denver, CO: US Geological Survey.

ABSTRACT: Los Medanos area of eastern Eddy and western Lea Counties, NM, is being considered for possible siting of a repository facility for experimental studies of nuclear waste emplacement in salt beds of the Salado Formation of Permian age. The potential repository site encompasses about 29 mi² (75 km²) of sandy terrain near the center of Los Medanos. The site is underlain by evaporite and red bed formations having an aggregate thickness of 4,462 ft (1,360 m).

The Salado Formation, which is the main salt-bearing unit of the area, lies at a depth of 1,000 ft (305 m). The formation is almost 1,970 ft (600 m) of rock salt with prominent interbeds of anhydrite, polyhalite, glauberite, some widely spaced seams of fine-grained clastic rocks, and a few potash deposits containing sylvite and langbeinite. The potash deposits occur in salt beds 517-871 ft (158-265 m) below the top of the formation. The lower half of the formation includes some salt beds that may be used for the experimental emplacement of nuclear wastes.

Most, if not nearly all, of the potential repository site is underlain by potash deposits that contain sylvite and langbeinite. The deposits grade 12-13% K₂O as sylvite and 3-11% K₂O as langbeinite, and must be regarded as having economic potential for potassium minerals. There is considerable uncertainty concerning the full extent and total range in quality of the ores in the deposit, and subsurface investigation will be required to assess their potential.

Jones, C.L. 1978. *Test Drilling for Potash Resources: Waste Isolation Pilot Plant Site, Eddy County, New Mexico*. Open-File Report 78-592. Denver, CO: US Geological Survey. Vols. 1-2.

ABSTRACT: Twenty-one borings to augment existing information on potash resources at the proposed site for a Waste Isolation Pilot Plant (WIPP) in eastern Eddy County, NM, were drilled and logged in an 11-week period, mid-August to November 1976. The basic data developed from the borings are tabulated in the present report. The tabulation includes lithologic and geophysical logs of all the borings, as well as the results of chemical analyses, X-ray determinations, and calculations to establish a modal mineralogical composition of core samples from potash ore zones and mineralized salt beds.

ANNOTATION: The potash holes drilled by the Department of Energy (DOE) in 1976 provided core for evaluation of the potash resources in the WIPP Site area, as assessed in the reports by Alderman et al. (1978), Seedorf (1978) and John et al. (1978). However, the report by Jones is important because it includes the core descriptions and geophysical logs obtained by the US Geological Survey (USGS) from these 21 bore holes. The lithologic descriptions and log data provide a consistent data set with well distributed coverage of the rocks down to the middle part of the Salado. This has particularly been valuable for studies of the distribution of halite in the Rustler Formation (e.g., Snyder, 1985; Holt and Powers, 1988).

Jones, C.L. 1981a. *Geologic Data for Borehole ERDA-6, Eddy County, New Mexico*. Open-File Report 81-468. Denver, CO: US Geological Survey.

ABSTRACT: ERDA-6 is an exploratory test hole drilled in eastern Eddy County, NM, to evaluate a candidate site for a nuclear waste repository that was subsequently rejected on the basis of geologic data. The rocks penetrated include surficial deposits of Quaternary age; the Santa Rosa Sandstone of Triassic age; and the Dewey Lake Red Beds, the Rustler Formation, the Salado Formation, and part of the Castile Formation, all of Permian age. The pre-Quaternary rocks are sharply deformed into an anticline that has a faulted core of salt and

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worthy of consideration" (p. 35); the interval just above MB 139 is being developed as the disposal horizon.

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Kannenberg, M., C. Francke, and W.M. Roggenthen. 1990. "Ground Probing Studies of the Waste Isolation Pilot Plant (WIPP) Underground," *Abstracts with Programs, Geological Society of America, 1990 Annual Meeting, October 29-November 1, 1990*. Vol. 22, no. 7, 99-100. (Abstract Only).

ABSTRACT: Creep closure of the Waste Isolation Pilot Plant (WIPP) excavations produces brittle fracturing in the floor, pillars, and roof of the repository near the openings. Previously, observation of subsurface fracturing was achieved primarily through direct observations in bore holes, which provided limited data. Ground probing radar is being developed as a tool for characterization of fracturing in the roof and floors of the facility. The accuracy of the radar method has been verified through correlation with direct observations in bore holes. Transmitters with center frequencies of 500 MHz were used because of their increased resolution and the generally low conductivity of the halite, which resulted in lower attenuation than in many other types of geologic materials. Typical wave velocities in the salt sequences range between 0.13 and 0.17 m/ns depending primarily upon clay and water content. The radar clearly images air-filled and brine-filled fractures, as well as clearly defining interfaces between halite and anhydrite units, to depths of over 3 m from the surfaces of the excavations. Recording of the reflected signal in the field allows further digital signal analysis using image processing techniques that have resulted in better control in determining fracture locations.

Lee Keeling & Associates, Inc. [1977.] *Appraisal Report Section 31, Township 22 South, Range 31 East, Eddy County, New Mexico*. Tulsa, OK: Lee Keeling & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The fair-market value of oil and gas leases of the south half of section 31, T22S, R31E, is \$1,007,000 with full access to the surface and \$365,000 with no access to the surface and loss of subsurface rights to 6,000 ft. The estimated compensation for loss of fair-market value would be \$642,000. Potash rights to the property are not leased. The principal producing zone for this area is the Atoka, producing in the James Ranch Unit No. 1. The reserves can be recovered from other well locations if this well is not drilled. DWP

Lee Keeling & Associates, Inc. 1977. *Appraisal Report, Potash Rights, Waste Isolation Pilot Plant, Eddy County, New Mexico*. Tulsa, OK: Lee Keeling & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Fair-market values have been determined for potash rights under tracts 301, 302, 303, and 304, within the limits of the Waste Isolation Pilot Plant (WIPP). The date of the appraisal is November 15, 1977. The appraised rights for tract 301 total \$64,000. Tract 302 rights are appraised at \$61,917. Tract 303 is appraised at \$1,251,280. Tract 304 is appraised at \$400. The appraised potash rights total \$1,377,597. Core and report data were available from industry and government sources, part of which was not verified. The appraisal for tract 302 is based on data from ERDA holes outside the tract. Tract 301 has insufficient tonnage for a new mine, and the langbeinite is sub-economic. Tract 302 contains insufficient tonnage for a new mine, and the langbeinite ore is low grade. Tract 303 has insufficient tonnage for a new mine, but it is contiguous to Duval leases. Drill holes adjacent to tract 304 indicate that there is no economic ore present. DWP

ANNOTATION: The appraised value of the potash rights for the WIPP Site area reflects a generally low grade and volume of ore. The appraisal reflects current (as of 1977) economics

and reserves of higher quality here and in Canada. The special mineral langbeinite was not concentrated enough to be of value at the time of appraisal. Basic data about the ore grade and volume are unlikely to change, as further test drilling for potash is unlikely. The appraised value can change.

Keeseey, J.J. 1977. *Hydrocarbon Evaluation, Waste Isolation Pilot Plant Site Area to State and Federal Royalty Interests, Eddy County, New Mexico.* (Copy on file in the Sandia WIPP Central Files, Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The future net revenue and fair-market value to royalty interests, held by the State of New Mexico and by the Federal Government, in the Waste Isolation Pilot Plant (WIPP) Site area have been determined as of April 1, 1977. These values are based on 178,223 barrels of oil and 44,137,000 million ft³ of gas as the total net reserves. The total hydrocarbon and acreage fair-market values are \$886,861 and \$3,040,529 for the State and Federal Governments, respectively. DWP

ANNOTATION: Details for the hydrocarbon reserves and exploitation projections used in the fair-market evaluation were presented in Sipes, Williamson, and Aycock (1976a, 1977b). This evaluation differs from that of Foster (1974, 1979) in concentrating on the immediate economic values of resources that might be denied by the WIPP, in this case the royalties to state and federal governments. Other reports examine the economic consequences of permitting drilling in outer zones or directional drilling from outside control zones.

Kehrman, R., K. Broberg, G. Tatro, R. Richardson, and W. Dasczyszak. 1990. "Groundwater Monitoring at the Waste Isolation Pilot Plant," *Waste Management 90, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 25-March 1, 1990.* Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. II, 75-84.

ABSTRACT: This paper discusses the Groundwater Monitoring Program (GMP) being conducted at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM. The Regulatory and Environmental Programs (REP) section of the Environment, Safety, and Health department (ES&H) is responsible for conducting environmental monitoring at the WIPP. Groundwater monitoring is one of the ongoing environmental activities currently taking place. The REP section includes water-quality sampling and water-level monitoring.

The WIPP Project is a research and development facility designed to demonstrate the safe disposal of defense-generated transuranic (TRU) and mixed waste in a geologic repository. The Salado Formation of Permian age serves as the repository medium. The Salado Formation consists of bedded salt and associated evaporites. The formation is 602 m thick at the site area; the top surface is located at a subsurface depth of 262 m. The repository lies at a subsurface depth of 655 m.

Water-quality sampling for physical, chemical, and radiological parameters has been an ongoing activity at the WIPP Site for the past six years and will continue through the life of the project. Data collected from this program to date, has been used by Sandia National Laboratories (SNL) for site characterization and performance assessment work. The data has also been used to establish a baseline of preoperational radiological and nonradiological groundwater quality. Once the facility begins receiving waste, this baseline will be used to determine if the WIPP Facility influences or alters groundwater quality over time.

The water quality of a well is determined while the well is continuously pumped. Serial samples of the pumped water are collected and tested for pH, Eh, temperature, specific

gravity, specific conductivity, alkalinity, chlorides, divalent cations, ferrous iron, and total iron. Stabilization of serial sampling parameters determines if a representative sample is being obtained. Representative samples are sent to laboratories and analyzed for general chemistry and radionuclides. Samples are provided to the New Mexico Environmental Evaluation Group (EEG) and SNL for independent analysis.

Keller, G.R., and A.M. Rogers. 1978. *Central Basin Platform Seismicity for the period October 1, 1977, to June 30, 1978.* Open-File Report 78-1100. Denver, CO: US Geological Survey.

ABSTRACT: This report compiles the seismic data collected for the Central Basin Platform in Texas and New Mexico (and data processing completed) during the period October 1, 1977, to June 30, 1978. The data were recorded using a 12-station seismograph network that is radiotelemetered to Winkler County Airport, TX, and subsequently relayed to Golden, CO, where the data are permanently stored on photographic film. These data will serve as a basis for assessing the seismic hazard to the Waste Isolation Pilot Plant (WIPP) in New Mexico.

Epicenter maps for the periods October 1977 to June 1978 and February 1975 to June 1977 show that activity during this reporting period was similar to the activity observed in previous years with one notable exception. An earthquake swarm in the southwest corner of the array occurred during the period of December 1977 to February 1978. Although this area (the War-Wink, S. gas field) has been active throughout the study, activity greatly increased during this swarm, producing 281 events that could be located. We hope to learn more about this area during the next phase of the project. The data gathered for the period October 1, 1977, to June 30, 1978, are listed in detail for epicenter locations, phase lists, and monthly epicenter maps.

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Keller, G.R., A.M. Rogers, R.J. Lund, and C.D. Orr. 1981. *A Seismicity and Seismotectonic Study of the Kermit Seismic Zone, Texas.* Open-File Report 81-37. Denver, CO: US Geological Survey.

ABSTRACT: Recent seismic activity at the Central Basin Platform (CBP) is important for assessing the seismic risk to a proposed radioactive waste disposal site in southeastern New Mexico. CBP seismicity was the only significant activity within 100 km of the proposed site. CBPs are also interesting because they are near major oil fields that have been or are currently undergoing secondary recovery operations. It has been suggested that the CBP earthquakes are related to the water injection-secondary recovery operations in the CBP oil fields. A network of telemetered seismographs was deployed around the epicenters of past events to record seismic activity from December 1975 to September 1979.

Small earthquakes are widespread within the network area, suggesting that microearthquake studies closer to the Waste Isolation Pilot Plant (WIPP) are warranted to determine the shortest distance between the seismic zone and the facility. The apparent relationship between hydrocarbon production and earthquakes suggests that the WIPP Site should not be included in the same seismic zone as the CBP because the site is isolated from major hydrocarbon producing zones. The maximum magnitude of earthquakes in the zone may be limited because the area of artificial pressure increases is limited and pressure increases of more than 70 bars result in earthquakes with magnitudes consistently less than 4.0.

DWP

ANNOTATION: As indicated by Sanford in his earlier reports (e.g., Sanford et al., 1978), earthquakes are frequent in the area southeast of the site, near Kermit, TX. The local magnitudes of these events are small; standard analysis applied to natural earthquakes would show this to be a significant seismic source in evaluating the tectonic stability of the WIPP Site. Yet the area does not show any evidence of fault scarps consistent with such a source of natural seismic activity. Rogers began this study, and Keller continued it, to determine if the

seismic activity was attributable to water injection for secondary hydrocarbon recovery. Seismic data from the CBP have been interpreted as due to recovery project (e.g., Sanford and Topozada, 1974), though Keller et al. are more cautious in this report.

ANNOTATION: Doser and others have reviewed data and interpretations from the seismic activity in the Jal-Kermit area. Sanford and others have also provided a location for the January 2, 1992 earthquake north of Jal ("Rattlesnake Canyon" earthquake, local magnitude about 5) in an open-file report (#70) of the Department of Geoscience, New Mexico Institute of Mining and Technology.

Kelley, V.A., and J.F. Pickens. 1986. *Interpretation of the Convergent-Flow Tracer Tests Conducted in the Culebra Dolomite at the H-3 and H-4 Hydropads at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-7161. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Tracer tests utilizing conservative organic tracers have been conducted in the Culebra Dolomite Member of the Rustler Formation at the locations of the H-2, H-3, H-4, and H-6 hydropads. The objective of this report is to present a quantitative evaluation of the physical solute-transport parameters of the Culebra dolomite at the H-3 and H-4 hydropad locations from interpretation of the tracer-test data. The tracer-test configurations consisted of a pumping well and two tracer-addition wells arranged in approximate equilateral triangles with 30-m sides. The transport of organic tracers from the tracer-addition wells to the pumping wells was analyzed using the finite-difference model SWIFT II, which is capable of simulating single- and double-porosity flow and transport.

The interpretive approach for analyzing the tracer-breakthrough curves at the pumping well first consisted of estimating the appropriate governing processes using the information base for each specific hydropad. For the H-3 hydropad, the test data indicated that a double-porosity interpretation approach was the most appropriate. In this conceptualization, the fractures represented the principal transport medium and the matrix provided the bulk of the solute-storage capability. The simulation model accounted for advective-dispersive transport in the fractures and diffusive transport in the matrix. Calibration of the tracer-breakthrough curves included conducting a parameter sensitivity analysis on longitudinal dispersivity, tortuosity, matrix porosity, fracture porosity, effective matrix block size, pumping rate, initial tracer-input distribution, and distance between pumping and tracer-addition wells. Calibration of the tracer-breakthrough curves for the H-3 tracer test resulted in longitudinal dispersivities from 5 to 10% of the flow path (well-separation distance), a fracture porosity of 1.9×10^{-3} , and effective matrix block sizes of 0.25 to 2.1 m.

There is uncertainty in the assumed or calibrated values for tortuosity, fracture porosity, matrix porosity, and matrix block size that were used to describe solute transport in the Culebra at the H-3 hydropad. Reduction in this uncertainty would require additional laboratory and field testing (e.g., additional drilling and coring, additional matrix porosity determinations on core, diffusion experiments, and additional on-site tracer testing). The results obtained from the conservative-tracer test suggest that fracture flow and matrix diffusion dominate solute transport in the Culebra at the H-3 hydropad. Further, the parameters derived to fit the tracer-breakthrough curves are thought to be consistent with the physical conceptualization of the Culebra at the H-3 hydropad.

The interpretation of the H-4 hydropad tracer test has not provided quantitative estimates of the physical solute-transport parameters for the Culebra. Qualitatively, the observed tracer-breakthrough curves could be simulated by representing the Culebra with a layered system of higher- and lower-permeability units. In this system, transport would be dominated by the higher-permeability zones with diffusive interaction with the lower-permeability zones. No evidence was obtained to indicate that transport of the tracers had occurred through fractures; however, considering the fractured nature of the Culebra at the H-3 and H-6 hydropads and other locations at the Waste Isolation Pilot Plant (WIPP) Site, the existence of fractures in the

Culebra at the H-4 hydropad should still be considered a possibility. However, if present, these fractures do not appear to have had a significant effect on solute transport on paths examined in the H-4 tracer test.

Kelley, V.A., and G.J. Saulnier, Jr. 1990. *Core Analyses for Selected Samples from the Culebra Dolomite at the Waste Isolation Pilot Plant Site.* SAND90-7011. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Two groups of core samples from the Culebra Dolomite Member of the Rustler Formation at and near the Waste Isolation Pilot Plant (WIPP) were analyzed to provide estimates of hydrologic parameters for use in flow-and-transport modeling. Whole-core and core-plug samples were analyzed by helium porosimetry, resaturation porosimetry, mercury-intrusion porosimetry, electrical-resistivity techniques, and gas-permeability methods.

Seventy-nine helium-porosity determinations indicated that the distribution of Culebra porosities was skewed toward lower porosity values with an arithmetic mean and standard deviation of 0.153 and 0.053, respectively.

The vertical heterogeneity of porosity was indicated by 21 pairs of helium-porosity determinations where each sample of the pair was separated by approximately 5 cm. The porosity differences between the samples in the pairs varied from 0.050 to 0.093.

Water-resaturation-porosimetry results showed a near 1-to-1 correlation with the results from helium-porosity determinations. In some cases, the resaturation porosities were slightly larger than the helium porosities, possibly due to mineral dissolution by the resaturation fluid (deionized water) or to the experimental reproducibility of the two measuring techniques.

Endpoint mercury pore-volume saturations for 25 samples ranged from 66.7 to 99.9%, with an average endpoint pore-volume saturation of 95.4%. The endpoint pressure was 207 MPa. The median pore-throat radius varied over an order of magnitude from 0.077 microns (μm) to 0.588 μm , with an arithmetic average value of 0.315 μm . Eighty-four percent of the pore-throat radii in the samples analyzed were between 0.1 μm and 0.5 μm . The average mercury-intrusion porosity was 0.148, as compared with the helium-porosity average of 0.154.

Seventy-three grain-density measurements indicated a skewed distribution toward larger values of grain density with an arithmetic average of 2.82 g/cm³ and a standard deviation of 0.019 g/cm³. The most common value of grain density was 2.83 g/cm³, which was also the median of the distribution.

Electrical-resistivity measurements of 15 saturated core plugs were used to calculate estimates of formation factor and tortuosity. Formation-factor values were log-normally distributed and values ranged from 12 to 407, with a geometric mean of 58.8. Tortuosity ranged from 0.04 to 0.33, with an arithmetic average of 0.14 and a median of 0.12. The results show a general trend of increasing tortuosity with increasing porosity. The diffusion porosities and diffusion tortuosities determined by Dykhuizen and Casey (1989) agree with the lower range of the values determined by this core-analysis study.

Sixty-six horizontal-permeability measurements ranged from 7.9E-18 m² to 3.6E-13 m², and the distribution had an arithmetic average of 6.2E-15 m², a geometric mean of 4.5E-16 m², and a median of 2.7E-16 m². Twenty-six vertical-permeability measurements ranged from 8.4E-18 m² to 5.2E-14 m², with an arithmetic mean of 5.1E-15 m², a geometric mean of 9.0E-16 m², and a median of 3.5E-16 m². Plots of the log₁₀ of permeability versus porosity indicated a weak correlation between the log₁₀ of permeability and porosity. A plot of log₁₀ of horizontal permeability versus the median pore-throat radii determined for the same samples indicated that the log₁₀ horizontal permeability is directly related to median pore-throat radius.

Kelley, V.A., J.F. Pickens, M. Reeves, and R.L. Beauheim. 1987. "Double-Porosity Tracer-Test Analysis for Interpretation of the Fracture Characteristics of a Dolomite Formation," *Proceedings of the Solving Ground Water Problems with Models, Conference and Exposition, Denver, CO, February 10-12, 1987*. Dublin, OH: National Water Well Association. Vol. 1, 147-169.

ABSTRACT: Hydraulic and tracer testing studies have been performed as part of the regional hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) site in southeastern New Mexico. The interpretation of hydraulic tests and tracer tests from a number of locations has indicated the importance of the double-porosity concept in the interpretation of both the hydraulic and solute-transport characteristics of the fractured dolomite under study. While identification of fracture flow and estimation of formation transmissivity can be obtained from hydraulic-test interpretation methods, tracer tests are necessary to provide realistic estimates of parameters such as fracture porosity and representative matrix unit size. Without estimates of these parameters, predictions of containment transport in fractured rock systems are very uncertain.

A convergent-flow tracer test conducted in the Culebra Dolomite Member of the Rustler Formation at the WIPP Site was analyzed using a double-porosity flow and transport model. The tracer test set-up consisted of one pumping well and tracer-addition wells arranged in an approximate equilateral triangle with 100-ft (30-m) sides. The transport of conservative tracers from each of the tracer-addition wells was simulated using the double-porosity flow and transport model SWIFT II. The simulation model accounts for advective-dispersive transport in the fractures and diffusive transport in the matrix. Calibration of the tracer-breakthrough curves included conducting a sensitivity analysis on the important parameters: diffusion coefficient, tortuosity, matrix porosity, fracture porosity, effective matrix-block size, pumping rate, initial tracer input distribution, and distance between pumping and tracer-addition wells. Calibration of the tracer-breakthrough curves resulted in longitudinal dispersivities from 5 to 10% of the flow path length (well-separation distance), a fracture porosity of 0.002, and effective matrix-block sizes of 0.8 ft (0.25 m) to 3.9 ft (1.2 m). Even though these estimates of fracture porosity and effective matrix-block size are specific to the location of the tracer test, they provide an initial estimate on which to base predictions of the regional transport of solutes in the Culebra Dolomite.

Key, S.W., Z.E. Beisinger, and R.D. Krieg. 1978. *HONDO II: A Finite Element Computer Program for the Large Deformation Dynamics Response of Axisymmetric Solids*. SAND78-0422. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: HONDO is a finite-element method computer program designed to calculate the large deformation elastic and inelastic transient dynamic response of two-dimensional solids. To accommodate a wide variety of applications, finite-strain calculations are incorporated. Spatially, the program employs a four node isoparametric quadrilateral element. In time, the program performs the integration using a central difference method time integrator. Since the time integration scheme is only conditionally stable with respect to step size, the program continuously monitors the step size and adjusts it to keep the calculation stable. The program contains five material subroutines covering elastic, viscoelastic, elastic-plastic, crushable foam, and soil behavior. Initial conditions on velocity but not displacement are allowed. Pressure loadings are allowed. Thermal loads are not implemented. The program functions entirely in core, and because no stiffness matrices are calculated and stored, rather large problems are easily accommodated.

Key, S.W., C.M. Stone, and R.D. Krieg. 1981. "Dynamic Relaxation Applied to the Quasi-Static, Large Deformation, Inelastic Response of Axisymmetric Solids," *US/Europe Workshop on Nonlinear Finite Element Analysis in Structural Mechanics, Ruhr, Germany, July 28, 1980*.

Eds. W. Wunderlich, E. Stein, and K.J. Bathe. SAND80-1605C; CONF-800 781-1. Berlin: Springer, 585-620.

ABSTRACT: The use of dynamic relaxation as a solution strategy for the quasi-static, large deformation, inelastic response of solids is examined. The underlying mechanics, the constitutive theories of interest, the incremental form of the equations, the spatial discretization, and the implementation of dynamic relaxation for path and/or time-dependent material response are each discussed. The mechanics are carried out in the current configuration of the body described by a fixed spatial coordinate system and using the Cauchy stress. Finite-strain constitutive theories for elastic, elastoplastic, and creep behavior are introduced. An incremental form of the problem allowing a sequence of equilibrium solutions to be found is presented. A constant bulk strain, bilinear displacement isoparametric quadrilateral finite element is employed for the spatial discretization. The solution strategy used to generate the sequence of equilibrium solutions is dynamic relaxation which, in the form adopted, is based on explicit central difference pseudo-time integration and artificial damping. It is used to find the next solution as a result of an increment in time and/or load. Each solution must satisfy equilibrium within a prescribed tolerance before proceeding to the next increment. Several example calculations are presented.

Klasi, M.L., A. Melo, and A.F. Fossum. 1981. *Second Benchmark Problem for WIPP Structural Computations*. Topical Report RSI-0145. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The second benchmark problem was proposed by Sandia National Laboratories to compare directly the results and computer codes of different researchers with specified conditions, including stratigraphy, constitutive laws and geometry. Finite element computer codes, SPECTROM-41A for heat transfer and SPECTROM-23A for thermo/viscoelastic properties, developed by RE/SPEC have been used for the analysis. The vertical closure at ten years is 0.2567 m for the isothermal room and 0.3522 m for the heated room. Midpillar horizontal displacements for both cases are inward and are 0.1701 m and 0.03965 m, respectively. The slip line models used could easily accommodate up to ten proposed slip lines. Radiative heat transfer from surface to surface is not included in the present code but could easily be added. Adding thin geological layers to the model will increase storage requirements and solution time. The loss in accuracy is difficult to estimate. A third benchmark problem could "include nonhomogeneous initial stress fields in layered material and a finite series of room with provision for sequential excavation, emplacement, and subsequent long-term creep. Additional complexity could involve fracture and dilation of slide lines and/or radiative heat transfer."
DWP

Kopp, O.C., and D.W. Combs. 1975. *Mineral Sources of Water in Evaporite Sequences (Salado Salt and Adjacent Beds at the Proposed Waste Disposal Facility Near Carlsbad in Lea and Eddy Counties, New Mexico)*. Knoxville, TN: Department of Geological Sciences, University of Tennessee. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Samples from two cores of the Salado Formation in southeastern New Mexico were studied to determine mineralogy, petrology, and water loss by heating. The samples consist primarily of fine to coarse-grained halite with polyhalite, anhydrite, and clay minerals. Other minerals detected include gypsum, magnesite, quartz, feldspar, sylvite, carnallite, celestite (?), glauconite, and kainite (?). The samples are from halite-rich zones, and several other evaporite minerals known from potash zones were not detected. Numerous hopper crystals and intergrown euhedral halite with clay and sulfates indicate that the Salado was deposited in shallow water to subaerial mudflat environments. This depositional environment

is a major change from the underlying Castile Formation. Trapped fluid inclusions, altered minerals, and zones with secondary minerals along beds and seams of clay and silt suggests that fluids have moved along these paths.

Water loss from 80 samples ranged from 0.0 to 3.5 weight % at $102 \pm 5^\circ\text{C}$. Sample splits used for the study were generally 1.5 to 2.0 g in weight and sieved to obtain the 60 to 120 mesh size fraction. "Most of the dehydration water ... appears to come from clay minerals, although gypsum may make a contribution...." Polyhalite will dehydrate between 170 and 300° . These samples release much less water than samples from the Hutchinson Salt in Kansas. The ranges of water loss for shallower samples from Kansas appear to merge with the range for deeper samples from the New Mexico site. It is not known if this is fortuitous. In addition, some samples released H_2S . The weight losses from this study compare generally well with other work using the dynamic method of thermogravimetric analysis, though some discrepancies exist. These are because of the method and the fact that different samples were analyzed.

DWP

Kosowski, B.A., S.L. Robbins, and J.W. Schmoker. 1978. *Principal Facts for Borehole Gravity Stations in Stratigraphic Test Well ERDA No. 9, Eddy County, New Mexico*. Open-File Report 78-696. Denver, CO: US Geological Survey.

ABSTRACT: Drillhole ERDA-9 at the Waste Isolation Pilot Plant (WIPP) Site was logged during March 1978, with the US Geological Survey (USGS) bore hole gravity meter. Forty-four subsurface gravity observations, including stations reoccupied for drift control, cover the depth interval from 196.6 to 2779.8 ft. The data are corrected for tide, terrain, and drift.

DWP

Krause, W.B., and M.C. Loken. 1980. *Thermomechanical Modeling of a Thin-Disk Rock Salt Core Specimen Exposed to Temperature Gradients*. Topical Report RSI-0113. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A thin-disk core specimen of rock salt has been modeled to determine the mechanical response of the salt core to a transient thermal gradient and also a uniformly increasing thermal gradient. The model results will be used to study moisture loss from a specimen with similar geometry. A heat transfer computer code (SPECTROM-41) and a thermomechanical computer code (SPECTROM-22) were used for the study of potential brine inflow into a heated nuclear waste disposal site. A steady thermal gradient of $10^\circ\text{C}/\text{cm}$ and a mean salt temperature of 235°C were the desired conditions.

A non-linear transient thermal gradient resulted in specimen failure because of large initial temperature gradients. The failure condition is based on the failure envelope for salt from Mississippi Chemical Corp. mine. A uniform linear and steadily increasing thermal gradient prevented failure in the simulation. The same procedures for analysis can be applied to the planned thick-walled cylinder experiment.

DWP

Krieg, R.D. 1980. "A Unified Creep-Plasticity Model for Halite," *Mechanical Testing for Deformation Model Development*. American Society for Testing and Materials Symposium, Bar Harbor, FL, November 12-13, 1980. American Society for Testing and Materials Special Technical Publication 765. SAND80-1195. Philadelphia, PA: American Society for Testing and Materials. Vol. 765, 139-147.

ABSTRACT: There are two national energy programs that are considering caverns in geological salt (NaCl) as a storage repository. One is the disposal of nuclear wastes and the other is the storage of oil. Both short-time and long-time structural deformations and stresses

must be predictable for these applications. At 300K, the nominal initial temperature for both applications, the salt is at 0.28 of the melting temperature and exhibits a significant time-dependent behavior. A constitutive model has been developed that describes the behavior observed in an extensive set of triaxial creep tests. Analysis of these tests showed that a single deformation mechanism seems to be operative over the stress and temperature range of interest so that the secondary creep data can be represented by a power of the stress over the entire test range. This simple behavior allowed a new unified creep-plasticity model to be applied with some confidence. The resulting model recognizes no inherent difference between plastic and creep strains yet models the total inelastic strain reasonably well, including primary and secondary creep and reverse loadings. A multiaxial formulation is applied with back stress. A Bauschinger effect is exhibited as a consequence and is present regardless of the time scale over which the loading is applied. The model would be interpreted as kinematic hardening in the sense of classical plasticity. Comparisons are made between test data and model behavior.

Krieg, R.D. 1984. *Reference Stratigraphy and Rock Properties for the Waste Isolation Pilot Plant (WIPP) Project*. SAND83-1908. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A stratigraphic description of the country rock near the working horizon at the Waste Isolation Pilot Plant (WIPP) is presented along with a set of mechanical and thermal properties of the materials involved. Data from 41 cores and shafts are examined. The entire stratigraphic section is found to vary in elevation in a regular manner, but individual layer thicknesses and relative separation between layers are found to have no statistically significant variation over the one mile north to south extent of the working horizon. The stratigraphic description is taken to be relative to the local elevation of Anhydrite B. The material properties have been updated slightly from those in the July 1981 reference stratigraphy. This reference stratigraphy/properties document is intended primarily for use in thermal/structural analyses. This document supersedes the July 1981 stratigraphy/properties document.

Krieg, R.D., and T.O. Hunter. 1980. "Geomechanics Activities Conducted at Sandia National Laboratories in Support of the Waste Isolation Pilot Plant," *Proceedings of Workshop on Thermomechanical-Hydrochemical Modeling for a Hardrock Waste Repository*, Berkeley, CA, July 29-31, 1980. Ed. W.J. Schwarz. LBL-11204; ONWI-164; SAND80-1592C. Berkeley, CA: Lawrence Berkeley Laboratory. 81-88.

ABSTRACT: An overview of the structural mechanics work on the Waste Isolation Pilot Plant (WIPP) Project is presented. The site in southeastern New Mexico was chosen for its thick halite (NaCl) beds and favorable hydrology and geology. The creep of halite is both an advantage for a repository and for a complication in stress and deformation prediction. The materials structural characterization test program and subsequent constitutive modeling are presented, followed by the code development activities. This includes the development of two new computer codes. Code qualification and verification on these and other codes are discussed. The lack of good field data is currently a handicap to code verification. Finally, a typical drift stability analysis is presented that illustrates the present state of the art.

Krieg, R.D., H.S. Morgan, and T.O. Hunter. 1980. *Second Benchmark Problem for WIPP Structural Computations*. SAND80-1331. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report describes the second benchmark problem for comparison of the structural codes used in the Waste Isolation Pilot Plant (WIPP) Project. The first benchmark problem consisted of heated and unheated drifts at a depth of 790 m, whereas this problem considers a shallower level (650 m) more typical of the repository horizon. But more important, the first problem considered a homogeneous salt configuration, whereas this problem considers a configuration with 27 distinct geologic layers, including 10 clay layers--4

of which are to be modeled as possible slip planes. The inclusion of layering introduces complications in structural and thermal calculations that were not present in the first benchmark problem. These additional complications will be handled differently by the various codes used to compute drift closure rates. This second benchmark problem will assess these codes by evaluating the treatment of these complications.

Krieg, R.D., H.S. Morgan, and C.M. Stone. 1988. "Structural Analyses Overview on the WIPP Project," *The Mechanical Behavior of Salt. Proceedings of the Second Conference, Hanover, Germany, September 24-28, 1984*, Eds. H.R. Hardy, Jr. and M. Langer. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 533-549.

ABSTRACT: Advanced structural mechanics methods are being applied to the Waste Isolation Pilot Plant (WIPP) nuclear waste repository being constructed in bedded rock salt. Careful coring and laboratory testing have been used to characterize the material properties and to build mathematical material models. State of the art computer programs have been constructed and extensively checked. Field data is now available and is compared against predictions. The predictions of closure are roughly a third of that observed in the South Drift at the WIPP Site. No reasonable changes to the model have been found to explain the discrepancy. Because of the success of these methods in other applications, the prognosis is still optimistic.

Krieg, R.D., C.M. Stone, and S.W. Key. 1981. *Comparisons of the Structural Behavior of Three Storage Room Designs for the WIPP Project*. SAND80-1629. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A set of structural calculations has been made on three storage drift designs for the storage of contact handled transuranic (CH TRU) wastes at the site of the proposed Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. One design is a quad room configuration, a four drift cluster of equal sized drifts. The second design has uniformly spaced drifts each of the same dimensions and with the same net extraction ratio as the first design. The third design is a uniformly spaced but much larger drift of slightly lower extraction ratio. The study emphasizes the relative merits of the three designs, but only in regard to the deformations of the drifts associated stresses in the surrounding rocks.

The analyses included modeling of anhydrite, polyhalite, clay seams, and salt layering in a 90 m interval near the 663 m CH floor level. No thermal strains are included since the TRU wastes produce virtually no heat.

The analyses showed that while all of the configurations may be acceptable, the uniformly spaced drifts are definitely superior to the quad room configuration. Strains exceeding a prescribed failure criterion in the 0.6-m-thick salt at the floor surface were indicated in all configurations. This floor fracture was evident within a year in the quad room but delayed until seven years in the small single drift configuration. Very high strains were seen in the walls of the quad room with surface failure in one wall at ten years. The walls of the uniformly spaced drifts experienced much lower creep strains out to ten years. Floor heave was a possible deformation mode in all the analyses but was never observed.

Krumhansl, J.L. 1982. "Mineralogic Stability of a Bentonite Backfill in a Bedded Salt Repository," *Abstracts with Programs, Geological Society of America, 95th Annual Meeting, New Orleans, LA, October 18-21, 1982*. SAND82-0951A. Vol. 14, no. 7, 536. (Abstract Only).

ABSTRACT: For a bentonite backfill to function, the smectite crystal structure must survive several decades in a high-temperature, high-radiation, low-pressure environment, as well as

for longer times under hydrothermal conditions. High-temperature effects at one atm were assessed by holding samples of "Brock" bentonite at 320°C for up to six months. Although heating broadened and decreased the intensity of the (001) x-ray diffraction peaks both heated and unheated samples expanded to essentially the same degree when placed in a saturated NaCl solution. Exposure of "Brock" bentonite to 10^{10} rads of ^{60}Co gamma radiation produced no changes that could be detected by x-ray diffraction or by differential thermal analysis to 350°C. The atmosphere over the clay, however, was depleted in oxygen and contained in excess of ten mole percent hydrogen in several cases. Radiolysis effects on the sorbed water were, therefore, more important than structural damage to the silicate lattice. To assess backfill stability during the hydrothermal phase of repository operation, samples were heated in NaCl rich brines at 250°C for up to 95 days. The more diffuse (001) diffraction peaks noted afterwards probably reflect partial recrystallization of the smectite to incorporate more magnesium rather than development of a mixed layer illite-smectite. Thus, those aspects of the smectite crystal structure that make it an attractive backfill component have not been adversely effected during the experimental program carried out to date.

Krumhansl, J.L. 1984. *Observations Regarding the Stability of Bentonite Backfill in a High-Level Waste (HLW) Repository in Rock Salt*. SAND83-1293. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Consideration of bentonite as a component of the engineered barrier system surrounding high-level nuclear waste (HLW) canisters in rock salt raised several questions regarding the stability of this clay. Dehydration studies pertinent to the period immediately following waste emplacement showed a partial loss in swelling ability, the extent of which depended on the composition of the rehydrating brine increased with temperatures from 150 to 320°C. At a later date, hydrothermal reactions between brine and bentonite may occur as pressure in the repository rises and the backfill saturates with brine. In pure sodium chloride brines, little change in the bentonite was observed after two months at 250°C. In the same amount of time, brines rich in potassium formed mixed-layer, illite-smectite clays. Adding magnesium to the brine arrested mixed-layer clay formation; instead a magnesium-enriched montmorillonite formed and the brine pH dropped. Radiation stability studies to 10^{10} rads were conducted in both wet and dry environments, but caused no detectable alteration of the clay. In contrast, fluid-phase compositions changed significantly. Gamma irradiation of dry bentonite produced an oxygen-depleted atmosphere that was enriched in both hydrogen and carbon dioxide. Mixed bentonite brine slurries produced copious amounts of both hydrogen and oxygen gas when irradiated. These irradiated slurries generally had posttest pH values between 4 and 6. Solutions made by exposing pre-irradiated salt and bentonite to unirradiated water, or brine, had pH values between 6 and 8.5 and, in the case of salt solutions, were highly oxidizing. Although more research is needed for a complete performance assessment, it appears that such backfills may prove useful in a variety of rock-salt environments.

Krumhansl, J.L. 1989. *Waste Isolation Pilot Plant Brine Field pH Measurements: Technique and Interpretation*. SAND88-3352. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: pH measurements made in conjunction with the Waste Isolation Pilot Plant (WIPP) Materials Interface Interactions Test (MIIT) are interpreted. The pH drop noted over time is correlated with other changes associated with MIIT brine evaporation. Magnesium buildup appears important because a combination of high concentrations and elevated temperatures (about 90°C) can produce hydrochloric acid through hydrolysis of the magnesium ion, possibly explaining why the brines appeared to become more acid over time.

For pH measurement techniques in concentrated brines, pH papers were useless in concentrated saline solutions. When traditional glass pH electrodes were substituted, other complications arose. For mildly acidic brines of known hydrogen ion concentration, the measured pH generally fell below the expected value. Also, the electrode responded differently to different

salts. Magnesium chloride had a greater effect than sodium chloride, which in turn had a greater effect than potassium chloride. For nearly neutral brines, electrode drift became a serious problem, and when the meter finally stabilized, readings were significantly above those of the solutions from which the brines were prepared. The size of this positive deviation depended on the electrode being used and its previous conditioning. Both drift and the unusual high values were mitigated or eliminated in brines where a buffer was present in concentrations greater than about 0.001 molar. In still more basic brines, it was found that the electrode response was less capricious, and that the measured pH values were again below those of the stock solution from which the brine was prepared. Limited experimentation was also done at higher temperatures to demonstrate that these trends held at conditions appropriate to the MIIT (-90°C).

There is evidence for a buildup of hydrogen ion activity during the test even if the hydrogen ion has a large positive activity coefficient. However, the hydrogen ion concentrations in the various brines probably were in the range 10^{-6} to $10^{-7.3}$, rather than rising to values as large as $10^{-3.7}$ as the raw pH data imply. Thus, much of the apparent shift probably reflects an increased hydrogen ion activity coefficient accompanying the continued buildup of salts in solution, rather than the generation of high acid concentrations. Concerning the discrepancy between the pH readings obtained from full-strength brines and from brines diluted with five parts of deionized water, measurements on diluted samples taken later in the test showed no indication of acid buildup. This can be explained as follows: the addition of freshwater decreases the hydrogen ion concentration in proportion to the amount of freshwater added, the addition of freshwater also decreases the effect of salt on the electrode, and dilution causes the buffers to re-equilibrate in a way that consumes hydrogen ions. The net effect is that diluted samples show a relatively uniform, nearly neutral pH, while the undiluted samples are much more variable and apparently more acidic.

In general, this report concludes that a number of factors other than the hydrogen ion concentration may affect the reading obtained from a glass pH electrode in brine. To make the transition from raw data to an estimate of true pH incorporates many experimental uncertainties and untestable theoretical assumptions. Under some circumstances, however, it is possible to rigorously correlate a pH meter reading with the hydrogen ion concentration of a brine. Such readings are useful in tracing the progress of a system's chemistry over time, particularly if used in conjunction with a full chemical analysis of the brine.

Krumhansl, J.L., K.M. Kimball, and C.L. Stein. 1990. *A Review of WIPP Repository Clays and Their Relationship to Clays of Adjacent Strata*. SAND90-0549. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Salado Formation is a thick evaporite sequence located in the Permian Delaware Basin of southeastern New Mexico. This study focuses on the intense diagenetic alteration that has affected the small amounts of clay, feldspar, and quartz washed into the basin during salt deposition. These changes are of more than academic interest because this formation also houses the Waste Isolation Pilot Plant (WIPP). Site characterization concerns warrant compiling a detailed data base describing the clays in and around the facility horizon. Further, because of their diagenetic history, the minerals indigenous to the Salado also provide a natural analog for the fate of sand/bentonite backfills that may be used in sealing the facility.

An extensive sampling effort was undertaken to address these programmatic issues as well as to provide additional insight regarding diagenetic mechanisms in the Salado. Seventy-five samples were collected from argillaceous partings in halite at the stratigraphic level of the WIPP. These were compared with twenty-eight samples from cores of the Vaca Triste member of the Salado, a thin clastic unit at the top of the McNutt potash zone, and with a clay-rich sample from the lower contact of the Culebra dolomite (in the overlying Rustler Formation). These settings were compared to assess the influence of differences in brine chemistry (i.e.,

halite and potash facies, normal to hypersaline marine condition) and sediment composition (clays, sandy silt, dolomitized limestone) on diagenetic processes.

X-ray diffraction analyses and electron microscopy identified a clay similar to corrensite from all three stratigraphic horizons. Authigenic quartz and potassium feldspar were found in both Vaca Triste samples and in those from the WIPP. The feldspar occurred in greater abundance in the Vaca Triste samples than in those from the WIPP horizon. Fluid inclusion compositions from halite in the Vaca Triste were compared with those from the WIPP repository horizon. The solution speciation/mineral solubility code EQ3NR was used to calculate ionic activities of relevant species in WIPP and Vaca Triste brines. In both cases, the predicted assemblage was consistent with the observed mineralogy.

We propose a diagenetic interpretation in which the original, detrital clays reacted with magnesium-rich brines to produce a suite of Mg-rich, mixed-layer species. By-products of these reactions were authigenic quartz and K-feldspar. The dissolution of plagioclase, kaolinite, and fine-grained, detrital illite probably contributed components precipitated in the authigenic phases.

Of programmatic concern, it was found that clays exposed in the repository workings resemble those occurring throughout the rest of the Salado; though corrensite or similar mixed-layer phases always predominate, the proportions of corrensite, chlorite, and illite in the clay vary from place to place in individual strata; and bentonite-sand backfills will probably undergo significant mineralogic changes if exposed to WIPP brines for a geologically significant span of time.

Kuhn, A.K. 1979. *The Stress Control Technique--Its History and Suitability for WIPP*. TME 2970. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The Stress Control Technique (SCT) has been recommended by the Waste Isolation Pilot Plant (WIPP) designer (Bechtel) and the developer of the SCT (Serata) as the approach for designing the underground layout for the WIPP. The SCT approach would generally require rapid mining of multiple rooms with relatively narrow yield pillars. A composite larger stress envelope around the rooms would be expected to develop, reducing stresses close to the openings and transferring a large stress field to a much greater distance from the mine opening. The Technical Support Contractor for the WIPP, its consultants, and Sandia National Laboratories have major reservations about this approach: 1) The basis of the approach is proprietary and has not been open to review and discussion. 2) This will not be an acceptable condition for WIPP as a publicly-reviewed project. 3) Empirical data reveal relative success for SCT in Canadian potash mines but failure in the Carlsbad district as well as in other mines. 4) The method is dependent on site geology, which is still little known in detail for applying these methods. 5) The SCT design is irreversible, whereas more conventional designs retain options such as rock-bolting or developing an SCT design in conventional room and pillar area; if the high stressed region is problematic, it is removed too far from the opening to reach or reinforce. 6) Failure of a composite stress envelope can affect all rooms in a panel. 7) Two physical phenomena assumed by Serata may not be valid. 8) Advantages of the SCT method mainly relate to production mining rather than to WIPP, which will have low extraction ratios. 9) Mining would likely be periodic under SCT approaches, which would not be efficient to schedule. DWP

Kuhn, A.K. 1981. *WIPP Site Validation Program*. TME 2975. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office.

ABSTRACT: Site validation is a process of identifying and investigating conditions that require further study to develop the highest practical confidence in the site for a repository.

In this report, the validation plan is formulated and presented. Remaining phases include implementing and validating the plan.

Twenty-one site qualification criteria have been identified. Each criterion is evaluated for the degree to which it has been satisfied (complete, adequate, partial). Criteria satisfied completely or adequately do not require additional data, but additional data will be obtained for those areas judged "adequate" to increase the level of satisfaction. General criteria judged adequate or partial include host rock thickness, lateral extent, lithology, stratigraphy, dissolution, groundwater, tectonic stability, and physiochemical compatibility. Eight investigative objectives with twenty-one activities are identified to satisfy these criteria. These activities are scheduled for completion by September 1983. DWP

Kuhn, M.W., W.A. Stensrud, and G.R. Walter. 1985. "Comparison of Hydraulic Properties of Fractured Dolomite Determined by Pressure Pulse, Slug/Bailer, and Pumping Tests," *International Association of Hydrogeologists Memoires, Hydrogeology of Rocks of Low Permeability, Tucson, AZ, January 7-12, 1985*. Vol. XVII, pt. 2, 801. (Abstract Only).

ABSTRACT: Theoretical and intuitive arguments suggest that the validity of field tests to determine the hydraulic conductivity of fractured rocks will depend on the volume of rock affected by the particular testing method. While time and monetary constraints usually favor the use of pressure-pulse or slug/bailer techniques for single-hole tests in tight rocks, the validity of such tests is often challenged because these tests have a small radius of influence and their analysis is based on porous media models. For these reasons, pump tests are often favored, when time and money permit, because of their large radius of influence and the availability of analytical techniques for handling discrete fracture responses.

This paper compares the results of pressure-pulse, slug/bailer, and pump tests performed on several different wells completed in the Culebra dolomite at the Waste Isolation Pilot Plant (WIPP), southeastern New Mexico. Although independent geologic and tracer-test data suggest that groundwater movement takes place primarily through systems of fractures or solution channels, agreement was found between hydraulic conductivities determined on the same well using the different hydraulic testing procedures. These tests were performed on wells with transmissivities ranging from 4×10^{-4} to 1×10^{-9} m²/sec and no consistent differences between the techniques were observed.

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Labreche, D.A., and L.L. Van Sambeek. 1988. *Analysis of Data from Expansive Salt-Water Concrete Seals in Series B Small-Scale Seal Performance Tests.* SAND87-7155. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Series B Small-Scale Seal Performance Tests was the second set of in situ experiments at the Waste Isolation Pilot Plant (WIPP) designed to evaluate candidate salt repository seal materials. Expansive salt-water concrete seals were placed in large diameter horizontal bore holes in M Drift. Structural response data from two instrumented seals are presented and discussed. The results of supporting finite-element calculations are compared to measured seal response. Representative comparisons are made between the Series B seals and the Series A seals (expansive salt-water concrete seals placed in a vertical configuration). Series A structural data are presented in an appendix.

Lambert, S.J. 1978. "The Geochemistry of Delaware Basin Groundwaters," *Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas, Carlsbad, NM, May 4, 1977.* Ed. G.S. Austin. New Mexico Bureau of Mines and Mineral Resources Circular 159; SAND77-0420J. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 33-37.

ABSTRACT: Subsurface samples of water from various rock types in the Delaware Basin of southeastern New Mexico and West Texas have been analyzed for their solute contents and $^{18}\text{O}/^{16}\text{O}$ and D/H ratios. Saturated brines (TDS > 300,000 mg/L) were found in one well in the Bell Canyon Formation, two wells in the Castile Formation, and in potash mine seeps in the Salado Formation. According to Cl/Br ratios, all the water samples have derived their dominant solute (NaCl) from nearby rocks. Potash mine seeps and saline Capitan water samples contained solutes corresponding to common primary evaporite mineral assemblages indicative of simple uptake of dissolved solids. Brines from the Bell Canyon and Morrow contained less magnesium but more calcium than primary evaporite assemblages and have participated in ion exchange reactions. Stable isotope measurements indicated that sampled waters from the Santa Rosa, Rustler, and Capitan Formations were meteoric, while samples from the Salado, Bell Canyon, and Morrow Formations, along with one from the Castile Formation (ERDA-6 drill hole), have undergone episodes of low-temperature isotopic exchange with oxygen- and hydrogen-bearing minerals. Isotopically, the Carlsbad Caverns hydrologic system is unique to the Guadalupe Mountains, unrelated to the Delaware Basin as a whole. The ERDA-6 occurrence of saturated brine and H_2S -rich gas in the Castile Formation represents a biogenically-produced sulfide-sulfate disequilibrium. The brine's Na_2SO_4 content may have arisen by rock/fluid ion exchange involving a replacement of magnesium by sodium in the solution. None of the saline groundwaters were found to be original evaporite mother-liquors or products of partial evaporation.

Lambert, S.J. 1980a. "A Strategy for Evaluating the Long-Term Stability of Hole-Plugging Materials in Their Geological Environments," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980.* SAND80-0359C. Paris, France: Organisation for Economic Co-operation and Development. 343-352. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Material used to plug bore holes will not in general be in chemical equilibrium with its host rock. Adverse long-term performance of a plug can involve changes in phase assemblage in the plug/rock system that are difficult to observe at low temperatures in real time. The thermodynamics of multiphase equilibria provides a technique of predicting what

phase changes might occur. The thermodynamic treatment of plug/rock systems uses a formulation of possible chemical reactions among phases in the system and determinations of changes in values of Gibb's free energies for the hypothetical reactions to identify the theroretically-permitted reactions that could degrade plug performance. Time-dependent prediction of phase changes requires a knowledge of rate laws and constants for specific reactions whose mechanisms are well known.

Lambert, S.J. 1980b. *Mineralogical Aspects of Fluid Migration in the Salt Block II Experiment*. SAND79-2423. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A block of evaporite rock containing the mineral assemblage halite (88%) - polyhalite (8%) - sylvite (4%) was machined into a cylinder one m in diameter and one m high, and was fitted with an axial heater, thermocouples and an off-gas collection system. After about 100 days of heating, identification of mineral efflorescences at the heater hole (carnallite and bischofite) showed that a significant portion of the 111 g of water recovered (out of around 8500 g available in the rock) migrated as a liquid, not as a vapor. A microscopic examination of rock slices from within 15 cm of the heater hole (where the temperature was 100 to 200°C, and the gradient was 3 to 15°C/cm) revealed that fluid inclusions had migrated, but rarely across grain boundaries, fluid inclusions had not been mobilized at distances greater than about 15 cm from the heater hole, and intergranular liquid had been conspicuously mobilized within 15 cm of the heater hole.

Lambert, S.J. 1980c. "Shallow-Seated Dissolution of Bedded Evaporites in the Northern Delaware Basin (Southeastern New Mexico)," *Bulletin of the American Association of Petroleum Geologists*. SAND79-2475A. Vol. 65, no. 4, 764. (Abstract Only).

ABSTRACT: Studies of bore holes penetrating the Dewey Lake, Rustler, and uppermost Salado Formations in the northern Delaware basin (southeastern New Mexico) have investigated subsurface dissolution of bedded evaporites in the vicinity of Nash Draw, a depression 5 to 10 mi wide and about 250 ft deep. The thickness of the section between the top of the Salado Formation and the base of marker bed 103 varies from an intact 210 ft (east of Nash Draw), to a residual 45 ft (in the Draw), where gypsification of Rustler anhydrite and removal of Rustler halite are virtually complete. The uppermost occurrence of Permian halite has been previously described as a dissolution zone (the "brine aquifer"). Within 130 ft below this zone, there are halite-filled fractures, cubic-shaped cavities, and gypsum after anhydrite. Above are remnant "islets" of halite and anhydrite, gypsum replacing anhydrite and polyhalite, and dissolution breccia. The mineralogy and stratigraphy suggest that the shallow-seated "dissolution front" is a series of "fingers" moving laterally along bedding planes, rather than a single surface migrating downward. The sequence of alterations appears to be the fracture of brittle rock, the dissolution of halite adjacent to the fracture rock, the gypsification of interbedded polyhalite and then anhydrite, and the dissolution of gypsum. Waters of higher salinity and lower flow rate in the "brine aquifer" east of Nash Draw exhibit an oxygen isotope enrichment with respect to meteoric waters, indicating that the low fluid-to-rock ratio there has thus far precluded significant alteration of rock by water.

Lambert, S.J. 1983a. *Dissolution of Evaporites In and Around the Delaware Basin, Southeastern New Mexico and West Texas*. SAND82-0461. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Permian evaporites in the Ochoan Castile, Salado, and Rustler Formations in the Delaware Basin of southeast New Mexico and West Texas have been subjected to various degrees of dissolution (notably of halite and gypsum) through geologic time. Eastward tilting of the Delaware Basin has resulted in the exhumation and erosion of Ochoan rocks in the

western part of the basin. Waters in the Capitan, Rustler, Castile, and Bell Canyon Formations have previously been proposed as agents or consequences of evaporite dissolution according, to four principal models: solution-and-fill, phreatic dissolution, brine density flow, and strata-bound dissolution (along bedding planes). Several geomorphological features of positive and negative relief have previously been cited as indicators of evaporite dissolution. Brine density flow has been used to explain the selective dissolution of certain evaporite horizons during the late Cenozoic. A review of available geological data has revealed that halite deposition was probably not so extensive as formerly believed; waters with the potential to dissolve evaporites are in the Rustler and Capitan, but not in the Bell Canyon, Salado mine seeps, or the Castile brine reservoirs; brine density flow has not been active in removing most of the "missing" halite, nor are "point-source" dissolution features likely to have their roots at the Bell Canyon; major evaporite dissolution has not been confined to the late Cenozoic, but much of it took place during the Permian, Triassic, Jurassic, and Tertiary periods; and the Bell Canyon Formation has not been a sink for dissolution-derived brine.

Strata-bound dissolution is an efficient process for the removal of evaporites and is well exemplified in Nash Draw. This process entails downdip migration of meteoric water within beds of competent fractured rock, with upward and downward excursions of the water into adjacent halite-bearing beds. The chief weakness in the strata-bound model for dissolution is the as-yet-unidentified sink for dissolution brine. If the strata-bound model of dissolution is active in the removal of lower Salado halite, the threat of dissolution to the Waste Isolation Pilot Plant (WIPP) in the next 250,000 years is comparable to the threat to the same area posed by the growth of Nash Draw during the past 600,000 years. The regional geological history showed the past threat to be negligible.

ANNOTATION: Lambert prepared this report "...in response to a request by the State of New Mexico for a 'detailed review paper...specifically addressing Roger Anderson's (1978) hypothesis about extensive deep dissolution in the lower part of the Ochoan evaporite deposits in the Delaware Basin.'" Because of this requirement, which was not of Lambert's choosing, some have misunderstood this report as a pointed attack on Anderson. It is a critical look at the arguments that were made to that time, with emphasis on Anderson's work. While critical of certain aspects of solution hypothesis, Lambert also provided his own analysis and model of dissolution for further examination.

Lambert extensively reviewed uncritical assumptions about deposition patterns for the Castile. For example, Anderson (1981) assumed rather uniform, margin to margin deposition of halite in the Castile and Salado and calculated volume and percentage of "missing" halite. Lambert examined the overall thickness of units, concluding that depositional facies and deformation account for certain amounts of the "missing" halite. Lambert also pointed out that features of some Castile "dissolution residues" are similar to the reported elastic anhydrite of the Zechstein, preceding the findings of Robinson (1989) and Robinson and Powers (1987). Lambert also discussed other likely cases of syndepositional dissolution or nondeposition contrasting with assumptions of dissolution.

The Bell Canyon has been proposed as both a source of rising water for dissolution and a sink for the subsequent brine (Anderson, 1978). Though the process of brine density flow is physically possible, it is not likely to be significant (Wood et al., 1982). Lambert demonstrates that such a process is insignificant on the basis of geochemical evidence.

Lambert proposed a variation on "strata-bound" dissolution as previously proposed by Anderson. The principal difference is that Lambert believes that the sink or escape for brine is through a local low point or kind of base level within the unit, because he does not think the underlying Bell Canyon is a significant sink, given its hydrological and geochemical character.

The review by Lambert is noteworthy for several reasons. It is well written and is succinct, despite the variety of topics covered. Lambert critically examined many of the assumptions, often unstated, made in reports on dissolution. The most important assumption concerns the

original extent and thickness of Castile halite. The great difficulty with most mechanisms is how to remove the brine. As Lambert points out, "If an efficient sink for brine disposal does not exist, there is *no* active dissolution, regardless of the postulated mechanisms." This same conclusion led Robinson and Powers (1987) to directly examine alleged dissolution breccias. Finally, the review by Lambert is helpful by proposing a mechanism and possible tests of the mechanism.

Lambert, S.J. 1983b. "The Search for Active Geologic Processes in Evaluating Radioactive Waste Disposal Sites," *Abstracts with Programs 1983, 96th Annual Meeting, The Geological Society of America, Indianapolis, IN, October 31-November 3, 1983. SAND83-1033A. Vol. 15, no. 6, 622. (Abstract Only).*

ABSTRACT: Several methods in geology are applicable for identifying and evaluating the possible threat of active geologic processes to a disposal site for radioactive waste. It is useful to compare the site's host rock with modern analogs to evaluate the degree of preservation through geologic time. The origin of the rock notwithstanding, the site's geologic environment (including rocks and groundwaters) is likely to have undergone some epigenetic changes. In many cases, the time of the last major change can be determined by geochronologic methods. Isochron methods, involving the distribution of trace isotopes among coexisting solid phases at equilibrium, provide the most reliable age estimates. Other dating methods require a knowledge of the inferred initial, as well as the observed final state of the system. In certain methods, including all known groundwater-dating schemes, the initial state may be entirely dependent upon an inferred origin of groundwater. An active process will result in characteristic products. Rock textures will indicate strain or recrystallization in response to a measurable in situ stress or to interaction with groundwaters. Application of isotopic methods is, in many cases, the only way to detect such processes as continuous meteoric recharge of groundwater from a modern source, biogenic origin of certain minerals and gases, and the recrystallization of mineral phases in the presence of groundwater. Methods involving observations of distribution of rock, the degree of chemical equilibrium or disequilibrium, and the degree of geological homogeneity or differentiation should not be used alone to demonstrate the presence or absence of active processes, as it may be impossible to assign rates to processes that affect such observations.

Lambert, S.J. 1983c. "Evaporite Dissolution Relevant to the WIPP Site, Northern Delaware Basin, Southeastern New Mexico," *Scientific Basis for Nuclear Waste Management, Materials Research Society Proceedings VI, Boston, MA, November 1-4, 1982. Ed. D.G. Brookins. SAND82-1416C. New York, NY: Elsevier Science Publishing Company. Vol. 15, 291-298.*

ABSTRACT: Evaluation of the threat of natural dissolution of host evaporites to the integrity of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico has taken into consideration the volume of "missing" rock salt, the occurrence (or not) of characteristic dissolution brines, geomorphic features, some of which are unrelated to dissolution, and the time intervals over which dissolution may have been active. Even under the assumption that all "missing" halite was originally present and has been removed by dissolution, there is no evidence of active preferential removal of the lower Salado Formation halite by any geologically reasonable process. The geologic record contains evidence of dissolution in the Triassic and Jurassic; to constrain all removal of basinal halite to the late Cenozoic yields an unrealistically high rate of removal. Application to the lower Salado of a strata-bound mechanism known to be active in Nash Draw, a near-surface feature within the basin, allows a minimum survival time of 2,500,000 years to be predicted for the subsurface facility for storage of radioactive waste at WIPP. This calculation is based on an analysis of all known dissolution features in the Delaware Basin and takes into account the wetter (pluvial) climate during the past 600,000 years.

Lambert, S.J. 1987a. *Feasibility Study: Applicability of Geochronologic Methods Involving Radiocarbon and Other Nuclides to the Groundwater Hydrology of the Rustler Formation, Southeastern New Mexico.* SAND86-1054. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Radiocarbon, tritium, and ^{36}Cl were measured in groundwaters from the dolomite aquifers of the Rustler Formation in the northern Delaware Basin of southeastern New Mexico to determine the feasibility of using these nuclides in dating the groundwater at and near the Waste Isolation Pilot Plant (WIPP), a facility for geological disposal of radioactive waste. No measurable ^{36}Cl was found in any of these groundwaters, which derive their dissolved chloride from Permian evaporites. Demonstrably uncontaminated groundwaters contained no significant amounts of tritium (<0.2 TU). Percent modern carbon (PMC) correlates linearly and directly with bicarbonate concentration, indicating mixing of a high-PMC/high-bicarbonate reservoir with a low-PMC/low-bicarbonate reservoir. This relationship, together with the history of development of the wells sampling the groundwaters, indicates contamination by anthropogenic modern carbon rather than simple dilution by dissolving rock carbonate. $\delta^{13}\text{C}$ does not linearly correlate with bicarbonate, indicating no single source of contaminant radiocarbon. Values of PMC and $\delta^{13}\text{C}$ for groundwaters were used to calculate apparent radiocarbon ages according to an interpretive model that accounts for water/rock interactions in carbonate aquifers. All but six pairs of values gave significant negative ages (-1,000 to -7,000 years). This suggests that in contaminated samples the model over-adjusts (based on $\delta^{13}\text{C}$) for radiocarbon loss caused by dilution and isotopic exchange with the rock. Four groundwater samples (3 from the Rustler and 1 from the overlying Dewey Lake Red Beds) gave apparent radiocarbon ages $> 10,000$ years, and their carbon-isotope systematics suggest that their apparent ages are all the result of a single evolutionary trend of rock/water interaction involving carbon isotope exchange, with a probable recharge age of 13,000 years before the present. This time of isolation from the atmosphere, which is unrelated to travel time within the Rustler, is consistent with paleoclimatic evidence of wetter conditions more conducive to recharge in the late Pleistocene than at present.

Lambert, S.J. 1987b. "Stable-Isotope Studies of Groundwaters in Southeastern New Mexico," *The Rustler Formation at the WIPP Site.* Ed. L. Chaturvedi. EEG-34; SAND85-1978C. Santa Fe, NM: Environmental Evaluation Group. 36-57.

ABSTRACT: Oxygen-18/16 and deuterium/hydrogen ratio measurements have been made on groundwaters sampled according to specific field criteria applied during pump tests of the Rustler Formation (the uppermost Permian evaporite unit) in Nash Draw, a solution-subsidence valley west of the Waste Isolation Pilot Plant (WIPP) Site in the northern Delaware Basin of southeastern New Mexico. Comparison of these data with similar measurements on other groundwaters from the northern Delaware Basin indicates two nonoverlapping populations of meteoric groundwaters in $\delta\text{-O-18}/\delta\text{-D}$ space. Most of the Rustler waters in Nash Draw and at the WIPP Site and older waters from the eastern two-thirds of the Capitan Limestone constitute one population, while unconfined groundwaters originating as observable modern surface recharge to alluvium, the near-surface Rustler in southwestern Nash Draw, and the Capitan in the Guadalupe Mountains (Carlsbad Caverns) constitute the other. The isotopic distinction suggests that Rustler groundwater in most of Nash Draw and at the WIPP Site is not receiving significant modern meteoric recharge. A likely explanation for this distinction is that meteoric recharge to most of the Rustler and Capitan took place in the geologic past under climatic conditions significantly different from the present.

Lambert, S.J., and J.A. Carter. 1984. *Uranium-Isotope Disequilibrium in Brine Reservoirs of the Castile Formation, Northern Delaware Basin, Southeastern New Mexico. I: Principles and Methods.* SAND83-0144. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: We evaluated uranium isotope activity ratios with respect to models for the origin of the brines in two brine reservoirs in the Castile Formation (ERDA-6 and WIPP-12). In Castile anhydrite, a completely closed water system that was continuously leaching Th-recoil-produced ^{234}U from freshly exposed surfaces of fractured host rock would give rise to uranium 234/238 isotope activity ratio (α) values significantly higher than observed values. Therefore, the brine occurrences are not the result of continuous deformation. Similarly, a model assuming movement of intergranular Permian seawater into fractures was found inconsistent with observed uranium isotope systematics. The observed α -values (95% confidence limits) of ERDA-6 (1.34 to 1.58) and WIPP-12 (1.74 to 2.54), used in conjunction with an inferred initial α_0 higher than observed values, allows calculation of reasonable finite minimum ages, involving no preferential leaching of ^{234}U in the host rock. If the brine occurrences are inferred to have been connected at one time with a more extensive nearby hydrologic system, the Capitan limestone ($\alpha_0 = 5.1$), calculated minimum ages of isolation from that system are 700,000 to 880,000 years for ERDA-6 and 360,000 to 610,000 years for WIPP-12. These ranges in ages are the 95% confidence limits based on experimental determinations of α -values. The ages thus derived may reflect an episode of structural deformation in the Pleistocene that allowed water to enter the resulting fractures.

Lambert, S.J., and J.A. Carter. 1987. *Uranium-Isotope Systematics in Groundwaters of the Rustler Formation, Northern Delaware Basin, Southeastern New Mexico. 1: Principles and Preliminary Results.* SAND87-0388. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Values for uranium concentration ([U]) and $^{234}\text{U}/^{238}\text{U}$ activity ratio (AR) have been determined for groundwaters and host rocks from the Rustler Formation near the Waste Isolation Pilot Plant (WIPP) Site in the northern Delaware Basin of southeastern New Mexico. [U] varies from about 0.02 to 40×10^{-9} g/g, increasing westward across the WIPP Site to Nash Draw, a dissolution valley underlain by outcrops of Rustler Formation evaporites. Large deviations from secular equilibrium ($\text{AR} \approx 1$) in the groundwaters increase eastward from about 2 to 3 in Nash Draw to almost 12 in the eastern part of the WIPP site. [U] and AR variations cannot be completely explained by simple mixing caused by congruent dissolution of uranium from rock (without isotopic fractionation). AR values typically increase along the flow path in a reducing environment, and the observed eastward increase in AR suggests a relict flow system whose dominant flow direction (eastward) was at high angles to that now observed. A westward decrease in AR coupled with a steady increase in [U] indicates not only that there was a change in flow direction since recharge, but that Rustler groundwater is now draining from areas of high potentiometric level and low permeability near the WIPP Site, without appreciable recharge. The maximum time required for this westward drainage is about 200,000 years. The minimum time required to achieve the highest observed ARs during the earlier episode of eastward flow from recharge in the west is 10,000 to 30,000 years. Radiocarbon and stable-isotope studies of the Rustler Formation near the WIPP indicate that the modern Rustler flow system is not at steady state, recharge being dominated by wetter climatic conditions in the Pleistocene. Uranium-isotope studies are consistent with these results, and further suggest that present flow directions are qualitatively different from those existing at the time of recharge.

Lambert, S.J., and D.M. Harvey. 1987. *Stable-Isotope Geochemistry of Groundwaters in the Delaware Basin of Southeastern New Mexico.* SAND87-0138. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: $^{18}\text{O}/^{16}\text{O}$ and D/H ratio measurements have been made on groundwaters sampled from the Rustler Formation (Ochoan, Permian) and related rocks in the northern Delaware Basin of southeastern New Mexico. Most confined Rustler waters at the Waste Isolation Pilot Plant (WIPP) Site and to the west in Nash Draw and confined waters from the Capitan limestone constitute one population in $\delta\text{D}/\delta^{18}\text{O}$ space, while unconfined groundwaters inferred to originate as modern surface recharge to alluvium, sandstones in the Ogallala Formation, the

near-surface Rustler in southwestern Nash Draw, and the Capitan vadose zone in the Guadalupe Mountains (Carlsbad Caverns) constitute a distinctly different population; the two do not overlap. A likely explanation for this distinction is that meteoric recharge to most of the Rustler and Capitan took place in the geologic past under climatic conditions significantly different from the present. Available tritium and radiocarbon data are consistent with this hypothesis, and the apparent age of confined groundwaters is in excess of 12,000 radiocarbon years, suggesting that recharge took place under wetter conditions in the late Pleistocene. Processes governing recharge in the Delaware Basin are significantly different from those in the nearby Roswell Artesian Basin, but may be similar to those previously described for the Albuquerque (New Mexico) and Murray (South Australia) Basins. Rustler water from the WIPP Site and east-central Nash Draw is not discharging from springs in southwestern Nash Draw; the discharge there is part of a local shallow groundwater system associated with surficial gypsum karst and discharge from nearby potash refining. Water at the Rustler/Salado contact at the WIPP Site is of meteoric origin, but has experienced isotope shift that increases with decreasing permeability, and is part of the same isotopic trend as the ERDA-6 brine occurrence and fluid inclusions from Salado Formation halite core. Radiometric ages of secondary Salado minerals are not consistent with vertical mixing between deep brines and meteoric waters to form the fluid inclusions. Mine seeps and WIPP fluid inclusions have similar isotopic compositions, perhaps related to syndepositional mixing of evaporite brines and rainwaters. Rustler dolomites have not recrystallized in isotopic equilibrium with Rustler water, but much of the gypsum in the Ochoan section has done so. The absence of modern meteoric recharge to the Rustler at and near the WIPP Site indicates that the hydrologic system there is not at steady state. Instead, the system is responding to the cessation of local recharge, this cessation occurring some 10,000 to 30,000 years ago.

Lambert, S.J., and J.W. Mercer. 1978. *Hydrologic Investigations of the Los Medanos Area, Southeastern New Mexico, 1977.* SAND77-1401. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Five semi-independent documents within this report outline the philosophy and strategy for hydrologic testing in support of the Waste Isolation Pilot Plant (WIPP) Program. The hydrologic testing will provide the basic data for numerical modeling of the hydrologic systems and will be applied to radionuclide migration and assessments of risks to the WIPP. The main objectives are to construct piezometric potential contours for aquifers, determine fluid production, recover rock samples for studies of rock-fluid interactions, relate hydrology to salt dissolution subsidence and geomorphology, and understand the water budget.

The initial chapter reviews general geologic and hydrologic conditions in the vicinity of the WIPP. The broad outlines of study programs are provided in support of two objectives: "to evaluate the geologic integrity of salt units (with respect to dissolution power of adjacent aquifers) that may be called upon to serve as radionuclide disposal horizons and to provide input for numerical modeling of radionuclide migration...." Field tests are to be complemented with data from climatic records, meteorology, and laboratory studies of chemistry and core permeability. The second chapter outlines details of hydrologic testing of aquifers less than 1000 ft deep at hydrologic holes drilled for potash exploration (H-1, H-2 complex, and H-3) and four holes (P-14, -15, -17, -18). Potentiometric heads, rates of fluid production, and geochemical parameters of fluids will be measured over horizontal ranges of less than 100 ft, 2000 to 2500 ft, and 2 to 3 mi. The third document outlines broad program needs and background for testing hydrologic capabilities of units from the Salado to Pennsylvanian age rocks at depths of about 13,000 ft. Longer tests of the evaporites will be needed to determine fluid sources, and brine reservoirs can be tested by re-entering ERDA-6. The fourth and fifth chapters in this report provide detailed plans for testing the hydrology of the Bell Canyon Formation in AEC-8 and ERDA-10, respectively. AEC-8 is available for longer term testing and monitoring, while ERDA-10 will be tested with much shorter drill-stem tests before plugging.

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Lambert, S.J., and K.L. Robinson. 1984. *Field Geochemical Studies of Groundwaters in Nash Draw, Southeastern New Mexico.* SAND83-1122. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Physiochemical properties of effluents from 15 pump tests in the water-producing horizons intercepted by six holes in Nash Draw east of the WIPP Site in southeastern New Mexico were field-measured at intervals of a few hours. These properties were Eh, pH, specific conductance, specific gravity, bicarbonate/carbonate, chloride, divalent cations, calcium, hydrogen sulfide, and total iron. Observations were made over periods of 17 to 184 hours, during which the measurements reached varying degrees of steady state, but not necessarily equilibrium. The most useful indicators of steady state were divalent cations, chloride, and in some cases Eh. Typically, bicarbonate changed significantly during a pump test, seldom reaching steady state. This observation and the drilling history have shown that, given the nongeological sources of carbon, radiocarbon results will be difficult to interpret. Heavy-metal contamination from iron pipe in a well was not purged simply by displacing a well-bore volume, but is some complex function of "armor coating" of iron by corrosion. This process of armor-coating is, in turn, influenced by pump rate, instantaneous solid-to-liquid ratio, dissolved gases, and aqueous thermodynamic properties. Thus, further determinations of trace constituents associated with heavy metals must be interpreted with care in view of the iron content. Reliable sampling of pumped wells requires a long observation time; detailed documentation of procedures, apparatus, and hole history; and a commitment of human and financial resources that may be much greater than those required for conventional laboratory analyses.

Lambert, S.J., and H.C. Shefelbine. 1980. *A Strategy for Investigation of Fluid Migration in Evaporites (Waste Isolation Pilot Plant - WIPP).* SAND79-1889. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The proposed strategy for Waste Isolation Pilot Plant (WIPP) Project investigations of fluid migration in evaporites focuses upon a quantitative evaluation of each of several processes. Potential short- and long-term problems arising from fluid migration are complication of waste retrieval and mobilization of waste nuclides. The strategy will attempt to determine the degree to which these potentials are realized with respect to five hypothetical types of waste-rock interactions: movement of waste containers, migration of nuclides, formation of radioactive brine pocket, radiolytic generation of gas, and degradation of waste container. Of eight identified processes whose combinations could lead to the five types of interactions, only five are to be quantitatively investigated by the studies of fluid migration per se: presence of fluids, fluid mobilization toward heat-producing and contact handled (CH) waste, encounter of fluids with influence of waste form, reversal of direction of fluid mobilization, and entrainment of nuclides in fluids. Methods of investigation entail an iterative combination of laboratory experimentation and mathematical modeling.

Lappin, A.R. 1987. "Recent Developments in the Conceptual Geologic and Hydrologic Understanding of the WIPP Site, Southeastern New Mexico," *Waste Management 87, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 1-5, 1987.* Ed. R.G. Post. SAND87-0224C. Tucson, AZ: University of Arizona. Vol. 2, 255-259.

ABSTRACT: Hydrologic and geochemical characterization of the Waste Isolation Pilot Plant (WIPP) Site has progressed significantly since the 1980 WIPP *Final Environmental Impact Statement (FEIS)*. In 1980, the entire Rustler Formation was modeled as a single hydrologic unit, assumed to be isotropic, single-porosity, and completely confined. Variability within the Rustler was evaluated only on the basis of testing at individual wells. In the 1983 WIPP Site and Preliminary Design Validation (SPDV) effort, the Salado Formation, in which the WIPP

Facility is being constructed, was assumed to be anhydrous, except for fluid inclusions and mineralogically bound water.

Recent hydrologic and tracer testing at the WIPP indicates the local importance of dual-porosity behavior in hydraulic response and transport in parts of the Culebra Dolomite member of the Rustler Formation, the presence of distinct high- and low-transmissivity regions within the Culebra, and the possible importance of vertical fluid flow within the Rustler. Recent analyses indicate that fluids encountered in the WIPP Facility and in experimental brine-migration studies are grain-boundary fluids, chemically distinct from fluid inclusions. Fluid-inclusion compositions appear to have been determined shortly after the halite deposition. Because of the times required for diagenetic reactions controlling their compositions, the grain-boundary fluids within the Salado probably have a residence time of several million years.

Lappin, A.R. 1988a. *Summary of Site-Characterization Studies Conducted From 1983 Through 1987 at the Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico.* SAND88-0157. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is being constructed at a depth of 650 m in bedded halites of the Salado Formation. The geologic setting of the WIPP Site has been active for at least 250 million years and is presently responding to the end of the last pluvial period, within the 10,000-year time scale of regulatory interest. Both construction of the WIPP Facility and WIPP site-characterization activities impose additional transient effects, some of which will last until the hydrologic and structural closure of the facility.

The Bell Canyon Formation beneath the WIPP Facility contains shales, siltstones, and sandstones. Studies suggest that no channel sandstone is present in the Bell Canyon beneath the WIPP Site. Fluid movement would be downward if drilling interconnected the Bell Canyon with the Rustler Formation, the first water-bearing zone above the WIPP Facility.

The Salado and Castile Formations contain abundant bedded halites and anhydrites and deform in response to gravity. Fluids play a major role in this deformation, although the regional permeabilities of both units are extremely low. Pressurized brines may be present within the Castile Formation 200 m or more beneath the WIPP waste-emplacement panels. The hydrologic and structural characteristics of the Salado change within an altered zone extending a few meters from the WIPP underground workings.

The permeability within this altered zone is enhanced, and deformation includes local opening of preexisting fractures in anhydrite and formation of new fractures in halite. Within a few meters of the facility, the Salado characteristics become those of the far field, in which permeability is extremely low and deformation is dominated by creep. Brine seepage into the WIPP Facility is extremely slow and involves transient behavior resulting from the combined effects of deformation, low permeability, and ventilation.

At the WIPP Site, the hydrology and geochemistry of the Rustler Formation and younger units overlying the Salado are dominated by confined flow within the Culebra Dolomite. Rustler karst is not present at the WIPP Site but is present in and near Nash Draw. The combination of modern heads and transmissivities of units other than the Culebra indicates the potential for limited vertical flow within the Rustler and from the Salado into the Rustler, but is not consistent with infiltration of water from the surface to the Rustler carbonates at the WIPP Site. Isotopic studies indicate that surficial water was required for formation of secondary gypsum veins within the Dewey Lake Red Beds overlying the Rustler. The distribution of hydrochemical facies in Culebra groundwaters and the results of stable-isotope, radiocarbon, and uranium-disequilibrium studies are all consistent with the interpretation that there is no modern recharge to the Rustler at the WIPP Site, and that a change of flow directions in the Culebra dolomite has occurred over approximately the last 10,000 years.

The transmissivity of the Culebra dolomite varies by approximately 6 orders of magnitude at and near the WIPP Site. The transmissivity in the central portion of the site, including the locations of all four WIPP shafts, is low (less than 10^{-6} m²/sec). Higher Culebra transmissivities are found south, northwest, and west of the site, especially in Nash Draw. Fracturing within the Culebra affects local hydrology and contaminant transport, but is not significant in regional-scale behavior at and near the site, at least so long as the present distribution of head potentials is not significantly disturbed.

Lappin, A.R. 1988b. "Summary of Site-Characterization Studies Conducted From 1983 Through 1987 at the Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal. Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988.* Ed. R.G. Post. SAND88-0157C. Tucson, AZ: University of Arizona. Vol. 2, 371-375.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is being excavated at a depth of approximately 655 m in bedded halites. Site-characterization activities at the WIPP Site began in 1976. Characterization activities since 1983 have had the objective of updating the conceptual model for the geologic and hydrologic behavior of the WIPP Site and vicinity. This paper discusses aspects of the general conceptual model significant to both site characterization and performance assessment. The geologic and hydrologic behavior of the WIPP Site and vicinity is transient, and has been transient since at least deposition of the Permian Salado Formation containing the underground workings of the WIPP Facility. The Salado Formation deforms regionally in response to gravity, but is very low in permeability, except within approximately 2 m of the WIPP Facility. The Culebra Dolomite Member of the Rustler Formation dominates the hydrology at the WIPP Site. Hydrologic measurements, geologic studies, major-element and minor-element distributions in Culebra fluids, and the results of isotopic studies (stable-isotope, radiocarbon, uranium-disequilibrium, and ⁸⁷Sr/⁸⁶Sr) are consistent with interpretations that, although the Culebra dominates flow within the Rustler at the WIPP Site and Rustler karst is not present, there has been limited vertical fluid movement within the Rustler and between the Rustler and the overlying Dewey Lake Red Beds. These same studies are consistent with the interpretation that there has been little or no surficial recharge to the Rustler at the WIPP Site for at least the last 12,000 years.

Lappin, A.R. 1989. "Summary of Site-Characterization Results at the [Waste] Isolation Pilot Plant (WIPP) Site, Southeastern, New Mexico," *28th International Geological Congress, Abstracts, Washington, DC, July 9-19, 1989.* SAND88-3278A. Vol. 28, 2-259 through 2-260. (Abstract Only).

ABSTRACT: Site-characterization activities at the Waste Isolation Pilot Plant (WIPP) Site, located in an aseismic portion of the northern Delaware Basin, began in 1976. The WIPP Facility, designed for storage and isolation of defense-generated transuranic (TRU) wastes, is being excavated at a depth of approximately 650 m in bedded halites of the Permian Salado Formation.

This presentation will summarize the results of WIPP site-characterization studies since 1983 and describe the present conceptual geologic model of the WIPP Site. WIPP site-characterization studies through 1987 were summarized in 1988; hydrologic and geochemical interpretations are treated in more detail in various reports.

The shales, siltstones, and sandstones of the Bell Canyon Formation contain the first relatively continuous water-bearing zone beneath the WIPP disposal horizon, while the Rustler Formation contains the first laterally continuous water-bearing zones above the disposal horizon. The two units are, respectively, 650 m below and 450 m above the disposal horizon. Recent studies indicate that the final direction of fluid flow following interconnection of the Bell Canyon, Salado, and Rustler Formations would be downward into the Bell Canyon.

The Castile and Salado Formations contain layered anhydrites and halites and are very low-permeability units that have deformed significantly in response to gravity. Regional halite deformation is by coherent creep. Undisturbed formation permeabilities in both units are very low (approximately 10 nanodarcies or less). The stratigraphic variability of permeabilities in the Salado has not yet been determined. Within the Delaware Basin, isolated occurrences of brine in Castile anhydrites and gas in the Salado Formation have been encountered. Both types of occurrence are apparently fracture-controlled, can be large in volume, and can be under pressures between lithostatic and hydrostatic. Geophysical studies indicate that Castile brines probably are present beneath a portion of the WIPP waste-emplacement panels, but 200 m or more below the facility horizon. These brines are of concern to performance of the WIPP Facility only in the event of human intrusion.

The hydrologic and structural characteristics of the Salado in the disturbed zone around the WIPP Facility are different than in the far field. Permeability increases by orders of magnitude within a couple of meters of the underground workings. Deformation of the Salado Formation with the disturbed zone involves both the opening of pre-existing fractures in an anhydrite marker bed 2 m beneath the facility horizon and generation of new fractures in halite. The extent, characteristics, and importance of the time-dependent disturbed rock zone (DRZ) around the WIPP Facility are being determined in detail.

The Rustler Formation is a layered unit of anhydrites, siltstones, and halites. It contains the most significant aquifer at the WIPP, the variably fractured Culebra dolomite. Measured Culebra transmissivities range from less than 10^{-7} m²/sec to greater than 10^{-3} m²/sec. Where Culebra transmissivity is greater than approximately 10^{-6} m²/sec, fracturing may be sufficient to affect both hydraulic and transport behavior over distances of at least 30 m. However, interpretation of regional-scale interference tests in the Culebra indicates that fracturing need not be incorporated in numerical modeling of regional-scale hydraulic behavior. Detailed transport calculations also indicate that fracturing effects are not significant in regional-scale radionuclide transport in the Culebra Dolomite, as long as the modern north-south gradients are not significantly disturbed.

The Dewey Lake Red Beds overlying the Rustler Formation contain siltstones and claystones, with subordinate sandstones. In most locations, the Dewey Lake is hydrologically unsaturated and/or too low in hydraulic conductivity for successful hydrologic testing (10^{-11} m/sec).

Isotopic relations suggest that surficial waters have been involved in the formation of secondary gypsum veins within the Dewey Lake, but that the Dewey Lake and Rustler hydrologic systems are largely separate.

The major near-surface units at the WIPP Site are the Gatuña Formation and Mescalero caliche. The sandstones and stream-channel conglomerates within the Gatuña indicate major changes in local climate over the last 600,000 years. The widespread preservation of the Mescalero caliche indicates the relative structural stability of the WIPP Site over the last 400,000 years.

Both the bulk chemistry and uranium-isotopic relations of Culebra waters are inconsistent with modern flow directions, if steady-state confined flow is assumed. Because of the relative permeabilities and modern head potentials of the different members of the Rustler Formation, horizontal flow within the Culebra dolomite dominates the short-term hydrology of the Rustler Formation at and near the WIPP Site.

However, available head and permeability data are consistent with both limited fluid flow from the underlying Salado Formation into the Rustler and vertical fluid flow within the Rustler. The limited data available, however, are not consistent with vertical recharge from the surface to Rustler carbonates. Evaporite karst is not developed within the Rustler Formation at the WIPP Site, but is developed in and along the flanks of a solution valley (Nash Draw) west of the site.

Hydrologic, radiocarbon, stable-isotope, and geochemical data from the Rustler Formation data are consistent with the interpretation that discernible modern meteoric recharge to the Rustler carbonates is not occurring at or near the WIPP Site; Rustler groundwaters at the WIPP Site were isolated from the atmosphere at least 12,000 to 16,000 years ago; and the transient response of the Culebra to the effective end of local recharge approximately 12,000 to 16,000 years ago has involved a significant change in flow directions.

In fact, the geologic and hydrologic settings of the WIPP Site have been transient since before the beginning of deposition of the Bell Canyon Formation, approximately 250 million years ago, and will continue to be transient on geologic time scales after closure of the WIPP Facility. Many events, such as formation of the Mescalero caliche, have taken place on a very long time scale relative to the 10,000 year time frame considered by WIPP performance assessment. Two types of transient response are occurring within the 10,000 year time frame of regulatory interest. These are the natural response of at least the Culebra hydrologic system to the end of the last pluvial period, and the responses to man-induced transients resulting from WIPP Site characterization and facility construction.

ANNOTATION: The site characterization studies for WIPP from 1983 through 1987 are summarized in Lappin (1988a). Hydrologic interpretations are treated in more detail in reports such as LaVenue et al. (1988).

Lappin, A.R. 1990. "Site-Characterization Studies at the Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico," *Radioactive Waste Management and the Nuclear Fuel Cycle*. SAND88-1105J. Vol. 14, no. 1-2, 101-121.

ABSTRACT: Underground workings for the US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico are being excavated at a depth of approximately 655 m in bedded halites within the Salado Formation of Permian age. Site-characterization activities at the WIPP began in 1976. Early WIPP site-characterization and consequence-assessment studies were documented in 1978 and 1980. A second major round of documentation was completed in 1983, at the end of the WIPP Site and Preliminary Design Validation (SPDV) activities. Site-characterization activities since 1983 have had the objective of updating the conceptual model for the geologic and hydrologic behavior of the WIPP Site and vicinity. This paper discusses aspects of this conceptual model relevant to both site characterization and performance assessment and incorporates the results of site-characterization studies conducted from 1983 through 1987.

The geologic and hydrologic behavior of the WIPP Site and vicinity is transient (time-dependent) on geologic time scales of interest and has been transient since before deposition of the Salado Formation containing the WIPP underground workings, more than 200 million years ago. Both natural and man-induced transient responses are now occurring at the WIPP Site, on time scales well within the 10,000-year time frame of regulatory interest. The Salado and Castile Formations deform regionally in response to gravity. The Salado is generally very low in permeability, except within approximately 2 m of the WIPP underground workings where it is structurally and hydrologically disturbed by the presence of the facility itself. However, both the permeability and water content of Salado halites, while small, are nonzero.

The Culebra Dolomite Member of the Rustler Formation dominates the hydrology at the WIPP Site above the Salado. Rustler karst is not present at the WIPP Site, which is defined here as the 16 mi² under DOE control. Within Nash Draw, 2 mi or more west of the edge of the WIPP Site, the exposure of Rustler gypsums/anhydrites to surficial processes has resulted in an evaporite-karst terrain including small caverns in gypsiferous zones near the surface. At the WIPP Site, hydrologic measurements, geologic studies, major-element and minor-element distributions in Culebra fluids, and results of isotopic studies (stable-isotope, radiocarbon, uranium-disequilibrium, and ⁸⁷Sr/⁸⁶Sr) are all consistent with the interpretation that there has been only limited vertical fluid movement within the Rustler and between the Rustler and the

overlying Dewey Lake Red Beds. These same studies are consistent with the interpretations that there has been little or no surficial recharge to the Rustler at the WIPP Site for at least the last 12,000 years; and as a result of the cessation or reduction in recharge in response to climatic change, there has been a change in flow directions within the Culebra, from the southeasterly flow during the last recharge event to the present generally north-south flow.

Lappin, A.R., R.L. Hunter, D.P. Garber, and P.B. Davies, eds. 1989. *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; March 1989.* SAND89-0462. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report summarizes current understanding of the expected long-term behavior of the Waste Isolation Pilot Plant (WIPP) and estimates long-term radionuclide doses for both undisturbed repository performance (Case I) and in response to a relatively high-consequence human intrusion (Case II). The report has several objectives: to briefly summarize current understanding of major components of long-term performance of the WIPP repository; to compare current conceptual and numerical models with those available in the *WIPP Final Environmental Impact Statement (FEIS)* (US DOE, 1980a); to document the parameter values now thought to be "representative" or "most likely" for numerical predictions of the long-term behavior of the repository; and to describe, document, and interpret calculations estimating the potential health effects to individuals from contact handled transuranic (CH TRU) wastes in the WIPP, saturation of the repository, direct and indirect exposure during and after drilling (where appropriate), and groundwater transport of radionuclides to a hypothetical stock well south of the WIPP Site.

Several factors are understood differently from the *FEIS* of 1980. The Salado Formation is now considered hydraulically saturated, and the estimated far-field permeability is now significantly less than in 1980. The estimates of total gas-generation capacity are smaller now. Reduced gas generation and greatly decreased permeability lead to the conclusion that the waste-filled rooms and drifts at the WIPP may not be saturated with brine within 10,000 years. The gas generated by waste degradation may exceed the gas-storage volume of the waste-disposal rooms. It is not now possible to evaluate the likelihood of whether the rooms will expand, fractures or disturbed rock will store gas, gas will migrate along fractures in MB-139, or gas will migrate into shafts and adjacent marker beds after moving through MB-139. Pressurized brine is now assumed to occur in the Castile Formation under part of the WIPP. Assumptions about bore hole-plugging affect calculations involving drill holes through the repository into a brine reservoir. The plugging of industry holes was not specifically addressed in the *FEIS*. The Culebra Dolomite Member is now treated as a separate hydrologic unit affected by fractures. Calculations now emphasize 10,000 years after closure rather than 1,000,000 years, and the transport is evaluated at a hypothetical stock well 4 mi south of the WIPP Site center rather than at Malaga Bend on the Pecos River.

Case I predicts no radionuclides transported to the Culebra Member or land surface within 10,000 years. The repository is assumed to be saturated with brine 2,000 years after closure. Case II showed very low release to the surface and doses to a farm family 500 m downwind. Case II involves drilling into an underlying pressurized brine reservoir. Waste properties, repository permeabilities, and Culebra properties are varied in Case II. The combination of parameter values resulted in a calculated arrival time of radionuclides at the hypothetical stock well of slightly < 100 years and "maximum whole-body 50-year dose commitment from one year of [eating beef] ... estimated to be 130 mrem ... occurring ~1,350 years after repository decommissioning."

The undisturbed WIPP is not expected to release any radioactivity to either the Culebra or to the surface within 10,000 years. If several "expected" properties of waste, backfill, bore hole plugs, and the Culebra are supported during the WIPP demonstration phase, there is high confidence the WIPP will comply with regulatory guidelines. If these properties are

significantly "worse" than expected, significant releases might occur. If so, waste and backfill may be modified to comply with regulatory guidelines.

These calculations are based mainly on data collected since the *FEIS*, but some data are uncertain or do not exist. Some areas of uncertainty will be reduced during the demonstration phase. Expert judgment will be used for other areas of uncertainties. The calculations assume probabilities of 1.0 and calculate doses at 10,000 years, thus differing from the performance assessment.

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ANNOTATION: The performance assessment referred to here is an alternative process that will be used ultimately to evaluate compliance with 40 CFR 191B. See Bertram-Howery et al., 1989, 1990 and Marietta et al., 1989 for report of preliminary PAS.

Lappin, A.R., R.L. Hunter, P.B. Davies, D.J. Borns, M. Reeves, J. Pickens, and H.J. Iuzzolino. 1990. *Systems Analysis, Long-Term Radionuclide Transport, and Dose Assessments, Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; September 1989.* SAND89-1996. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This study supports the Waste Isolation Pilot Plant (WIPP) *Final Supplement, Environmental Impact Statement* (DOE/EIS-0026-FS) and has two main objectives. First, it describes current ideas about the characteristics and potential impacts of the disturbed rock zone (DRZ) known to develop with time around excavations at the WIPP horizon. Second, it presents new calculations of radionuclide migration within and from the WIPP repository for steady-state undisturbed conditions and for two cases that consider human intrusion into the repository.

A DRZ will develop near underground openings in salt. At the WIPP, the presence of a DRZ has been confirmed by geophysical studies, gas-flow tests, and direct observations. The DRZ results from dilation and rapid strain rates near the excavation. The behavior of the DRZ may include slabbing of the roofs of rooms, entryway, and accessways. The DRZ will allow gas or brine from waste-emplacement panels to bypass panel seals and flow into adjacent portions of the underground workings unless preventive measures are taken. The DRZ may alter fluid-flow behavior within the Salado Formation near the repository and increase the flow of brine into the repository, but fractures within the DRZ should also provide significant storage capacity for gases that may be generated as a result of brine inflow.

Revised calculations of the undisturbed performance of the repository indicate that no radionuclides will be released into the Culebra Dolomite within the regulatory period of 10,000 years. Because no exposures to human beings are possible, no dose calculations are warranted.

The human-intrusion calculations included here assume a connection between the WIPP repository, an occurrence of pressurized brine within the underlying Castile Formation, and the overlying Culebra Dolomite. The calculations differ in three important ways from earlier calculations performed in support of the *Draft Supplemental Environmental Impact Statement* (DOE/EIS-0026-DS): two-dimensional contaminant transport within the Culebra is modeled more realistically; the new calculations use a revised Culebra transmissivity distribution; and the new calculations explicitly compare and contrast results of single- and double-porosity calculations. The improved calculations change the previous estimates of the consequences of human intrusion in several ways. For expected conditions within the Castile Formation, the repository, and the Culebra Dolomite, integrated releases at the WIPP Site boundary are several orders of magnitude below those allowed by the present form of 40 CFR 191. For unlikely, degraded flow-and-transport conditions within the repository and the Culebra Dolomite, integrated releases at the WIPP Site boundary at 10,000 years are calculated to be 3.2 times the limit presently set by 40 CFR 191 for releases with probabilities greater than 0.1 and less than the limit set for releases with probabilities less than 0.1. The calculated release at 5 km is 0.7 times that limit. Calculated individual 50-year dose commitments from daily ingestion of beef

contaminated by Culebra groundwaters are 7.9×10^{-7} mrem/50 years for expected conditions and 28 mrem/50 years for degraded conditions. Both dose commitments are lower than calculated earlier.

LaVenue, A.M., T.L. Cauffman, and J.F. Pickens. 1990. *Ground-Water Flow Modeling of the Culebra Dolomite. Volume I: Model Calibration.* SAND89-7068/1. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This hydrogeologic modeling study has been performed as part of the regional hydrologic characterization of the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. The study has produced an estimation of the transmissivity and Darcy-velocity distributions in the Culebra Dolomite Member of the Permian Rustler Formation at the WIPP Site. The results of this study are intended to support Sandia National Laboratories (SNL) performance-assessment calculations.

The three-dimensional finite-difference code SWIFT II was employed for the numerical modeling, using a variable-fluid-density and single-porosity formulation. The spatial scale of the model, 21.3 km by 30.6 km, was chosen to allow simulation of regional-scale pumping tests conducted at the H-3 and H-11 hydropads and the WIPP-13 borehole, which are located south, southeast, and northwest, respectively, of the center of the WIPP Site. The modeled area includes and extends beyond the controlled area defined by the WIPP Site boundaries.

The work performed in this study consisted of modeling the hydrogeology of the Culebra in two stages: steady-state modeling to develop the best estimate of the undisturbed head distribution (i.e., of the hydraulic conditions before excavation of the WIPP shafts, which began in 1981) and superimposed transient modeling of local hydrologic responses to excavation of the four WIPP shafts at the center of the WIPP Site, as well as to various well tests. The transient modeling used the calculated steady-state freshwater heads as initial conditions.

The steady-state calibrated transmissivity field contains transmissivities that vary over seven orders of magnitude increasing westward toward Nash Draw. The most significant feature of the transmissivity field is a high-transmissivity zone in the vicinity of wells H-17, P-17, and H-11. Modeled transmissivities within this zone are approximately 5×10^{-5} m²/sec. The location of and transmissivities within the zone are similar to those proposed in a previous interim modeling report.

After calibration of the steady-state model, the major drilling and testing activities at the WIPP shafts and well locations were incorporated into the model. The transient simulation of the major hydraulic stresses in the Culebra Dolomite extended from January 1, 1981 to June 16, 1989. Calibration of the model to the transient events required additional changes to the steady-state calibrated transmissivity field in order to reduce the differences between the calculated and observed transient heads. The major difference between the transient calibrated transmissivity field and the steady-state calibrated transmissivity field is the extension of the higher transmissivity zone near H-11 northward toward H-15.

The travel times for nonsorbing particles released within the steady-state flow field, using the transient calibrated model, were computed from selected locations within the model to the southern model (down-gradient) boundary. The predicted travel time from a release point within the Culebra that is coincident with the centroid of the waste panels to the southern WIPP Site boundary is 1.4×10^4 years. Calculations were performed to assess the sensitivity of the above travel time to the grid-block transmissivities and the pressures assigned to the model boundaries.

LaVenue, A.M., A. Haug, and V.A. Kelley. 1988. *Numerical Simulation of Ground-Water Flow in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site: Second Interim Report.* SAND88-7002. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The transmissivity distribution, hydraulic potentials, flow field, and fluid densities in the Culebra Dolomite Member were estimated at the WIPP Site. The three-dimensional finite-difference code SWIFT-II was used with variable-fluid-density and a single-porosity formulation. Brine density changes caused by the present flow field or caused by local reactions, such as halite dissolution, are not included in the model. The model area extends beyond WIPP control zones, and it was chosen to allow simulation of a 62-day pumping test at the H-3 hydropad and a 36-day pumping test at WIPP-13.

The Culebra was modeled with steady-state conditions to best estimate the undisturbed head distribution (i.e., before sinking the WIPP shafts in 1981) and with superimposed transient responses to excavation of the three WIPP shafts as well as to various well tests. Constant fluid pressures and densities were estimated using data from about 40 wells. The transient modeling used the calculated steady-state freshwater heads as initial conditions.

The initial spatial transmissivity distributions using two different kriging techniques are very similar, with low transmissivities ($< 1 \times 10^{-7} \text{ m}^2/\text{sec}$) in the eastern model area, intermediate transmissivities (1×10^{-6} to $1 \times 10^{-4} \text{ m}^2/\text{sec}$) in the central part of the model area, and high transmissivities ($> 1 \times 10^{-3} \text{ m}^2/\text{sec}$) in the western part of the model area representing Nash Draw. The initial steady-state model was calibrated so that differences between calculated and observed freshwater heads are less than the uncertainties associated with observed heads.

The steady-state transmissivity distribution contains a relatively high-transmissivity (approximately $5 \times 10^{-5} \text{ m}^2/\text{sec}$) zone between wells H-17 and P-17. The zone is approximately the same as that previously proposed, but the transmissivity is four times lower in magnitude. Sensitivity analyses demonstrate that a higher transmissivity feature between H-17 and P-17 is required to reduce the differences between the calculated and observed heads in the vicinity of DOE-1 and H-11 below the uncertainties of the observed heads. A relatively large area of low transmissivities (less than approximately $10^{-6} \text{ m}^2/\text{sec}$) occurs near the center of the site.

The following activities at the WIPP shafts and well locations were incorporated into the model and superimposed onto the steady-state head distribution: a simplified but complete shaft history since 1981; three pumping tests and a series of slug tests conducted at the H-2 hydropad in 1982 and 1981; the H-3 convergent-flow tracer test conducted in 1984; the H-3 step-drawdown test conducted in 1985; the H-3 multipad pumping test in 1985 and 1986; the convergent-flow tracer test at the H-4 hydropad conducted between 1982 and 1984; and the WIPP-13 multipad pumping test conducted in 1987. The transient simulation of these hydraulic stresses in the Culebra extended from January 1, 1981 to December 31, 1987.

The initial transient simulation adequately reproduced the observed drawdowns at P-14, DOE-2, and H-6 during the WIPP-13 multipad pumping test. The calculated drawdowns at H-11 and DOE-1 during the simulation of the H-3 multipad pumping test are also very similar to the observed drawdowns. The steady-state calibrated transmissivities do not adequately reproduce the observed transient responses generated from the shaft events or the observed drawdowns at the pumping wells used in the simulation, H-2, H-3, H-4, and WIPP-13. The calculated drawdowns at these wells are a factor of two greater than observed drawdowns. Similarly, calculated drawdowns caused by shaft events are a factor of two greater than the observed drawdown at H-1, H-2, and H-3.

Sensitivity analyses indicate that the steady-state calibrated transmissivities must be adjusted to reduce the differences between the calculated and observed transient data. Lower transmissivities are required between the shafts and H-1, H-2, H-3, and the WIPP wells in the vicinity of the shafts. Higher transmissivities are necessary in the vicinity of H-2, H-3, H-4, and WIPP-13. A higher transmissivity, low-storage zone between WIPP-13 and the WIPP

wells north of the shafts is necessary to reproduce the observed transient responses during the WIPP-13 multipad pumping test.

This study is based on transmissivity data available as of November 1987, and hydraulic-head data available as of August 1987. The next step will incorporate the transient effects caused by pumping during a tracer test at the H-11 hydropad and the transient effects caused by the construction of the fourth shaft. Adjoint-sensitivity techniques will provide quantitative estimates of sensitivities of model results to the spatial distribution of the model parameters and the boundary conditions. DWP

LaVenue, A.M., M. Reeves, and B.S. Rama Rao. 1989. "An Application of Coupled Adjoint-Sensitivity and Kriging Techniques to Calibrate a Groundwater Flow Model in the Vicinity of a Nuclear Waste Repository," *28th International Geological Congress, Abstracts, Washington, DC, July 9-19, 1989.* SAND88-7150A. Vol. 28, 2-250 through 2-251. (Abstract Only).

ABSTRACT: Site-characterization efforts are being conducted at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico as part of the evaluation of the suitability of the bedded salt of the Salado Formation for isolation of defense transuranic (TRU) wastes. Studies investigating regional and local geologic, geochemical, and hydrogeologic processes have primarily focused on the Culebra Dolomite Member of the Rustler Formation, which is the most transmissive and laterally continuous hydrogeologic unit above the Salado Formation. The Culebra is considered the principal pathway for radionuclide transport in the subsurface should an accidental breach of the repository occur.

Numerical-simulation studies have been performed over the last three years to understand the groundwater flow regime within the Culebra; develop best estimates of the regional transmissivities, regional head distribution, and groundwater travel times under modern or "undisturbed" conditions; and determine model sensitivity and parameter uncertainties. The results of these studies will be used in subsequent performance-assessment investigations. The objective of this paper is to present an approach coupling the adjoint-sensitivity technique and kriging. This approach greatly reduces the effort required during the calibration process of a flow model. This study is being coordinated with regional-scale studies carried out at both the US Geological Survey (USGS) and Sandia National Laboratories (SNL).

A coupled adjoint-kriging technique was first used by Marsily and others in 1984 to direct the adjustment of pilot-point transmissivity values as a means for automatically calibrating an inverse model. This paper presents a modification of this coupled adjoint-kriging technique that allows identification of the most sensitive regions for transmissivity changes during model calibration to observed heads. The application of this technique to the Culebra flow model is discussed.

The adjoint-sensitivity technique can be used to determine model sensitivities. The adjoint technique determines the sensitivity of a system performance measure (a dependent variable, such as cumulative differences in observed and calculated heads at several locations in the model) to a selected system parameter (an independent variable, such as the transmissivity of the performance measure with respect to the system parameter). Either local-scale or regional-scale performance measures may be selected. For instance, the sensitivity of the calculated head at a selected location to the transmissivities in neighboring grid blocks may be determined. On a regional scale, the sensitivity of calculated heads at several locations to the transmissivity in a selected grid block may be calculated.

Kriging has also played an important role in the calibration process of the regional-scale Culebra model as a tool for developing and selectively adjusting the transmissivity distribution for model input. Transmissivity distribution adjustments have been implemented by introducing "pilot points" to the observed transmissivity data base. A pilot point is simply an additional transmissivity value assigned to a location selected by the modeler, which is included

in the transmissivity data base for kriging. The pilot-point approach, first proposed by Marsily et al. in 1984, facilitates the local adjustment of a model's transmissivity distribution by the inclusion of additional transmissivity values to the kriging data set. The approach used in the initial Culebra modeling studies required the modeler to use judgement to select the location of a pilot point in order to maximize its effect upon the model transmissivity distribution to reduce the difference between model calculated and observed heads. This approach is inefficient because determination of optimum pilot-point locations usually requires several iterations. Thus, determining the most sensitive area of the model-calculated heads to the location of a pilot point would greatly reduce the effort needed to calibrate a flow model.

The methodology in this study employs a technique of coupling adjoint and block-kriging techniques to identify optimal locations for pilot points. The approach greatly reduces the effort required to obtain a calibrated model by identifying regions where transmissivity changes are needed in order to reduce a cumulative least-squares performance measure consisting of the difference between model-calculated and observed heads. Because this approach allows for the specification of both steady-state or transient cumulative least-squares performance measures, a model may be calibrated to steady-state head data and to drawdown data from a pumping test simultaneously. The present methodology uses the modeler's judgement to adjust the magnitude of pilot-point transmissivities in preference to an automatic inversion algorithm. Such a procedure permits the inclusion of the modeler's geologic and hydrologic knowledge of the system and allows the modeler to maintain consistency between the pilot-point transmissivities and the field data.

The combined adjoint-kriging methodology was employed to guide the calibration process of the Culebra groundwater flow model at the WIPP Site and is an extension of previous studies. The flow model consists of a single layer with 30 x 45 grid blocks extending 24.0 x 30.5 k. Boundary conditions were determined using water-level data from bore holes near the boundaries of the model. Conceptually, the Culebra is modeled as a confined flow system with no recharge or leakage occurring over the site area. Calibration efforts were directed toward reproduction of undisturbed, equivalent freshwater heads, the transient effects from shaft construction and sealing operations, and the transient effects from three regional-scale pumping tests, which produced hydraulic stresses over distances of approximately 6 km.

Conclusions determined using the coupled adjoint-kriging methodology in this study include: calculated sensitivities aid in a deeper insight to the characterization of the geohydrology of the site, model calibration is more efficient than with the traditional approach, and the present methodology provides an objective guide to the location of potential high- and low-transmissivity features required to match the steady-state and transient head data.

Likar, V.F., and T.P. Burrington. 1990. "Construction of a Cylindrical Brine Test Room Using a Tunnel Boring Machine," *Waste Management 90, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 25-March 1, 1990*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. II, 869-872.

ABSTRACT: This paper discusses the construction of a horizontal cylindrical brine test room at the Waste Isolation Pilot Plant (WIPP). The room was constructed in the bedded salt formation at a depth of 655 m with a tunnel boring machine. The machine leasing, technical and operational management, parameters involved, and successful completion of this effort are included.

Little, C.C., F.O. Gurney, and D.S. Bell. 1980. *A Description of the Site and Preliminary Design Validation Program for the WIPP Site*. TME 3063. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant.

ABSTRACT: The Site and Preliminary Design Validation Program (SPDV) for the Waste Isolation Pilot Plant (WIPP) is designed to confirm the characteristics of the proposed site by directly observing the geology at the facility horizon. Two shafts will be drilled to the facility horizon of approximately 2150 ft below the surface. Underground workings will include a shaft station and passageways covering a length of about 2100 ft. Horizontal holes will be cored south and north of the shafts for distances of about 3000 ft.

The SPDV represents a conservative, efficient program to confirm the acceptability of the site with minimal environmental impact. The exploration program is consistent with either developing the site or setting it aside until it is compared to other potential sites. DWP

ANNOTATION: Rev. 1 of TME3063 is Hart & Register, 1982.

Little, M.S. 1982. *Potential Release Scenario and Radiological Consequence Evaluation of Mineral Resources at WIPP*. EEG-12. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Hydrologic breach scenarios considered by the Department of Energy (DOE) and the Environmental Evaluation Group (EEG) probably bound the radiological consequences of potash mining and hydrocarbon production, and the doses would not constitute a significant threat to public health.

Although solution mining of halite in the Delaware Basin is not likely at present, significant economic, social, or climatic changes a few hundred years after emplacement may make these resources more attractive. This report evaluates radiological consequences of solution mining at the Waste Isolation Pilot Plant Site.

"The fifty-year individual dose commitment from the ingestion of the average adult consumption of salt (contaminated with the radioactive waste from the repository) was 72 millirems for one year." The average lifetime dose from natural background radiation is 7500 millirem. "Assuming that 0.2% of the radioactive inventory was mined and contaminated the salt during the solution mining event, and that about 2.5% of the total salt was consumed by food products, the total whole body dose to a population at risk of 300 million would be 0.9 million person/rem. This represents about 0.06% of the 50-year dose commitment from natural background. Although this population dose may not be considered insignificant, the small probability of such an event, and the very conservative assumptions used would lead one to conclude that the risk of such an event is small."

"It is unlikely that the small doses resulting from this solution mining breach event would produce any detectable biological effects. It is possible that the long term consequences would be an increase in the normal incidence of cancer in the population, but such an increase would be within the range of statistical variation. Based on the recent conclusions of the National Academy of Sciences BIER Committee the total risk of such cancers would be about 0.32 fatal cancers per million population over the 50 years. This can be compared with the current incidence of 167,000 cancers per year per million population, or 8.35 million cancers over 50 years." DWP

Little, M.S. 1985. *Evaluation of the Safety Analysis Report for the Waste Isolation Pilot Plant Project*. EEG-29. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The *Safety Analysis Report (SAR)* and eight subsequent amendments have been analyzed by the Environmental Evaluation Group (EEG). Comments and recommendations have been submitted to the Waste Isolation Pilot Plant (WIPP) Project Office for consideration in subsequent amendments, and a number of meetings have been held to resolve issues and conflicts. This report summarizes areas of comments and some resolution. The most important

issues remaining to be resolved are an amendment of the topical content of the SAR to be more in accord with the Department of Energy (DOE) Order 5481.1A and AL 5481.1A (DOE and Albuquerque operations office orders about SAR content); substantial revisions of the classification of components, structures and systems, and related quality assurance; and revisions to the site, geological, and hydrologic data based on studies agreed to between DOE and New Mexico. DWP

Loehr, C.A. 1979. "Mineralogical and Geochemical Effects of Basaltic Dike Intrusion into Evaporite Sequences near Carlsbad, New Mexico." MS thesis. Socorro, NM: New Mexico Institute of Mining and Technology.

ABSTRACT: The alteration sequence imposed upon clay minerals associated with potash-rich evaporites surrounding Tertiary lamprophyre dikes in the Kerr McGee mine near Carlsbad, NM is characterized by a $1M_d$ phlogopitic clay $\pm$ saponite $\pm$ irregular saponite-rich chlorite/saponite mixed-layer $\pm$ talc silicate assemblage within 1.5 m of the intrusions. This assemblage changes to irregular chlorite/saponite mixed-layer + illite + chlorite + talc between 1.5 and 7.4 m. At a distance greater than 7-8 m from the dikes, the assemblage returns to normal; partially ordered corrensite + illite + talc + chlorite. It is suggested that clay seams, best developed near the dikes, played a major role in providing an open-system aqueous environment for altering these clay and associated nonclay mineral assemblages. Intense alteration of the water-soluble fraction takes the form of sulfate development and leaching of sylvite; the latter mechanism occurred throughout the altered profile.

The dikes display strong chemical, mineralogical, and textural effects of assimilation of host materials; the major reaction involved increased orthoclase/plagioclase ratios. Dike contribution of heat to the host rocks caused melting of the salts up to 15.2 cm from dike margins.

Long, G.J., and Associates, Inc. 1976. *Interpretation of Geophysical Data, Los Medanos and Vicinity, Lea and Eddy Counties, New Mexico.* Houston, TX: G.J. Long and Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Gravity and seismic reflection data in the area of the Waste Isolation Pilot Plant (WIPP) Site have been interpreted to identify anomalies including breccia pipes and dissolution zones. Gravity data covering about 15 townships were obtained by Sandia for interpretation. Seismic reflection data include 26 line mi recorded for Sandia, 189 line mi for which "use" rights were acquired for Sandia, and 709 line mi of proprietary data for examination in company offices. Anomalies in these data have been identified and mapped.

This study suggests several conclusions: (1) Breccia pipes and active salt solution phenomena can be identified by properly planned and executed seismic survey. (2) Structure favorable to the accumulation of a significant hydrocarbon reserve is seen in the center of the north half of the proposed site. (3) Minor faulting is seen within the withdrawal area near the Castile. (4) A definite relationship between the locations of known breccia pipes and gravity minima has not been established. (5) Regional structural control indicates a generally synclinal area to the south of the proposed site. (6) The site is tectonically stable except for possible faults in the Castile along the west side of section 17, T22S, R31E.

A detailed seismic survey of about 92 line mi is proposed to examine possible faults. Gravity and magnetic data, as well as proprietary seismic data, should be used to continue study of alternate sites. DWP

Lowenstein, T.K. 1987. *Post Burial Alteration of the Permian Rustler Formation Evaporites, WIPP Site, New Mexico: Textural Stratigraphic and Chemical Evidence*. EEG-36. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Four cores of the Rustler Formation along a north-south transect across the Waste Isolation Pilot Plant (WIPP) Site were described in order to distinguish syndepositional features from post-burial alteration. Thin sections were examined petrographically. Minerals were identified by X-ray diffraction. Depositional environments were interpreted based on vertical and lateral distribution of primary sedimentary features, sedimentary structures, textures, and fabrics.

Late stage brecciation, slumping, fracturing and faulting, and chemical processes were observed in all cores affecting all units except for the unnamed lower member. Two assumptions affect these interpretations. Detailed internal stratigraphy of many units can be correlated from core to core; "therefore, across the study area, major facies changes are not observed." "Abrupt thinning ... or changes in rock types ... should then sound a warning that some post-depositional processes may be at work." The second assumption is that most, if not all, sulfate in the Rustler was once anhydrite. Various gypsum features indicate late stage alteration. The most likely sources of water for alteration are the Magenta and Culebra...

Physical features of late-stage alteration are commonly associated with late-stage chemical alteration in intervals without primary sedimentary structures or with overprinted structures. Late-stage alteration varies in intensity across the study area except for the top of the unnamed lower member. DWP

Lucas, J.P. 1984. *Analysis of Rock Bolt Material Failures at the WIPP Site*. SAND84-0224. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The report describes an investigation conducted on rock-bolt material (AISI 1040 plain carbon steel), as called for in ASTM F-432. Failure analysis was performed on rock bolts that failed in-service, and mechanical tests were conducted on rock-bolt materials in a simulated Waste Isolation Pilot Plant (WIPP) environment. The mechanical tests results indicate that fracture was environmentally assisted. Strong evidence indicated that hydrogen embrittlement influenced the fracture mechanisms. In the most aggressive test environment, the ductility loss during sustained-load tensile testing was large. Such ductility loss was attributed to embrittlement caused by the absorption of hydrogen.

Lukow, T.E., and V. Daub. 1988. "An Overview of the WIPP R&D Program," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education*, Tucson, AZ, February 24-March 3, 1988. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 365-370.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) located in Carlsbad, NM is a research and development (R&D) facility established in 1979 by Public Law 96-164 to demonstrate the safe disposal of defense-generated transuranic (TRU) waste in a geologic repository. PL 96-164 defines the WIPP mission as "... a defense activity ... for the express purpose of providing a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States exempted from regulation by the Nuclear Regulatory Commission (NRC)." Specifically the WIPP was developed by the Department of Energy (DOE) to address technical issues concerning the safe disposal of defense TRU wastes in a rock salt underground storage room configuration and to determine WIPP's ability to comply with all regulations applicable for permanent storage of TRU waste in an underground repository. DOE was also directed by Congress to use the WIPP as an experimental facility to conduct radioactive waste experiments as well. However, the

radioactive waste used for experiments at the WIPP must be removed from the site at the end of the experiments.

This presentation provides information on the R&D program that will give a thorough understanding of how the salt repository will function both near term and long term, determine how TRU waste will behave in a salt repository, and develop the best engineered barriers to assure that the salt formation will isolate the waste from the environment. The main areas of the program include hydrologic and geologic activities, in situ testing program, and performance assessment (PA).

Lynch, A.W. 1979. "Migration of Cesium in Dolomite From the Rustler Formation in the Los Medanos Area in Southeastern New Mexico," *Scientific Basis for Nuclear Waste Management, Proceedings of the Symposium on Science Underlying Radioactive Waste Management, Materials Research Society Annual Meeting, Boston, MA, November 28-December 1, 1978*. Ed. G.J. McCarthy. SAND78-1179C. New York, NY: Plenum Press. Vol. 1, 399-402.

ABSTRACT: Column flow experiments are being conducted on Magenta dolomite rock taken from a potential site for the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. The experiments utilize monolithic samples machined from cores. The fluid phase is either deionized water pre-equilibrated with dolomite or a simulated brine composition doped with cesium-137 at a level of 0.1 $\mu\text{Ci/mL}$.

Lynch, A.W., and R.G. Dosch. 1980. *Sorption Coefficients for Radionuclides on Samples from the Water-Bearing Magenta and Culebra Members of the Rustler Formation*. SAND80-1064. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The sorbing characteristics of samples from the Magenta and Culebra dolomites of the Rustler Formation, which overlie the proposed site for the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico, for various radionuclides have been studied. Core samples extracted from various depths and bore holes within a given formation were selected to provide a cross-section of materials which are present in the formations. They varied in composition from pure dolomite to nearly pure anhydrite. The radionuclides used in the sorption coefficient measurements (isotopes of Cs, Sr, Tc, Eu, Am and Pu) were dissolved in a simulated Culebra groundwater at concentrations of 0.1 $\mu\text{Ci/mL}$ or less.

The results indicate that the sorption coefficients (K_d 's) of these water-bearing units may vary widely depending on the bore hole area and over several feet in depth in a common bore hole. Cesium K_d values varied from 0.6 to 218 mL/g and 1.2 to 68 on Magenta and Culebra samples, respectively. Strontium K_d values ranged from 1.1 to 30 on Magenta Samples and from 0.6 to 32 on Culebra samples. Variations of Eu, Pu, and Am K_d 's were generally less than an order of magnitude on both Culebra and Magenta samples. Technetium was not sorbed by any of the samples.

With few exceptions, samples with high dolomite contents had higher sorption coefficients than those with high anhydrite concentrations. Clay content may also be a factor for some radionuclides, particularly Cs, that has been shown to sorb preferentially on clay particles in Magenta.

Lynch, A.W., and R.G. Dosch. 1981. "Cesium Migration Through Solid Cores of Magenta Dolomite," *Scientific Basis for Nuclear Waste Management, Proceedings of the Third International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, MA, November 17-20, 1980*. Ed. J.G. Moore. SAND80-1335C. New York, NY: Plenum Press. Vol. 3, 457-464.

ABSTRACT: Column-flow experiments have been conducted on Magenta dolomite rock taken from a potential site for radioactive waste disposal, the Waste Isolation Pilot Plant (WIPP). The results indicate qualitative agreement with results from batch sorption coefficient (K_d) measurements. In one experiment, deionized water pre-equilibrated with crushed rock containing $0.1 \mu\text{Ci/mL } ^{137}\text{Cs}$ flowed through a column with an average velocity of 1.1 cm/day for 18 months. The ^{137}Cs penetrated approximately 0.4 cm into the column indicating a sorption coefficient of about 100 mL/g. Batch sorption experiments gave a value of 650 mL/g. When the water was changed to a pre-equilibrating groundwater and the Cs concentration was increased, both column and batch experiments gave values for the sorption coefficient of approximately 19 mL/g. Transmission electron microscopy results showed the Magenta samples to be primarily composed of dolomite and calcium sulfate and that a minor montmorillonite clay phase may control the retention of Cs on these rocks.

Lynch, A.W., R.G. Dosch, and C.R. Hills. 1981. *Migration of Cesium-137 Through a Solid Core of Magenta Dolomite Taken from the Rustler Formation in Southeastern New Mexico.* SAND80-1259. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A column-flow cesium migration experiment has been conducted in support of the safety assessment program for the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. The column was a monolithic cylinder of Magenta dolomite obtained from a core sample drilled near the proposed WIPP Site. The fluid was a Magenta equilibrated de-ionized water solution that had been doped with 0.001 ppm of ^{137}Cs . The experiment ran continuously for an 18 month period at flow rates comparable to those measured for natural groundwater at the site. After flowing for 18 months, the apparatus was disassembled and the dolomite column examined for cesium distribution. Cross-sectional radiographs of the sample showed that most of the cesium had penetrated only 0.4 cm into the solid Magenta column with a well-defined wave front. On the other hand, trace quantities (2×10^{-7} ppm) of ^{137}Cs were detected in effluent samples collected during the experiment.

The distribution coefficient (120 mL/gm) calculated (assuming porous flow) from the average depth of cesium penetration (0.3 cm) is considerably less than the value obtained from a batch equilibration measurement made on the same system (650 mL/gm), indicating that cesium will migrate through Magenta rock at a faster rate than batch equilibration value predicts.

Transmission electron microscope analysis of a piece of Magenta dolomite from the same core that had been soaked in 1 molar CsCl solution indicated that the cesium was preferentially sorbed on a montmorillonite clay phase that was inhomogeneously dispersed throughout the sample. These results indicate that if groundwater travels through Magenta rock, the dissolved cesium may be retarded by the clay content of the rock.

Lyon, M.L. 1989. *Annual Water Quality Data Report for the Waste Isolation Pilot Plant.* DOE/WIPP 89-001. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Water Quality Sampling Program (WQSP) was begun in 1985 "to collect reproducible and representative groundwater samples from water-bearing zones in the WIPP vicinity." Water quality data for 1988 were collected from 16 pre-operational monitoring wells, 2 additional wells, and 10 private wells. Water samples from the Air Intake Shaft were collected during construction. Most of the wells had previously been sampled. All samples from WIPP wells and shafts are from either Culebra or Magenta Dolomite Members of the Rustler Formation. Non-WIPP wells sample the Culebra, Dewey Lake Formation, or Dockum Group.

Samples were collected as serial and final samples. Serial samples were analyzed during collection for parameters in the field to identify steady-state conditions for final sampling. Analyses covered a wide range of general chemistry parameters, organic compounds, metals,

isotopes, dissolved gases, redox couples, and radionuclides. Trace metal analyses were improved during 1988 by using cation exchange resins to decrease the lower limit of detection into the microgram/liter range.

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Marchetti, S. 1980. *Dose Consequence of Repository Failure and Leach Events for the Waste Isolation Pilot Plant (Dose-to-Age-Specific Maximum)*. WTSD-TME-3066. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The dose consequences of postulated failure and leaching events have been analyzed using the SWIFT model and the LADWIP program, a modification of the LADTAP program developed by the Nuclear Regulatory Commission (NRC). Event 1 connects the Bell Canyon Formation, the repository, and the Rustler Formation. Event 2 allows water to flow from the Rustler to the repository and back to the Rustler. Event 3 allows the repository to connect vertically to the Rustler. Discharge for events 1-3 is at Malaga Bend, on the Pecos River. Event 4 is similar to 1, but with discharge occurring in the Rustler at one of three wells located 3 mi downstream of the repository. "In no event would an annual intake via the pathways considered result in exceeding either the existing 500 mrem per year total body limit or the 1500 mrem/year bone recommended dose limit for any member of the general public. Additionally, these results indicate that 4.5×10^4 years and 7.1×10^4 years of release at Malaga Bend at the maximum calculated concentration without decay or environmental removal would be required before the total body and bone dose limits respectively could be exceeded." DWP

Marietta, M.G., S.G. Bertram-Howery, D.R. Anderson, K.F. Brinster, R.V. Guzowski, H. Iuzzolino, and R.P. Rechard. 1989. *Performance Assessment Methodology Demonstration: Methodology Development for Evaluating Compliance with EPA 40 CFR 191, Subpart B, for the Waste Isolation Pilot Plant*. SAND89-2027. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report describes a demonstration of the performance assessment methodology for the Waste Isolation Pilot Plant (WIPP) to be used in assessing compliance with the Environmental Protection Agency's Standard, *Environmental Radiation Protection Standards for the Management and Disposal of Spent Nuclear Fuel, High Level and Transuranic Radioactive Wastes* (40 CFR Part 191, Subpart B). This demonstration incorporates development and screening of potentially disruptive scenarios. A preliminary analysis of the WIPP disposal system's response to human intrusion scenarios produces preliminary complementary cumulative distribution functions (CCDFs) similar to those that will ultimately be used to assess the compliance of the WIPP with the Containment Requirements of the Standard. Preliminary estimates of scenario probabilities are used to construct two demonstration CCDFs. The conceptual model of the disposal system consists of geologic, hydrologic, and disposal system subsystems along with the physical and chemical processes associated with these subsystems. Parameter values defining the systems contain uncertainties and modeling approximations of such a disposal system contributes to those uncertainties. The WIPP compliance assessment methodology consists of a system of techniques and computer codes that estimate releases of radionuclides from the disposal system, incorporating analysis of the parameter uncertainties in the estimates. Demonstration CCDFs are presented, but are not yet credible enough to judge the probability of compliance of the WIPP with the EPA Standard. One CCDF, based primarily on conservative reference data and conservative conceptual models, exceeds EPA limits, and another CCDF that represents effects of possible engineered alternatives does not exceed EPA limits.

Matalucci, R.V. [1984.] "The Waste Isolation Pilot Plant (WIPP) In Situ Testing Program," *American Society of Civil Engineers, Geotechnical Group Meeting, Albuquerque, NM, March 30, 1984*. SAND84-0661A. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Full-size, well-instrumented underground in situ tests are being implemented in the Waste Isolation Pilot Plant (WIPP) Facility in southeastern New Mexico for evaluating the response of bedded salt to the emplacement of heat-producing wastes. These tests are an essential part of a broad research and development program to resolve technical issues associated with the disposal of radioactive wastes from US defense programs. These tests are designed to provide in situ data for validating long-term prediction methods and for developing a design basis for a future repository. Current plans include tests concerning thermal/structural interactions, plugging and sealing, operational demonstrations, and waste package performance.

Matalucci, R.V. 1987. *Summary Report: The Integrated In Situ Testing Program for the Waste Isolation Pilot Plant (WIPP)*. SAND86-2716. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The US Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) Project in southeastern New Mexico as a research and development (R&D) facility for examining the response of bedded (layered) salt to the emplacement of radioactive wastes generated from defense programs. The WIPP Experimental Program consists of a technology development program, including laboratory testing and theoretical analysis activities, and an in situ testing program that is being done 659 m underground at the project site. This experimental program addresses three major technical areas that concern thermal/structural interactions, plugging and sealing, and waste package performance. To ensure that the technical issues involved in these areas are investigated with appropriate emphasis and timing, an in situ testing plan was developed to integrate the many activities and tasks associated with the technical issues of waste disposal.

Matalucci, R.V. 1988. *In Situ Testing at the Waste Isolation Pilot Plant*. SAND87-2382. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The In Situ Testing Program at the Waste Isolation Pilot Plant (WIPP) Site is providing answers to questions about the efficacy of storing radioactive wastes in the geologic medium of natural salt deposits. Specific issues, such as the capability of disposal rooms to adequately confine the waste and the ability of salt beds to isolate radiation from the environment, are integral to the safety of long-term waste storage.

The In Situ Testing Program is aimed at the total repository system, emphasizing the concepts of waste confinement and isolation. The three technical areas - Thermal/Structural Interaction (TSI), Waste Package Performance (WPP), and Plugging and Sealing (P&S) - together respond to the many issues associated with these concepts, from room stability to waste packaging to the final sealing of the site during decommissioning. Some of the in situ tests closely simulate the two-dimensional geometry of earlier laboratory tests and therefore afford a direct comparison between the models and the field. Other tests simulate the proposed repository configuration, so that any effects created by this configuration can be identified.

The challenge faced by the In Situ Testing program is to investigate the issues of radioactive waste storage in a salt repository environment well enough to provide dependable predictions of the long-term effects of waste disposal. Design methods, test procedures, and data results are carefully documented to ensure their availability for review by interested organizations and future repository designers. The program, which is expected to be active into the 1990s, will continue to gather important information for improving the repository designs.

Matalucci, R.V. 1990a. "The In Situ Testing Program at the Waste Isolation Pilot Plant," *Radioactive Waste Management and the Nuclear Fuel Cycle*. SAND88-1178J. Vol. 14, no. 1-2, 123-154.

ABSTRACT: The In Situ Testing Program is an integral part of the Waste Isolation Pilot Plant (WIPP) Technology Development Program, providing full-sized experiments for evaluation of constitutive models and laboratory data. The in situ tests are being performed about 659 m underground in the rock-salt environment of the WIPP Site and consist of three technical areas: Thermal/Structural Interactions (TSI); Plugging and Sealing (P&S); and Waste Package Performance (WPP). The in situ tests are designed to provide data for evaluating theoretical models and predictive techniques and demonstrate the actual behavior of the salt, engineered barrier backfills and seals, and waste packages in an underground salt environment.

The actual room creep closure data acquired from the TSI in situ tests are generally a factor of 3 greater than closures predicted with laboratory-developed constitutive models. Modified elastic properties (reduced by a factor of 12.5) currently yield calculations that more closely match measured closure. The preliminary results of in situ small-scale seal performance tests produce derived permeabilities that are in the submicrodarcy range, and that are often less than the resolution of the testing equipment (nanodarcy, 10^{-9} darcy). The seal experiments, which were performed in drilled and manually excavated bore holes in salt, tested the effectiveness of salt-based concretes and reconsolidated salt-bentonite blocks as seals for man-made openings. Data from the contact handled transuranic (CH TRU) drum durability tests confirmed that the aggressive nature of the salt backfill and brine environments induced drum pitting and enhanced crevice corrosion. Surface corrosion on remotely handled (RH TRU) containers emplaced in unlined horizontal bore holes was insignificant, except for superficial rust on all of the unpainted, mild steel pintles. For the simulated defense high-level waste (HLW) waste package performance test, including materials interface interactions tests, there is clear evidence that TiCode-12 canisters remained for several years without any observed corrosion effects.

Matalucci, R.V. 1990b. "In-Situ Testing at the US Department of Energy's Waste Isolation Pilot Plant," *Tunneling and Underground Space Technology*. Vol. 5, no. 1-2, 119-133.

ABSTRACT: The In Situ Testing Program at the US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) is providing answers to questions about the efficacy of storing radioactive wastes in the geologic medium of natural salt deposits. Specific issues, such as the capability of disposal rooms to adequately confine the waste and the ability of salt beds to isolate radiation from the environment, are integral to the safety of long-term waste storage. The In Situ Testing Program is aimed at the total repository system, emphasizing the concepts of waste confinement and isolation. The three technical areas--Thermal/Structural Interactions (TSI), Waste Package Performance (WPP), and Plugging and Sealing (P&S)--together respond to the many issues associated with these concepts. Some of the In Situ tests closely simulate the two-dimensional geometry of earlier laboratory tests and, therefore, afford a direct comparison between the models and the field. Other tests simulate the proposed repository configuration, so that any effects created by this configuration can be identified. The challenge faced by the In Situ Testing Program is to investigate the issue of radioactive waste storage in a salt repository environment well enough to provide dependable predictions of the long-term effects of waste disposal. The program, which is expected to be active into 1990s, will continue to gather important information for improving the repository designs.

Matalucci, R.V., and T.O. Hunter. 1984. "Geomechanical Applications for the Waste Isolation Pilot Plant (WIPP) Project," *The Mechanical Behavior of Salt: Proceedings of the First Conference, Pennsylvania State University, University Park, PA, November 9-11, 1981*. Eds.

H.R. Hardy, Jr. and M. Langer. SAND81-1203C. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 791-812.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a research and development facility in bedded salt addressing the technical issues associated with the demonstration of disposal of radioactive waste from the defense programs of the USA. The geomechanical program includes laboratory experimentation, constitutive model and computer code development, and in situ experimentation. Various material models, including creep for salt, and techniques for predicting room response under thermal and mechanical loads have been developed and are being applied to experiment and facility designs. A Benchmark II study has been conducted to compare the capabilities of nine structural codes to predict response of underground configuration under ambient temperature and with a thermal load of 7.5 W/m^2 . Parametric studies are being conducted to evaluate optimum room configurations. A series of in situ experiments is the next step towards validating models and predictive techniques. These experiments will be conducted in a facility in southeastern New Mexico mined at a depth of 659 m.

Matalucci, R.V., and D.E. Munson. 1988. "Planning, Developing and Organizing In Situ Tests for the Waste Isolation Pilot Plant (WIPP), *The Mechanical Behavior of Salt Proceedings of the Second Conference, Hanover, Federal Republic of Germany, September 24-28, 1984*. Eds. H.R. Hardy, Jr. and M. Langer. SAND84-1390C. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 329-360.

ABSTRACT: The US Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) Project in southeastern New Mexico as a research and development (R&D) facility to demonstrate the safe disposal of radioactive wastes in bedded (layered) salt. This project provides for an in situ testing facility to address the technical issues of repository development, waste package performance assessment, and waste handling demonstrations. In situ tests are part of the R&D program and were designed to verify laboratory data and theoretical analysis.

This report documents planning and development activities associated with the WIPP In Situ Testing Program. It describes the procedures followed during design, construction, and installation of the following tests: underground thermal/structural interactions, plugging and sealing, waste package performance, and operational demonstration tests. Successfully achieving this in situ test installation program required continuous coordination of Sandia's R&D testing requirements with the technical supporting activities of the other WIPP participants. Many fielding tasks were identified and assigned for accomplishment by Sandia National Laboratories (SNL) and technical support personnel, including monitoring construction, emplacing instruments, and installing a data acquisition system. Test installation proceeded simultaneously with the excavation and with the instrument bore hole drilling sequence.

Matalucci, R.V., H.S. Morgan, and R.D. Krieg. 1981. "The Role of Benchmarking in Assessing the Capability to Predict Room Response in Bedded Salt Repositories," *Proceedings of the Workshop on Near-Field Phenomena in Geologic Repositories for Radioactive Waste, Seattle, WA, August 31-September 3, 1981*. SAND81-1293C. Paris, France: Organisation for Economic Co-Operation and Development. 311-325.

ABSTRACT: An overview is presented of the Waste Isolation Pilot Plant (WIPP) Benchmark II study, which was used to assess the accuracy and reliability of computer codes used to predict drift response. Emphasis is placed on the objectives and philosophy of Benchmark II and on

procedures used to ensure that valid comparisons of results could be made. The problem definition, the selection of participants, and review procedures are all discussed. A sampling of results is also presented to illustrate the degree of variability in the results obtained with various computer codes.

Matalucci, R.V., C.L. Christensen, T.O. Hunter, M.A. Molecke, and D.E. Munson. 1982. *Waste Isolation Pilot Plant (WIPP) Research and Development Program: In Situ Testing Plan, March 1982.* SAND81-2628. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) in southeast New Mexico is being developed as a research and development (R&D) facility to demonstrate the safe disposal of radioactive defense wastes in bedded salt. This document is a baseline plan containing all the in situ tests proposed in the WIPP R&D Program that address the technical issues of isolating wastes in bedded salt. The in situ tests, at 659 m underground, address repository development and waste package interactions with the host rock salt. They are done first without radioactive materials and are followed by those with transuranic (TRU) waste and defense high-level waste (DHLW). Included are operational demonstration tests. Nonradioactive tests are planned for late summer 1983, continuing for up to 8 years. Radioactive wastes will be introduced in 1989 and continue for up to 15 years.

The thermal/structural interaction experiments include geomechanical evaluations of access drifts, vertical shafts, and isothermal TRU disposal rooms during the Site and Preliminary Validation Program; tests that represent the reference DHLW room configuration (5.5 m x 5.5 m) and areal thermal loading of 12 W/m²; an overtest of the DHLW configuration heated to about four times the reference thermal loading; geomechanical evaluations of various room widths up to 9.1 m, variable pillar widths, and a long-drift intersection; an 11-m-diameter axisymmetric heated pillar test; and miscellaneous tests to determine stress field and clay seam sliding resistance. The plugging and sealing experiments include salt permeability tests; tests to determine effects of size and scale on behavior of plugs and to determine backfill material behavior and emplacement techniques; and a plug test matrix to evaluate candidate sealing materials. Operations tests include demonstrations of mock and actual TRU waste handling and DHLW emplacement and retrieval.

Waste package interaction experiments include simulated-waste package tests that use several design options and engineered barrier materials under reference and accelerated DHLW environments; confirmatory brine migration tests; TRU drum durability tests in dry and wet conditions; options for radiation-source tests using cesium capsules; and actual DHLW tests using up to 40 canisters for technical demonstrations and for addressing concerns of wasteform chemistry, leaching, and near-field radionuclide migration.

A project management system is developed to execute the tests and to provide for quality assurance, technical peer review, and cost management. Modifications and refinements to the tests will be made by means of individual test plans.

Maxwell, D.E., K.K. Wahi, and B. Dial. 1980. *The Thermomechanical Response of WIPP Repositories.* SAND79-7111; SAI-FR-145. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: STEALTH 2D, a time-explicit finite-difference code, was used to investigate two candidate Waste Isolation Pilot Plant (WIPP) repositories. 30SF had a 20 acre circular disk source with thermal loading of 30 KW/acre at 650 m depth. 75HLW has a 1717 acre toroidal disk source with a thermal load of 75 kW/acre, an inner radius of 590 m, and outer radius at

1600 m, and at a depth of 815 m. The grid was designed for 100,000 years of response with modest computing costs.

The effects of stress and strain peaked between 1,000 and 2,000 years, at the time of maximum heat in the site. Though creep strains were quite small, a large volume of salt was involved, and the effects were significant. The peak surface uplift of 75HLW increased by about 25% because of creep. However, the deviatoric stress relaxation caused by creep produced large changes in the stress fields. The Rustler survived reasonable failure criterion for the 75HLW case with creep and failed both in tension and shear without creep.

Deviatoric stress fields concentrated near the repository, as expected, and also in the Rustler because of its relatively high Young's modulus. A lower Young's modulus in the aquifer confining layers would reduce the bending stresses. A high Young's modulus in neighboring layers would help carry the bending loads. The confining layers are not protected by creep in nearby units. However, creep near the repository is highly beneficial in reducing the deviatoric stress field and lowering the bending stresses in the upper strata. The tradeoff of these effects can be handled by computer simulation even if they may not be traded off in a real repository.

As the time of interest is so much shorter than the 100,000 years for this calculation, it is possible to model the WIPP stratigraphy in much more detail and still be able to calculate the response for the time of interest.

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McClain, W.C., and A.L. Boch. 1974. "Disposal of Radioactive Waste in Bedded Salt Formations," *Nuclear Technology*. Vol. 24, no. 3, 398-408.

ABSTRACT: The considerations involved in the evaluation of the suitability of any geological formations for the disposal of radioactive wastes are illustrated by summarizing some of the studies performed in the southeastern New Mexico region on the bedded salt concept. These investigations fall into three main categories:

1. Evaluation of the natural integrity of the formation. In addition to standard geological and hydrological studies, special investigations of the subsurface dissolution of the salt formation, the seismic stability of the region, and the possibility of previous mass flowage of the salt have been completed. These results will be confirmed by core drilling and testing currently in progress.
2. Evaluation of the effects of the operation of a waste disposal facility on the geological characteristics of the area over the short term. These studies include prediction of the thermal transient resulting from the radioactive decay heat deposited in the rocks and its effects, such as the migration of brine inclusions up the thermal gradients and the dehydration of moisture-bearing minerals. Other studies in this category are concerned with the possibility and consequences of radiation-induced energy storage in the salt and prediction of the deformations to be expected around the openings excavated in the salt formations.
3. Evaluation of the effects which the operation of a repository and other activities of man may have on the integrity of the geological containment over the long periods that the waste remains hazardous. The principal analyses in this category involve the long-term deformations of the rocks overlying the repository area (including the slow development of a subsidence basin at the ground surface) and the prevention of adverse conditions resulting from penetrations of the salt by exploratory drilling for oil and gas accumulations.

McTigue, D.F. 1987. "Flow to a Heated Borehole in Fluid-Saturated Thermoelastic Rock," *EOS Transactions, American Geophysical Union*. Vol. 68, no. 44, 1295. (Abstract Only).

ABSTRACT: An exact solution is presented for the response of a fluid-saturated, porous, thermoelastic medium to a constant flux of heat delivered to a long, open bore hole. The solution yields the transient pore pressure, fluid flux, stress, strain, and displacement fields. The pore pressure exhibits a peak that propagates outward from the bore hole, driving fluid both toward the hole and toward the far field. The response depends critically upon the ratio of the fluid and thermal diffusivities, or the characteristic times for transport of heat and fluid mass, respectively.

Experimental data from the heating of a large (1-m diameter, 1-m high) annular block of polycrystalline halite are examined in light of the model. Power was delivered to the bore hole from an electric, resistance heater in several stages. The total flux of fluid into the hole was monitored, as was the temperature at several points along a radius. The experimental configuration is idealized for modeling purposes as a one-dimensional, radial transport problem. The heat transfer is by conduction; inverse calculations based on data from four thermocouples indicate a thermal conductivity ($5.2 \text{ W m}^{-1} \text{ K}^{-1}$) and heat transfer coefficient (2.8 m^{-1}) within the range of expected values, and yield an excellent representation of the measurements. The pore-pressure field is governed by a diffusion equation with a source term proportional to the temperature rate. Application of the inverse method to data for the fluid flux to the bore hole yields the fluid diffusivity ($7.0 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$) and the source coefficient ($4.9 \times 10^4 \text{ Pa K}^{-1}$). The resulting values are in reasonable agreement with estimates based on independent knowledge of the thermal, mechanical, and hydraulic properties of the salt.

McTigue, D.F., and E.J. Nowak. 1988. "Brine Transport in the Bedded Salt of the Waste Isolation Pilot Plant (WIPP): Field Measurements and a Darcy Flow Model," *Scientific Basis for Nuclear Waste Management XI, Boston, MA, November 30-December 3, 1987*. Eds. M.J. Apted and R.E. Westerman. SAND87-1274C. Pittsburgh, PA: Materials Research Society. Vol. 112, 209-218.

ABSTRACT: Brine flow has been measured to unheated bore holes for periods of a few days and to heated holes for two years in the Waste Isolation Pilot Plant (WIPP) Facility. It is proposed that Darcy flow may dominate the observed influx of brine. Exact solutions to a linearized model for one-dimensional radial flow are evaluated for conditions approximating the field experiments. Flow rates of the correct order of magnitude are calculated for permeabilities in the range 10^{-21} - 10^{-20} m^2 (1-10 nanodarcy) for both the unheated and heated cases.

Mercer, J.W. 1983. *Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Los Medanos Area, Southeastern New Mexico*. Water-Resources Investigations Report 83-4016. Albuquerque, NM: US Geological Survey.

ABSTRACT: Geohydrologic data have been collected in the Los Medanos area at the US Department of Energy's (DOE) proposed Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico since 1975 as part of a study evaluating the feasibility of storing defense-associated nuclear wastes within the bedded salt of the Salado Formation of Permian age. Drilling and hydrologic testing have identified three principal water-bearing zones above the Salado Formation and one below that could potentially transport wastes to the biosphere if the proposed facility were breached. The zones above the Salado are the contact between the Rustler and Salado Formations and the Culebra and Magenta Dolomite Members of the Rustler Formation of Permian age. The zone below the Salado Formation consists of channel sandstones in the Bell Canyon Formation of the Permian Delaware Mountain Group.

Determinations of hydraulic gradients, directions of flow, and hydraulic properties were hindered because of the negligible permeability of the water-bearing zones. Special techniques

in drilling, well completion, and hydraulic testing have been developed to determine the hydrologic characteristics of these water-bearing zones.

The Rustler Formation contains the principal water-bearing zones identified at the WIPP Site, and thus was the most extensive studied. Calculations from pumping, slug, and pressure-pulse tests indicate that the transmissivities of the units vary laterally within, as well as between, the individual beds. The Culebra Dolomite Member is the most persistent and productive hydrologic unit in the WIPP Site area and also has the greatest variability of hydraulic properties. This variability results from the size and number of fractures, which in turn are related to the degree of evaporite dissolution within the Rustler Formation. Transmissivities calculated for the Culebra in Nash Draw immediately west of the WIPP Site range from 18 to 1,250 ft²/day, whereas they range from 1×10^{-3} to 140 ft²/day at the WIPP Site. Potentiometric-surface maps (as equivalent freshwater heads) indicate flow in the Culebra Dolomite Member of the Rustler Formation at the WIPP Site to be southerly, eventually flowing southwestward to Nash Draw. Determination of flow directions, however, may be significantly affected by directional differences in permeability along fractures. The dominant dissolved ions are sodium and chloride, with calcium, magnesium, potassium, and sulfate being other major ions present. Hydrochemistry studies indicate an increase of mineralization of water from west to east along with a decrease in circulation of the flow system. The dissolved-solids concentrations across the WIPP Site range from 3,200 to 420,000 mg/L.

The Magenta Dolomite Member is the uppermost hydrologic unit. Water in this unit occurs either in thin silt beds and silty dolomite or in fractures where extensive evaporite dissolution has occurred in the Rustler Formation. Transmissivities calculated for the Magenta in Nash Draw range from 53 to 375 ft²/day, whereas they range from 4×10^{-3} to 1×10^{-1} ft²/day at the WIPP Site. Potentiometric-surface maps (as equivalent freshwater heads) indicate flow in the Magenta to be westward toward Nash Draw where the flow direction is then controlled by the evaporite dissolution in the Rustler. The water is brackish to briny. The dominant dissolved ions are sodium and chloride with calcium, magnesium, potassium, and sulfate being other major ions. Dissolved-solids concentrations across the WIPP Site range from 5,460 to 270,000 mg/L.

The least productive water-producing zone is at the contact between the Rustler and Salado Formations where brine occurs either in an evaporite residuum or in clays along bedding planes. The residuum is concentrated along Nash Draw and is most extensive between Malaga Bend on the Pecos River, 10 mi southwest of the proposed WIPP Site, and Laguna Grande de la Sal, where transmissivities are as large as 8,000 ft²/day. North of Laguna Grande de la Sal in Nash Draw, the transmissivities range from 2×10^{-4} to 8 ft²/day; transmissivities at the WIPP Site range from 3×10^{-5} to 5×10^{-2} ft²/day. Potentiometric surface maps (as equivalent freshwater heads) indicate flow in the contact zone to the southwest across the WIPP Site toward Nash Draw. The dissolved solids in the brines at the Rustler/Salado contact are predominantly sodium chloride with dissolved-solids concentrations ranging from 79,800 to 480,000 mg/L. Large potassium and magnesium ion concentrations in the eastern part of the site may indicate restricted circulation of the brines.

The relative static heads or formation pressures of the hydrologic units in the Rustler decrease with depth; that is, static heads are the highest in the Magenta and the lowest at the contact zone between the Rustler and Salado. In the WIPP Site area, the presence of relatively impermeable interbeds of halite and anhydrite probably restricts vertical movement between units. The Rustler Formation probably is recharged in Bear Grass Draw about 20 mi northwest of the WIPP Site and in Clayton Basin, which is about 12 mi northwest of the WIPP Site. The major discharge occurs at Malaga Bend on the Pecos River.

Data collected from drill-stem tests in test wells penetrating the Bell Canyon Formation indicate that the brines associated with the unit usually occur in relatively isolated channel sandstones that are permeable (hydraulic conductivities ranging from 7×10^{-3} to 5×10^{-2} ft/day) but grade vertically and laterally into siltstones and shales with little permeability.

Potentiometric-surface maps (as equivalent freshwater heads) show flow in the Bell Canyon Formation to be laterally across the basin to the northeast, but the movement probably is extremely slow. The dissolved ions in the brines of the Bell Canyon are predominantly sodium and chloride with dissolved-solids concentrations ranging from 180,000 to 270,000 mg/L.

Mercer, J.W. 1987. *Compilation of Hydrologic Data From Drilling the Salado and Castile Formations Near the Waste Isolation Pilot Plant (WIPP) Site in Southeastern New Mexico*. SAND86-0954. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report compiles and evaluates data from tests performed on the Salado and Castile Formations during site characterization, exclusive of the "brine reservoirs" in the Castile. It also examines if regional data are consistent with the experience of fluid encounters in the mined facility--especially whether significant volumes of fluid might be involved in the Salado pressure buildups in the same way as small volumes were in the studies in the mined facility at the Waste Isolation Pilot Plant (WIPP). Preliminary analyses of recently completed data from reentry and testing in WIPP-12 and testing of the Salado in DOE-2 are also included. Results of this study indicate that probably no overall interpretive model can be applied to the Salado and Castile Formations. That is, no definitive or unique explanation exists for the brine and/or gas occurrences or pressure buildups or their distribution in the borehole. Because of certain basic problems of well testing from the surface in low-permeability rock and because of the apparent low permeabilities, we do not recommend continued hydrologic testing conducted from the surface and penetrating the halites and anhydrites of concern at the WIPP mining horizon is practicable and should be carried out with the more sensitive instrumentation developed for that purpose.

Mercer, J.W., and D.D. Gonzalez. 1981. "Geohydrology of the Proposed Waste Isolation Pilot Plant Site in Southeastern New Mexico," *Environmental Geology and Hydrology in New Mexico*. Eds. S.G. Wells, W. Lambert, and J.F. Callender. New Mexico Geological Society Special Publication No. 10; SAND81-0197C. [Roswell, NM:] New Mexico Geological Society. 123-131.

ABSTRACT: Hydrologic data have been collected at the US Department of Energy's (DOE's) proposed Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico since 1975 as part of a study evaluating the feasibility of storing defense-associated nuclear wastes within the bedded salt of the Salado Formation of Permian age. The drilling and testing of 30 hydrologic test holes have identified three flow zones above the Salado Formation that could potentially transport wastes to the biosphere if the proposed storage facility were breached. These zones include the contact between the Salado and Rustler Formations and the Culebra and Magenta Dolomite Members of the Permian Rustler Formation.

Potentiometric-surface maps (as equivalent freshwater heads) show flow to the west toward Nash Draw within the Rustler/Salado contact and the Magenta Dolomite Member, and flow to the south within the Culebra Dolomite Member. Determinations of hydraulic gradients, directions of flow, and hydraulic properties have been hindered because of the low permeability of the water-bearing zones. Special techniques in drilling completion and hydraulic testing have been developed to adapt conventional methods to low permeable rock.

Calculations from pump, slug, and pressure-pulse tests indicate that transmissivity varies laterally within, as well as between the beds. The Culebra Dolomite Member, the most permeable zone, has the greatest variability, with transmissivities ranging from 13 to 10^{-5} m²/day. The least productive zone is at the contact between the Rustler and Salado where transmissivity ranges from 10^{-2} to 10^{-6} m²/day. Data indicate that transmissivity variability

within the Rustler Formation, especially within the Culebra, is caused by subsidence and fracturing of overlying dolomite beds due to local dissolution of evaporite interbeds.

Because groundwater may flow predominantly along fractures, a two-well recirculating test was performed at the H-2 bore-hole complex of the Waste Isolation Pilot Plant (WIPP) Site to evaluate the effective porosity and coefficients of dispersivity. The test was conducted in the Culebra Dolomite Member at a depth of 192 m where aquifer-test analysis indicated a transmissivity of 4.6×10^{-2} m²/day and a storage coefficient of about 10^{-5} . The Culebra is confined and is about 6-m thick in the study area. The test, performed with thiocyanate and bromochlorodifluoromethane (BCF) as the injectates, required 250 days to complete. The injection period lasted 26 days with breakthrough occurring after 72 days of pumping at 1.1 L/min. Breakthrough occurred at 10^{-5} of initial concentration. On-site results, along with other hydrologic data, will be used in analytical and numerical modeling for safety analysis studies.

Mercer, J.W., and W.L. Hiss. 1978. "Solution of Permian Ochoan Evaporites, Northern Delaware Basin, New Mexico," *Geology and Mineral Deposits of Ochoan Rocks in Delaware Basin and Adjacent Areas*, Carlsbad, NM, May 4, 1977. Ed. G.S. Austin. New Mexico Bureau of Mines and Mineral Resources Circular 159. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. 86. (Abstract Only).

ABSTRACT: Solution of salt from the Castile, Salado, and Rustler Formations, which compose the Permian Ochoan evaporite sequence in the Delaware Basin, has resulted in the formation of numerous solution-collapse features. In many places, these depressions are filled with collapsed Triassic and Cretaceous strata and/or younger alluvium. Two distinctive types of salt-solution features have been recognized.

Linear, lens-shaped depressions follow an arcuate trend above and parallel to the Capitan aquifer of Guadalupian age along the north and east margins of the Delaware Basin. Groundwater moving eastward from the Guadalupe Mountains and northward from the Glass Mountains through the Capitan and shelf-aquifer systems dissolved and removed salt from the adjacent and overlying Castile and Salado Formations. Fractures and joints caused by differential compaction and regional tectonism probably aided this process. Collapse of the overlying beds and filling of the resulting depressions probably occurred simultaneously or followed shortly after removal of the salt.

Salt-solution features of distinctly different type are located along the present westernmost extension of soluble beds in the Ochoan Series in the northwestern part of the Delaware Basin. This set of solution-collapse features extends from near Balmorhea in Pecos County, TX northward to the vicinity of Loving in southeastern Eddy County, NM. In this part of the Delaware Basin, Ochoan evaporites were exposed and removed by erosion related to the Pecos River and uplift of the Guadalupe Mountains. The western limit of the soluble beds in the Castile, Salado, and Rustler Formations has been determined by the effects of both surface and groundwater. In places, dolomite beds in the Rustler Formation are water bearing. Groundwater moving through the Rustler aquifer has apparently dissolved and removed halite from salt-bearing members of the Rustler.

Because the Rustler Formation is in the uppermost salt-bearing unit, a map of the top of this formation depicts the configuration of the collapse features formed by removal of underlying salt beds. Recent detailed mapping of the Rustler Formation in eastern Eddy County, NM, has revealed the chaotic nature of these solution features and further defined the relation of salt solution to the movement of water in the major surface drainage and aquifer systems.

Mercer, J.W., and B.R. Orr. 1977. *Review and Analysis of Hydrogeologic Conditions Near the Site of a Potential Nuclear-Waste Repository, Eddy and Lea Counties, New Mexico.* Open-File Report 77-123. Albuquerque, NM: US Geological Survey.

ABSTRACT: This interim report reviews and summarizes the hydrogeology of rocks associated with the Permian salt beds (Castile and Salado Formations) of Los Medanos area in southeastern New Mexico. The information will be considered, together with other factors, in the preparation of an analysis of the impact of a potential nuclear-waste repository on the environment.

Most of the geologic units in and adjacent to the Permian salt deposits are characterized by low permeabilities and highly mineralized water. Sandstone of the Delaware Mountain Group, which underlies the salt, has an average hydraulic conductivity of 0.16 ft/day and an average porosity of 15.65%. Flow is north-northeastward toward the margin of the Capitan limestone, at velocities ranging from 0.0005 to 0.0008 ft/day.

The Capitan limestone, a relatively high yielding limestone-reef aquifer adjacent to the study area, has been reported to have transmissivity values ranging from 500 ft²/day to 10,000 ft²/day and an average hydraulic conductivity of about 5 ft/day. Water movement west of the Pecos River is northeastward in the reef, with discharge at Carlsbad Springs. East of the Pecos River, water moves at very low rates and the direction of movement is uncertain.

The Castile and Salado Formations, which might be used to contain the nuclear waste, have a few isolated pockets of brine and gas, but generally transmit little or no groundwater.

An evaporite residuum near the top of the Salado Formation was developed in localities where groundwater has dissolved the Upper Permian evaporites. Brine in the residuum moves southward along Nash Draw and discharges about 200 gal/min into the Pecos River at Malaga Bend. The transmissivity of the residuum is 8,000 ft²/day and the flow rate is 0.2 ft/day.

The Rustler Formation overlies the Salado. The major water-bearing beds in the Rustler Formation are the Culebra Dolomite Member and Magenta member, which in places are capable of yielding up to 700 gal/min. Values of transmissivity in the formation range from near 0 to 500 ft²/day. The porosity and permeability in the dolomite is attributed to fracturing and to solution activity. Groundwater movement is south-southwestward toward the Pecos River.

Water in the Dewey Lake Red Beds, which overlie the Rustler Formation, occurs in sand lenses. Movement of water in the formation is restricted by low permeabilities.

The Santa Rosa sandstone, overlying the Dewey Lake Red Beds, also has a low permeability. The porosity is about 10% and the rate of flow is 0.3 ft/day south-southwest toward the Pecos River.

Data on the occurrence of water in the Chinle Formation is sparse; however, its lithology indicates it would be a poor aquifer.

Other potential aquifers adjacent to the proposed repository area include the Ogallala Formation, Gatuña Formation, and alluvial deposits. Most water in the Ogallala moves to the southeast but some moves westward, recharging the Santa Rosa sandstone aquifer. The Gatuña Formation contains water in sand and gravel lenses. Groundwater movement in the alluvium is in the approximate direction of surface flow of the Pecos River. An average value of transmissivity for the alluvium is 13,600 ft²/day, and flow-velocity estimates are generally less than 1 ft/day.

Mercer, J.W., and B.R. Orr. 1979. *Interim Data Report on the Geohydrology of the Proposed Waste Isolation Pilot Plant Site, Southeast New Mexico.* Water-Resources Investigations 79-98. Albuquerque, NM: US Geological Survey.

ABSTRACT: Data were collected during hydrologic investigations at the Waste Isolation Pilot Plant (WIPP) Site in southeast New Mexico through September 1977. These data will be considered as part of a site characterization study evaluating the feasibility of nuclear waste storage within bedded salt of the Salado Formation of Permian age.

Liquids in the rocks overlying the Salado Formation are found at the contact between the Permian Rustler and Salado Formations, and in the Culebra and Magenta Dolomite Members of the Rustler Formation.

Calculations of hydraulic gradient and direction of flow of water moving along the Rustler/Salado contact have been hindered because heads are stabilizing very slowly. Preliminary calculations of transmissivity range from 10^{-1} ft²/day on the western margin of the site to 10^{-4} ft²/day on the eastern margin. Liquids from the Rustler/Salado contact contain from 311,000 to 325,800 mg/L total dissolved solids. Liquid chemistry suggests long residence times and extensive liquid-rock interaction, increasing with decreasing permeability.

Liquids in the Culebra Dolomite Member move southeast at gradients ranging from 7 to 120 ft/mi. Preliminary transmissivity calculations range from 140 ft²/day on the western margin to 10^{-4} ft²/day to the east. Total dissolved solids range from 23,721 mg/L along the western margin of the site to 118,292 mg/L to the east. Liquid chemistry within the Culebra varies from well to well, probably as a function of fracture distribution.

Liquids in the Magenta Dolomite Member move southwest at a gradient of about 50 ft/mi. Preliminary transmissivity estimates range from less than 1 ft²/day to 40 ft²/day. Total dissolved solids range from 10,347 mg/L to 29,683 mg/L.

The extremely low vertical hydraulic conductivity within the Rustler Formation restricts liquid migration between the Magenta and Culebra Dolomite Members, and between the Culebra and the Rustler/Salado contact. Heads are highest in the Magenta and lowest at the Rustler/Salado contact.

Liquid levels in wells tapping the Permian Bell Canyon Formation near the site are lower than levels in wells tapping the Rustler Formation. Liquids from the Bell Canyon Formation contain 189,000 mg/L total dissolved solids. Liquid density and chemistry indicate long residence times and extensive liquid-rock interaction.

Mercer, J.W., and R.P. Snyder. 1990a. *Basic Data Report for Drillholes at the H-11 Complex (Waste Isolation Pilot Plant-WIPP).* SAND89-0200. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Drillholes H-11b1, H-11b2, and H-11b3 were drilled from August to December 1983 for site characterization and hydrologic studies of the Culebra Dolomite Member of the upper Permian Rustler Formation at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. In October 1984, the three wells were subjected to a series of pumping tests designed to develop the wells, provide information on hydraulic communication between the wells, provide hydraulic properties information, and to obtain water samples for quality of water measurements. Based on these tests, it was determined that this location would provide an excellent pad to conduct a convergent-flow non-sorbing tracer test in the Culebra Dolomite. In 1988, a fourth hole (H-11b4) was drilled at this complex to provide a tracer-injection hole

for the H-11 convergent-flow tracer test and to provide an additional point at which the hydraulic response of the Culebra H-11 multipad pumping test could be monitored.

The geologic units penetrated in H-11b1 are surficial deposits (0-12.5 ft) of Holocene age, the undifferentiated Dockum Group (12.5-63 ft) of Upper Triassic age, the Dewey Lake Red beds (63-558 ft), and the Rustler Formation (558-785+ ft) of Upper Permian age. There was evidence of Rustler halite in the core at 763 ft, which was 7 ft into the unnamed lower member.

The geologic units penetrated in H-11b2 are surficial deposits (0-11 ft) of Holocene age, the Dockum Group (undifferentiated) (11-62 ft) of Triassic age, the Dewey Lake Red beds (62-560 ft) and the Rustler Formation (560-776+ ft) of Permian age. There was evidence of Rustler halite in place in the core at 764 ft, which was 7 ft into the unnamed lower member.

The geologic units penetrated in H-11b3 are surficial deposits (0-11 ft) of Holocene age, The Dockum Group (undifferentiated) (11-59.5 ft) of Upper Triassic age, the Dewey Lake Red beds (59.5- 560.2 ft), and the Rustler Formation (560.2-788.7 + ft) of Upper Permian age. There was evidence of Rustler halite in the core at 777.7 ft, which was 17.7 ft into the unnamed lower member.

The geologic units penetrated in H-11b4 are surficial deposits (0-11 ft) of Holocene age, the Dockum Group (undifferentiated) (11-60 ft) of Upper Triassic age, the Dewey Lake Red beds (60-554 ft), and the Rustler Formation (554-765.3+ ft) of Upper Permian age. There was no evidence of Rustler halite in the core to 765.3 ft, which was 19.2 ft into the unnamed lower member.

A suite of geophysical logs was run on the drill holes and was used to identify different lithologies and aided in interpretation of the hydraulic tests.

Mercer, J.W., and R.P. Snyder. 1990b. *Basic Data Report for Drillhole H-12 (Waste Isolation Pilot Plant-WIPP)*. SAND89-0201. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Drillhole H-12 was drilled where hydraulic data were needed to better establish flow characteristics existing south-southeast of the Waste Isolation Pilot Plant (WIPP) Site. The fluid-bearing zones of interest are the Magenta and Culebra Dolomite units of the Rustler Formation. The drill hole is located in section 15, T23S, R31E, and encountered (from top to bottom) surficial Holocene deposits (10 ft, including artificial fill for the drill pad), the undifferentiated Dockum Group (60 ft), the Dewey Lake Red beds (552 ft), the Rustler Formation (354 ft), and the upper 25 ft of the Salado Formation. Dissolution of halite in the Rustler Formation has occurred in the uppermost member, but has not yet begun in the lower halite-bearing members. Cuttings and cores were taken at selected intervals and geophysical logs were run over the entire depth of the hole.

Mercer, J.W., and R.P. Snyder. 1990c. *Basic Data Report for Drillholes H-14 and H-15 (Waste Isolation Pilot Plant-WIPP)*. SAND89-0202. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Drillholes H-14 and H-15 were drilled to investigate data gaps in the hydrologic hole distribution at the Waste Isolation Pilot Plant (WIPP) Site. One data gap existed on the southwestern quarter of the site (H-14) and the other existed on the eastern side of the site (H-15). To alleviate this problem, H-14 and H-15 were drilled and cored into the lower member of the Rustler Formation. In addition to the information gained on the Culebra Dolomite Member, the holes yielded hydraulic and/or stratigraphic information on the Forty-

niner, Magenta Dolomite, and Tamarisk Members of the Rustler Formation in an area where no such information was available. Hydraulic tests were also conducted on the lower part of the Dewey Lake Red beds in H-14.

The geologic units penetrated in H-14 are surficial deposits (0-6.5 ft) of Holocene age, the Gatuña Formation (6.5-40 ft) of Pleistocene age, the Dewey Lake Red beds (40-359 ft), and the Rustler Formation (359-589+ ft) of Permian age. There was no evidence of halite currently in place in the drilled or cored portion of the Rustler Formation (17 ft into the unnamed lower member).

The geologic units penetrated in H-15 are surficial deposits (0-18 ft) of Holocene age, the Gatuña Formation (18-42 ft) of Pleistocene age, the Triassic Dockum Group (42-168 ft), the Dewey Lake Red beds (168-692 ft) and the Rustler Formation (692-900+ ft) of Permian age. There was no evidence of halite currently in place in the drilled or cored portion of the Rustler Formation (17 ft into the unnamed lower member).

A suite of geophysical logs was run on the drill holes and was used to identify different lithologies and aided in the interpretation of the hydraulic tests.

Mercer, J.W., and R.P. Snyder. 1990d. *Basic Data Report for Drillhole H-16 (Waste Isolation Pilot Plant-WIPP)*. SAND89-0203. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: H-16 was drilled during July and August, 1987 to assess pre- and post-mining hydrologic parameters associated with the fourth shaft (air-intake shaft) to be constructed at the Waste Isolation Pilot Plant (WIPP) Site near Carlsbad, New Mexico. The drill hole is located about 50 ft northwest of the shaft location and was drilled in five separate phases with selected intervals in the Rustler Formation being cored and hydraulically tested. The hole was completed by setting five packers that isolated selected intervals of the Permian Rustler Formation, with transducers measuring pressures in each interval. The hole will provide near-field hydraulic-response data on both the construction of the air-intake shaft and all later activities, such as grouting and sealing.

The geologic units penetrated in H-16 are surficial deposits (0-12 ft) and Mescalero caliche (12-18 ft) of Holocene age, the Gatuña Formation (18-37 ft) of Pleistocene age, the undifferentiated Dockum Group (37-52 ft), the Dewey Lake Red beds (52-539.1 ft), the Rustler Formation (539.1-845.5 ft) of Permian age, and included the upper part of the Salado Formation (841.5 ft-850.9 ft), also of Permian age. There was no evidence of halite presently in place in the drilled or cored portion of the Rustler Formation above the lower unnamed member.

In addition to obtaining cuttings and core from the surface to total depth (850.9 ft), geophysical logs were taken to measure acoustic velocities, density, radioactivity, porosity, and formation resistivities.

Mercer, J.W., and R.P. Snyder. 1990e. *Basic Data Report for Drillholes H-17 and H-18 (Waste Isolation Pilot Plant-WIPP)*. SAND89-0204. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Drillholes H-17 and H-18 were drilled at the Waste Isolation Pilot Plant (WIPP) Site to assess uncertainties in site hydrologic parameters and to serve as monitoring points for planned hydrologic tests. H-17 was drilled south of H-11 and east of P-17 to evaluate the existence of a high-permeability region in the Culebra Dolomite Member that had been indicated by groundwater flow modeling and surface geophysical surveys. H-18 was drilled

north of H-2 to help reduce the uncertainties of boundaries between high and low transmissivities and fluid density that had been identified by drilling and by modeling.

The geologic units penetrated in H-17 are surficial deposits (0-21.5 ft) of Holocene age, the Dockum Group undifferentiated (21.5-55 ft) of Triassic age, the Dewey Lake Red beds, (55-509 ft), the Rustler Formation (509-855.7 ft), and the upper part of the Salado Formation (855.7-870.3+ ft), all of Permian age. There was no evidence of halite presently in place in the drilled or cored portion of the Forty-niner Member of the Rustler Formation (first halite encountered was in the Tamarisk member of the Rustler Formation).

The geologic units penetrated in H-18 are surficial deposits (caliche pad and unconsolidated sand 0-5 ft) and Mescalero caliche (5-8 ft) of Holocene age, the Dockum Group undifferentiated (8-20 ft) of Triassic age, the Dewey Lake Red beds (20-506.1 ft), the Rustler Formation (506.1-820.9 ft), and the upper part of the Salado Formation (820.9-830.5+ ft), all of Permian age. There was no evidence of halite presently in place in the drilled or cored portion of the upper Rustler Formation (the first halite entered was in the unnamed member below the Culebra Dolomite).

Mercer, J.W., R.L. Beauheim, R.P. Snyder, and G.M. Fairer. 1987. *Basic Data Report for Drilling and Hydrologic Testing of Drillhole DOE-2 at the Waste Isolation Pilot Plant (WIPP) Site.* SAND86-0611. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Drillhole DOE-2 was drilled to investigate a structural depression marked by the downward displacement of stratigraphic markers in the Salado Formation ~2 mi north of the center of the Waste Isolation Pilot Plant (WIPP) Site. This depression was named informally after the shallow bore hole FC-92 in which the structure was described. The presence of the depression was confirmed by drilling. Contrary to several hypotheses, halite layers were thicker in the lower part of the Salado, not thinner as a result of any removal of halite. The upper Castile anhydrite in Drillhole DOE-2 is anomalously thick and is strongly deformed relative to the anhydrite in adjacent drill holes. In contrast, the halite was < 8 ft thick and significantly thinner than usually encountered. The lower Castile anhydrite appears to be normal. The depression within the correlated marker beds in the Salado Formation Drillhole DOE-2 is interpreted as a result of gravity-driven deformation of the underlying Castile Formation.

Several stratigraphic units were hydrologically tested in Drillhole DOE-2. Testing of the unsaturated lower portion of the Dewey Lake Red Beds was unsuccessful because of exceptionally small rates of fluid intake. Drill-stem tests were conducted in five intervals in the Rustler Formation, over the Marker Beds 138-139 interval in the Salado Formation, and over three sandstone members of the Bell Canyon Formation. A pumping test was conducted in the Culebra Dolomite Member of the Rustler Formation. Pressure-pulse tests were conducted over the entire Salado Formation. Fluid samples were collected from the Culebra Dolomite Member and from the Hays Member of the Bell Canyon Formation.

Mercer, J.W., P. Davis, K.F. Dennehy, and C.L. Goetz. 1981. *Results of Hydrologic Tests and Water-Chemistry Analyses, Wells H-4A, H-4B, and H-4C at the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Water-Resources Investigations 81-36. Albuquerque, NM: US Geological Survey.

ABSTRACT: Data were collected during hydrologic testing at wells H-4A, H-4B, and H-4C in the southern part of the proposed Waste Isolation Pilot Plant Site in southeastern New Mexico. The three water-bearing zones tested, the Magenta and Culebra Dolomite Members of the Rustler Formation and the Rustler Formation/Salado Formation contact, yield water to

wells at rates less than 0.9 gal/min. Throughout the testing, water-pressure response in the tested zone was monitored by a pressure-transducer system. The calculated transmissivity values for the test zones were 0.06 ft²/day (estimated storage coefficient 10⁻⁶) for the Magenta Dolomite Member at well H-4A, 0.9 ft²/day (estimated storage coefficient 10⁻⁹) for the Culebra Dolomite Member at well H-4B, and 0.0006 ft²/day (estimated storage coefficient 10⁻⁴) for the Rustler Formation/Salado Formation contact at well H-4C.

Water samples from the Magenta and Culebra had dissolved-solids concentrations of 22,300 and 18,100 mg/L, respectively. The major chemical constituents of water samples from these two zones were sodium, chloride, and sulfate. Water samples from the Rustler/Salado contact had a dissolved-solids concentration of 322,000 mg/L and magnesium, sodium, and chloride were the major constituents. Radium-226, a naturally occurring radioactive element, was present in samples from all three zones.

Merrill, R.M. 1985. *The Analysis of Anions in Geological Brines Using Ion Chromatography*. SAND84-2297. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Ion chromatographic procedures for the determination of the anions bromide, sulfate, nitrite, nitrate, phosphate, and iodide in brine samples have been developed and are described. The techniques have been applied to the analysis of natural brines and geologic evaporites. Sample matrices varied over a range from 15,000 mg/L to 200,000 mg/L total halogens, nearly all of which is chloride. The analyzed anion concentrations ranged from less than 5 mg/L in the cases of nitrite, nitrate, and phosphate, to 20,000 mg/L in the case of sulfate. A technique for suppressing chloride and sulfate ions to facilitate the analysis of lower concentration anions is presented. Analysis times are typically less than 20 min for each procedure and the ion chromatographic results compare well with those obtained using more time-consuming classical chemical analysis.

Merritt, M.L. 1977. "Environmental Studies for the WIPP," *Transactions of the American Nuclear Society, 1977 Winter Meeting, San Francisco, CA, November 27-December 2, 1977*. SAND77-2017A. Vol. 27, 437-438. (Abstract Only).

ABSTRACT: Environmental studies have been underway since 1975 in archaeology, socioeconomics, geology, hydrology, seismology, meteorology, and biology to be used as a basis for analyzing environmental impacts for the Waste Isolation Pilot Plant (WIPP). Within 10 mi of the WIPP, there are two ranches and several potash mines and facilities, but no towns or villages. Seismicity is low (seismic Risk Zone J). The area is arid, and tornados seldom occur. Soils in the area support desert vegetation which has been altered by grazing pressure. The wildlife is varied in the area and no plant or animal on the federal list of threatened species has been found. Background radiation in the area is low. DWP

Miller, J.D., C.M. Stone, and L.J. Branstetter. 1982. *Reference Calculations for Underground Rooms of the WIPP*. SAND82-1176. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Results of the first reference calculation for the Waste Isolation Pilot Plant Project using the dynamic relaxation finite element code SANCHO are presented. The reference calculation is a two-part study involving a room design for storage of non heat-producing nuclear waste and another for an experimental configuration with heat-producing waste. Results are presented that include relevant deformations, relative clay seam displacements, stress and strain profiles, temperature profiles, and contour plots of a conservative postprocessed measure of potential salt failure. These results will be useful for

subsequent work, such as defining experiments and developing instrumentation. Highlights of the reported results include room closure histories, which reached maximum values of 0.21 m and 0.75 m in the vertical direction for the isothermal and heated cases, respectively, at 10 years, and the plots of potential halite failure. No failure of the salt is likely for the heated rooms, and the only possible salt fracturing that might occur in the isothermal room is confined to a small area in the center of the room floor.

Mining Geophysical Surveys. [1976]. *Experimental Geophysical Surveys of the Los Medaños Site and Surrounding Areas for Waste Isolation Pilot Plant Program, Eddy and Lea Counties, New Mexico.* [Tucson, AZ]: Mining Geophysical Surveys. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Resistivity and gravity surveys during the summer of 1976 examined, respectively, areas of the site for a proposed nuclear waste repository and several areas that may be breccia pipes. Fifty-three lines of resistivity data were acquired that are interpreted separately. For the site area, two types of electrode arrays were used; a Schlumberger sounding array and a pole-dipole profiling array. Gravity was measured in a grid system over Hills A, B, C, and D, and Weaver pipe. Two gravity crosslines were established and tied into the survey of Hills A and B. Gravity data have also been reduced and interpreted separately.

DWP

ANNOTATION: Elliot Geophysical Company (1977e,f) are printed and magnetic tape data files for this field surveys. Interpretive reports based on the data include Elliot Geophysical Company (1976a and 1976b).

Minnema, D.M., and L.W. Brewer. 1983. *Background Radiation Measurements at the Waste Isolation Pilot Plant (WIPP) Site, Carlsbad, New Mexico.* SAND83-1296. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A series of background radiation measurements were performed at the Waste Isolation Pilot Plant (WIPP) Site, Carlsbad, NM. The survey consisted of gross gamma and gamma spectral measurements of the radiation fields, soil and salt grab sample gamma analysis, and radon and working-level measurements. The survey included locations at the surface and within the mine itself.

Background radiation levels on the surface were measured to average 7.65 microR/hour, and 0.7 microR/hour within the mine. Radon and working levels were at or below detection levels at all locations, and the radon concentration was estimated to be about 0.01 pCi/L on the surface based on spectral measurements. The spectral measurements were performed using an intrinsic germanium spectrometer, and calculations from the spectra indicated that potassium-40 contributed about 28% to the surface level dose rates, natural uranium daughters contributed about 64%, and cesium-137 from weapons testing fallout contributed about 8%. In the mine, potassium-40 was the only identifiable contributor to the dose rate.

Molecke, M.A. 1977a. "The Waste Isolation Pilot Plant High-Level Waste Experimental Program," *Transactions of the American Nuclear Society, 1977 Winter Meeting, San Francisco, CA, November 27-December 2, 1977.* SAND77-1301A. Vol. 27, 440. (Abstract Only).

ABSTRACT: The scope of the Waste Isolation Pilot Plant (WIPP) Project includes experiments with high-level wastes and spent, unprocessed fuel elements to validate laboratory tests under

in situ conditions. These conditions include large thermal fields, large radiation fluxes, lithostatic pressure, and the corrosive salt mine environment. Laboratory experiments are measuring radionuclide migration, sorption, and distribution coefficients in rocks and brines from southeastern New Mexico. Leaching tests, rock mechanics, radiation-induced stored energy, actinide chemistry in salt environments, and barriers to migration are also being investigated. In situ experiments will begin about 1986 and will include unprotected waste, as well as full-size canisters. Monitoring will be extensive during these experiments. The data will provide experience to assure the safe, long-term isolation of radioactive waste from the environment. DWP

Molecke, M.A. 1977b. "Waste Isolation Pilot Plant Transuranic Wastes Experimental Program," *Transactions of the American Nuclear Society, 1977 Winter Meeting, San Francisco, CA, November 27-December 2, 1977*. SAND77-1300A. Vol. 27, 440-441. (Abstract Only).

ABSTRACT: Most of the waste disposed in the Waste Isolation Pilot Plant (WIPP) will be low- and intermediate-level transuranic (TRU) wastes. Chemical and physical experiments on the interactions of waste forms and salt environment will be undertaken in the laboratory before wastes are accepted in 1984. Some monitoring and experiments with waste are planned in the WIPP to demonstrate acceptable containment of wastes. Both long-term and operational concerns are being addressed. Experiments are in progress to assess the extent of gas generation from the TRU wastes and means of control, if necessary. Actinide mobility in the salt and brine system is also being investigated. Operational concerns mainly concentrate on fire hazards. These programs will help refine the waste acceptance criteria for the WIPP. DWP

Molecke, M.A. 1983. *A Comparison of Brines Relevant to Nuclear Waste Experimentation*. SAND83-0516. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The ionic compositions of 18 brines used in nuclear waste-related laboratory tests or obtained from field tests are described and compared. Also described is the origin of each brine, its predominant use for laboratory testing, and its relevancy for future testing. The brines include Brines A and B (Waste Isolation Pilot Plant (WIPP)/generic), Office of Nuclear Waste Isolation (ONWI) Composite Permian Brine P and Equilibrated Permian P No. 2, Battelle Pacific Northwest Laboratory (PNL), Sandia High-Level Waste (HLW) package interactions test brines (pretest, intermediate, and posttest samples), WIPP-12 brines (flow and downhole), ERDA-6 brines (flow and downhole), WIPP Inclusions No. 1 and No. 2, Materials Characterization Center (MCC) brine, German quaternary Brine Q, US Geological Survey bittern NBT-6a, saturated NaCl (20° and 100°C), and standard seawater.

Molecke, M.A. 1989. "Technical Operations and Data Collection Details of the In Situ WIPP Materials Interface Interactions Test," *Testing of High-Level Waste Forms Under Repository Conditions, Cadarache, France, October 17-21, 1988*. Ed. T. McMenamin. EUR 12017; SAND88-2022C. Luxembourg: Commission of the European Communities. 67-77.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Materials Interface Interaction Tests (MIIT) experiments involve the in situ testing of multiple "pineapple slice" shaped samples of simulated (nonradioactive) waste glasses, potential canister and overpack metals, brine, and rock salt in the salt repository environment at the WIPP. This series of experiments involves multiple emplacements of various US and foreign glass waste forms (all nonradioactive) in contact with/interacting with several container metals; rock salt, brine, etc., all maintained at approximately 90 ± 5°C. This paper focuses on the technical aspects and operations of the

MIT experimental program, including assorted repository-relevant observations and experience gathered after more than two years of in situ test operation. As such, this is primarily a descriptive "hardware" and test operations document; test data are presented in parallel documents.

Molecke, M.A. 1990. *Test Plan: WIPP Bin-Scale CH TRU Waste Tests*. SAND90-1974. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) bin-scale contact handled transuranic (CH TRU) waste test is a multi-phase experimental plan intended to provide relevant composition and kinetic rate data on gas generated and consumed from TRU waste degrading under conditions relevant to the WIPP repository. CH TRU wastes being tested include both radioactive and hazardous-mixed wastes representing current and expected output of various US Department of Energy (DOE) waste generating facilities. Waste degradation and consequent gas production will be affected by, and tested as a function of, many variables: synergistic interactions due to multiple degradation modes; waste form types and processing procedures; long-term repository environmental effects; intrusion of different types and quantities of brines; different repository periods from the operational phase to the longer-term, post-closure period; engineered barrier materials such as salt, backfill and getter materials, and perhaps grouts in contact with the wastes; and, possibly, engineered modifications of fixes (to be developed) that can reduce the quantities of gases to be generated or released. Gas samples will periodically be obtained from each test bin and analyzed quantitatively for gases generated by degradation and released as a function of time. Gases will be analyzed for potentially hazardous volatile organic compounds of environmental safety and Environmental Protection Agency Resource Conservation and Recovery Act (EPA RCRA) hazardous waste concerns.

Waste-brine leachate solutions will also periodically be obtained from the bins and analyzed for radionuclide concentrations, hazardous organic components, and toxic metal concentrations. The effects of organic or inorganic complexing agents mixed with the wastes on migration will be examined. Solution data, as well as the gas data and results, will be used directly in the WIPP performance assessment (PA) modeling studies and also evaluated for EPA RCRA (hazardous waste) characterization impacts and concerns.

The WIPP bin-scale test program involves about 600 drum-volumes of actual CH TRU wastes contained within about 124 separate test bins. A test bin is a metal container designed specifically to hold the wastes safely and to allow periodic sampling of released gases and waste leachant liquids. It is not intended to be a transportation or waste disposal container. Phase 3 allows more bins to be added as required and tested to accommodate: additional waste types; (more than those currently shippable to the WIPP); future processed waste types; engineered barriers or modifications that can significantly reduce the amount of gas to be generated; tests that can incorporate and help resolve further desired characterizations for EPA RCRA or other regulatory and/or programmatic concerns; and additional tests to reduce any unacceptably large, experimental uncertainties indicated by initial results.

Bin-scale test data will be linked by geochemical modeling and predictive calculations with related data from the parallel laboratory and WIPP in situ alcove CH TRU waste test programs. The combined data from laboratory, bin-scale, and in situ alcove test programs are required by the WIPP PA study. Full details on waste types and components to be used in this bin-scale test program are described here.

The quantitative data, results, and interpretations from these tests are required by the WIPP PA program. The bin-scale test program has been planned solely to obtain necessary data on radioactive and hazardous gas and leachate components which may be released and their impacts on both the short-term and long-term safe operation and containment capability of the WIPP Facility.

Molecke, M.A., and L. Abrego. 1980. "Status of Sandia HLW Canister/Overpack Program Studies," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980.* ONWI-212; SAND80-2191C. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 230-233.

ABSTRACT: Sandia National Laboratories have evaluated potential alloys, for high-level waste canisters or overpacks that can maintain integrity under the corrosive environment expected in a repository in salt. Laboratory and hot-cells tests are now used, and various field and other tests are in planning. From screening results, a titanium alloy (TiCode-12) has been selected as the prime candidate for further testing. The investigations cover five areas: 1) uniform and localized corrosion with variables including brine composition, temperatures, time, pH, oxygen content, moisture content, gamma irradiation, engineered backfill materials, heat treatment, and effects of welds and crevices; 2) stress corrosion cracking under tension at a constant strain rate with variables including temperature, environment, prior gamma radiation exposure, dissolved oxygen content, presence of welds, and heat treatment; 3) physical and mechanical metallurgy; 4) hydrogen embrittlement/sustained load cracking related to hydrogen produced by radiolysis of intruding fluids; and 5) hot-cell and field testing of a full-size TiCode-12 overpack in salt at the Asse facility in Germany. DWP

Molecke, M.A., and R. Beraun. 1986. "WIPP Simulated DHLW Tests: Status and Initial In Situ Backfill Thermal Conductivities," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 2-6, 1986.* Ed. R.G. Post. SAND86-0489C. Tucson, AZ: University of Arizona. Vol. 2, 231-236.

ABSTRACT: Several series of waste package performance technology experiments for simulated defense high-level waste (DHLW) packages have been emplaced and put into active operation at the Waste Isolation Pilot Plant (WIPP) Facility. These experiments involve 18 full-size DHLW packages emplaced in heavily instrumented vertical bore holes in the salt drift floor. These tests have been in heated operation for over 10 months now; the planned test duration is 3 to 7 years. A major purpose of these experiments is to evaluate the in situ materials performance (i.e., degradation or alteration) of various waste package components: metal canisters and overpacks, backfill materials, nonradioactive DHLW glass, and installed instrumentation. These evaluations are being performed under both near-reference and overtest or accelerated-aging repository conditions. This paper describes the current status of the WIPP simulated DHLW experiments and presents initial thermal conductivity results derived from in situ thermocouple (temperature) data. Current in situ backfill thermal conductivities range from 0.28 to 0.43 W/m-°C for bentonite/sand backfills and 1.12 W/m-°C for crushed salt backfill, depending on maximum waste package system temperature(s). Preliminary modeling calculations of thermal conductivity have also been performed using the SINDA and COYOTE codes. The numerically derived values are generally in good agreement with the experimentally measured values, except for the first several days after experiment (heater) turn on.

Molecke, M.A., and A.R. Lappin. 1990. *Test Plan Addendum #1: Waste Isolation Pilot Plant Bin-Scale CH TRU Waste Tests.* SAND90-2082. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The (CH TRU) contact-handled transuranic Waste Bin-Scale Test Plan is modified by this addendum to respond to concerns about the bin-scale tests, including interest in the "statistical representativeness" and "statistical justification" for waste characterization and specific tests. The test plan and addendum "...provide guidelines as to how the test program is

to be conducted and why, with supporting justifications and background information." Detailed instructions for tests will be provided in test procedures.

Significant changes to the test plan included in the Addendum are to: 1) add "...an experimental requirement for TRU waste leaching/solubility test program separate from the gas testing requirements"; 2) include CH TRU waste form descriptions and test details in Phase 3 of the gas test program, "identifying both general assumptions and specific statistical approaches"; 3) include preliminary description of CH TRU waste forms and test details in a "Phase 0" newly defined and recommended; and 4) "...technical modifications to bin-scale test details, and their potential impacts on WIPP site operations." "Phase 0 testing is considered crucial to provide a direct link between TRU waste characterization, basic statistical validation processes, and the approved Test Plan." Subsequent tests may be modified based on Phase 0 results.

The recommended revisions and requirements of the Addendum increase the number of required test bins from 124 to 146, with possibly 87 bins for contingencies. The 146 bins will fit in the two allocated test rooms; a third room may be necessary for bin tests, depending on results of Phases 0 and 1. DWP

Molecke, M.A., and R.V. Matalucci. 1984. *Preliminary Requirements for the Emplacement and Retrieval of Defense High-Level Waste (DHLW) Tests in the Waste Isolation Pilot Plant (WIPP)*. SAND84-1444. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The requirements for emplacing and retrieving defense high-level waste (DHLW) in the Waste Isolation Pilot Plant (WIPP) are summarized. Associated details are presented so that both the scientific intent and purposes for the test program can be defined and the parallel requirements of operational equipment designers are satisfied. The actual DHLW tests are divided into operational period, "reference" tests; containment period, "accelerated aging" tests; and long-term period, "1000-year-aged" waste tests. Consistent with the WIPP *Final Environmental Impact Statement (FEIS)* limitations, a maximum of 17.2×10^6 Ci will be used in these tests. Waste characteristics, tentative quantities, and test conditions are specified; details of associated instrumentation are also provided. The operational demonstrations for handling, emplacing, and retrieving DHLW in the WIPP are summarized. These demonstrations start with mock, nonradioactive canisters and conclude with actual, radioactive DHLW canisters. Test room considerations which can impact the operational demonstrations, such as room configuration and closure, and canister movement, are described. Hot cell design requirements mandated by the DHLW test and demonstration needs are listed. Finally, the tentative schedules of preliminary simulated DHLW technology experiments, operational demonstrations, and actual DHLW tests are provided.

Molecke, M.A., and E.J. Nowak. 1980. "Status of Sandia Backfill-Getter Development Studies," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting*. Columbus, OH, December 9-11, 1980. ONWI-212; SAND80-2190C. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 228-230.

ABSTRACT: The backfill and getter system is to function as a barrier to hydrologic intrusion, to sorb radionuclides, to modify chemically (Eh, pH, ionic composition) any intruding groundwater or brine, to buffer stress mechanically, and to conduct heat. Bentonite, a smectite swelling clay, is selected as a major component because it has good sorptive capacity, retains sorptive capacity in mixtures, buffers brine pH, has low permeability, swells in brine, has adequate thermal conductivity, buffers stress, and is reasonable in cost. Sorption of various fission products is being measured on bentonite and other materials. Accelerated tests and geochemical analyses will help determine the stability of backfill materials. Permeability

of bentonite and sand mixtures is in the range of microdarcies and should eliminate convective transport through backfill. Thermal conductivity is in the range of that of crushed rock salt; compacted and brine saturated conditions will be tested. The methods of placing backfill are being developed and will include work on compacted backfill, a field demonstration, and testing of backfill properties from bench scales to field tests. Backfill is being modeled mathematically as a function of empirical K_d , effective porosity, and backfill thickness. Radionuclide release delay times of 10^5 to 10^6 years for actinides and 10^3 to 10^4 years for fission products are expected. Data and modeling show backfill-getters minimize or significantly retard radionuclide release, even in the presence of brine. DWP

Molecke, M.A., and N.R. Sorensen. 1989. "Retrieval and Analysis of Simulated Defense HLW Package Experiments at the WIPP," *Scientific Basis for Nuclear Waste Management XII, Berlin, Germany, October 10-13, 1988*. Eds. W. Lutze and R.C. Ewing. SAND88-1135J. Pittsburgh, PA: Materials Research Society. Vol. 127, 653-660.

ABSTRACT: In situ waste package performance experiments involving simulated (nonradioactive) defense high-level waste (DHLW) containers have been in progress since late 1984 at the Waste Isolation Pilot Plant (WIPP) Facility. These experiments involve full-size, simulated DHLW containers of several metals and designs emplaced in the WIPP bedded rock salt. These test containers are surrounded by granular backfill (packing) materials, have in many cases been intentionally injected with brines, and are heavily instrumented. A majority of the test packages also contain nonradioactive DHLW borosilicate glass waste form, either within the container and/or outside of it. The primary purpose of these WIPP simulated DHLW experiments is to evaluate the in situ durability and performance of all waste package engineered barrier materials, and to perform package concept validation testing.

Twelve of the test DHLW containers, emplaced in WIPP test Room B, have been in heated operation since 1985 and had a maximum surface temperature of about 190°C. These containers were recently retrieved, after about 3 years of heated exposure, for detailed posttest laboratory analyses of general corrosion and metallurgical degradation, waste form and backfill materials alterations, and other rock salt-brine-barrier materials near-field interactions with the "repository" geochemical environment. Test canisters and overpacks made of ASTM Grade-12 titanium showed essentially no visible degradation in either the base metal or welds; cast mild steel A-216 WCA overpacks have suffered some uniform corrosion. Significant degradation of the removed instruments and associated test apparatus has been found: pieces of stainless steel (both 304L and 316) apparatus have undergone extensive stress-corrosion cracking failure and non-uniform attack; Inconel 600-sheathed instruments have undergone both extensive uniform and localized (pitting) attack. Granular backfill materials have been significantly compacted by creep closure to about a density of 2 kg/m³. Laboratory analyses are still in progress. Further details on these materials results plus instrumentation data and other in situ WIPP waste package test observations are discussed.

Molecke, M.A., and T.M. Torres. 1983. "The Waste Package Materials Field Test in S.E. New Mexico Salt," *Scientific Basis for Nuclear Waste Management VII, Boston, MA, November 14-17, 1983*. Ed. G.L. McVay. SAND83-1516C. New York, NY: North-Holland. Vol. 26, 69-76.

ABSTRACT: A six-part, waste package materials field test was conducted in a halite horizon of a potash mine in southeastern New Mexico. The primary purposes of this test were to evaluate the thermophysical and geochemical performance of candidate HLW package (high-level waste package) backfill materials emplaced in rock salt and the corrosion behavior of candidate waste canister or overpack alloys. This field test series also served as a precursor to forthcoming Waste Isolation Pilot Plant (WIPP) in situ waste package performance experiments

on simulated defense high-level waste packages, serving to develop applicable testing, instrumentation, and sampling techniques. The backfill materials tested (individually, in one- to five-month tests) were: low-density bentonite clay; low-density bentonite (70 wt.%)–silica sand (30 wt.%) mixtures, both dry and brine-injected; high-density bentonite sand annular compacts; trapped air; and finely crushed WIPP salt. The in situ measured thermal conductivities (at a maximum canister-heater surface temperature of 150 or 250°C) for the backfills ranged from 0.25 W/mK for pure bentonite to about 1.25 W/mK for the high-density bentonite-sand. No significant backfill material degradation products were detected in posttest analyses. No appreciable corrosion of the titanium-, nickel-, or iron-based alloys embedded in the hot backfill was found; potentially significant pitting corrosion of 2 1/4 Cr-1 Mo steel and copper was detected.

Molecke, M.A., R.B. Diegle, and J.A. Ruppen. 1982. "Materials for High-Level Waste Canister/Overpacks in Salt Formations," *Transactions, American Nuclear Society, Los Angeles, CA, June 6, 1982*. SAND82-0429J. La Grange Park, IL: American Nuclear Society. Vol. 41, 284-285. (Abstract Only).

ABSTRACT: Studies on the corrosion and mechanical behavior of TiCode-12 and other titanium alloys, for use as candidate canister or overpack barriers in a high-level waste repository or test facility in salt, are reported herein. These studies have been in progress at Sandia National Laboratories (SNL) since 1976. Titanium alloys were selected as the primary materials for detailed testing based on candidate screening analyses (general corrosion and economic assessments) of about 20 different alloys. Recent material results on titanium alloys are described and related to the long-term physical integrity of waste package barriers in salt; results on other candidate alloys are reviewed.

The corrosion behavior of TiCode-12 has been evaluated as a function of: brine composition, temperature, time, pH, oxygen concentration, and gamma radiolysis. Uniform corrosion rates are in the range of 0.1 to 10 $\mu\text{m}/\text{year}$; pitting or crevice corrosion has not yet been observed. The highly adherent, passivating titanium oxide film that provides the corrosion protection is being evaluated via electro-chemical polarization and surface analytical techniques to enable modeling of the corrosion mechanism(s). An increase in the corrosion rate by a factor of about two was observed for sensitized TiCode-12; changes in the alloy microstructure are being analyzed in order to model this phenomenon. Alterations in the chemistry and processing procedure of TiCode-12 are being evaluated to optimize corrosion, mechanical, and mill-producibility properties for high-level waste package applications.

Slow strain rate testing of TiCode-12 revealed no apparent susceptibility to stress corrosion cracking; no significant changes in tensile properties were observed, but alterations in fracture mode were determined to be caused by internal hydrogen content. Hydrogen effects on titanium alloy mechanical properties and crack susceptibility are being studied. Some hydrogen embrittlement occurs at hydrogen concentrations in the range of 200 to 300 ppm by weight, but the strength of TiCode-12 is not affected at concentrations up to 1100 wppm. Further research on slow crack growth threshold stress intensity as a function of H content is required.

Based on the analysis of available corrosion and metallurgical results, a TiCode-12 high-level waste (HLW) canister package for use in a repository or test facility in salt has been proposed. Such a simplified HLW canister could provide a long-term containment integrity and significantly minimize total HLW isolation system costs when compared to other waste package design concepts.

Molecke, M.A., N.R. Sorensen, and J.L. Krumhansl. 1988. "Summary of WIPP Materials Interface Interactions Test Data on Metals Interactions and Leachate Brine Analyses,"

Testing of High-Level Waste Forms Under Repository Conditions, Cadarache, France, October 17-21, 1988. Ed. T. McMenamin. SAND88-2023C; EUR 12017. Luxembourg: Commission of the European Communities. 192-203.

ABSTRACT: Several series of in situ, high-level waste form leaching and waste form engineered barrier materials interactions tests have been in progress at the Waste Isolation Pilot Plant (WIPP) Facility since July 22, 1986. This multinational effort, the WIPP Materials Interface Interactions Test (MIIT), involves the underground testing of about 1900 (nonradioactive) waste forms, metal, and geologic samples in the bedded salt at the WIPP, near Carlsbad, NM. Post-test analyses of metal and brine leachate samples retrieved after 0.5, 1, and 2 years of heated testing are in progress now; available data and interpretations thereof are summarized in this paper. Titanium, Inconel, and copper samples had very little degradation. Stainless steel 304L samples suffered from significant stress, corrosion, cracking, and pitting. Both mild steel A216/WCA and lead samples corroded severely, adding many ions and particulates to solution. Observed trends in brine leachate compositions for many test assemblies are very similar to those measured for control-blank tests and are, therefore, difficult to interpret at this time. Measured pH values are also difficult to interpret. The leachate analyses and associated geochemical evaluations are intended to supplement glass waste form surface studies, and to provide analysts and modelers with supporting information for their interpretations.

Molecke, M.A., D.W. Schaefer, R.S. Glass, and J.A. Ruppen. 1981. *Sandia HLW Canister Overpack Studies Applicable for a Salt Repository.* SAND81-1585. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: An experimental program to develop candidate materials for use as high-level waste (HLW) overpacks or canisters in a salt repository has been in progress at Sandia National Laboratories (SNL) since 1976. The main objective of this program has been to provide a waste package barrier having a long lifetime in the chemical and physical environment of a repository. This paper summarizes the recent corrosion and metallurgical results for the prime overpack material TiCode-12 in the areas of uniform corrosion (extremely low rate and extent), local attack, e.g., pits and crevices (none found), stress corrosion cracking susceptibility (no significant changes in macroscopic tensile properties detected), hydrogen sorption/embrittlement effects (testing still in process), effects of gamma irradiation in solution (still in process), and sensitizing effects (still in process). Previous candidate screening analyses on other alloys and recent work on alternate overpack alloys are reviewed. All phases of these interrelated laboratory, hot-cell, and field experimental studies are described.

Monsees, J.E., and D.E. Munson. 1982. "Design Considerations for a Nuclear Waste Repository in Salt." *Tunneling Technology Newsletter.* SAND82-0185J. Number 37, 1-19. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Developing a nuclear waste repository in salt requires a unique combination of conventional underground construction and design practice together with new techniques in rock mechanics. These techniques are required because of the need to account for two factors unique to this application: thermal loading of the rock by heat generated in the waste packages; and the need for long-term performance assessment calculations to ensure confidence on the parts of the public and regulatory agencies.

Although certain advances in technology and predictive capability are required, there is every reason to believe that the outstanding problems can soon be solved and that the repository can be designed and constructed to perform its function.

The design, construction, and operation of a mined radioactive waste repository will resolve a critical problem in the continued development of nuclear power. It will also represent a new level of technical capabilities in underground design and in the understanding of geologic materials. The challenge in repository design arises because of the concern for public safety and the rigorous regulatory climate that dictates analyses of mechanical, thermal, and hydrological performance well beyond the times and conditions that are important in conventional underground design. Repository design requires a sharply focused understanding of the tools of the design process (the analytical and numerical analyses, constitutive models, and material properties typically involved in rock mechanics analyses) that stems from a well-defined concept of the design process itself.

This article examines the unique features of the development of a radioactive waste repository in salt. It discusses the necessary design process and outlines the rock mechanics inputs peculiar to this process. It is written with the hope of encouraging the design community to examine the distinctive aspects of repository design and to contribute toward making the advances needed in both design and rock mechanics technology.

Montgomery, S.T. 1981. *Implementation of a Transient Creep Model for Natural Rock Salt as a Material Response Subroutine for SANCHO*. SAND81-1163. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The equations for determining the stress in a material response subroutine of SANCHO are formulated using a transient creep model for natural rock salt. It is shown that the equation for the primary creep strain causes the system of equations to be numerically stiff when Runge-Kutta-Fehlberg formulas are used for numerical integration. This stiffness can be eliminated by using an approximate solution of the primary creep strain equation. Sample calculations with a material response subroutine implementing the solution method for the transient creep law are described.

Morgan, H.S. 1981. *MARC Calculations for the Second WIPP Structural Benchmark Problem*. SAND81-0925. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report describes calculations made with the MARC structural finite element code for the second Waste Isolation Pilot Plant (WIPP) structural bench mark problem. Specific aspects of problem implementation such as element choice, slip line modeling, creep law implementation, and thermal-mechanical coupling are discussed in detail. Also included are the computational results specified in the bench-mark problem formulation.

Morgan, H.S. 1982. *Analysis of Borehole Inclusion Stress Measurement Concepts Proposed for Use in the Waste Isolation Pilot Plant In Situ Testing Program*. SAND82-1192. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Various bore hole inclusion stressmeters are analyzed to determine how the creep behavior of salt affects their performance. The analysis is based on a series of calculations in which gauge responses are computed for representative laboratory and in situ stress fields. Results are presented for the strain gauged stressmeter (SGS) which is being considered for use in the in situ testing program at the Waste Isolation Pilot Plant (WIPP). In addition, results are

presented for three general inclusions: a "stiff" inclusion, a "matching" inclusion, and a "soft" inclusion. The adjectives "stiff," "matching," and "soft" describe the elastic modulus of the inclusion relative to the modulus of the host rock salt. These results are useful in determining the importance of inclusion stiffness to gauge performance. The results for the SGS indicate that the gauge's performance is noticeably distorted by creep. Nevertheless, the SGS still responds to even small in situ stress changes. Of the general inclusions, only the "matching" stressmeter performs without distortion due to creep. "Soft" inclusion response is severely distorted by creep, and the "stiff" inclusion performance is slightly distorted by localized stress relaxation in the salt around the bore hole.

Morgan, H.S., and R.D. Krieg. 1988. *A Comparison of Unified Creep-Plasticity and Conventional Creep Models for Rock Salt Based on Predictions of Creep Behavior Measured in Several In Situ and Bench-Scale Experiments.* SAND87-1867. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A unified creep plasticity (UCP) model, a conventional elastic secondary creep (ESC) model, and an elastic secondary creep model with greatly reduced elastic moduli (RESC model) are used to compute creep responses for five experimental configurations in which rock salt is subjected to several different complex loadings. The UCP model is exercised with three sets of model parameters. Two sets are for salt from the site of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico, and the third is for salt from Avery Island, LA. The WIPP reference secondary creep parameters are used in both the ESC and RESC models. The WIPP reference values for the elastic moduli are also used in the ESC model. These moduli are divided by 12.5 in the RESC model. The geometrical configurations include the South Drift at the WIPP Site, a hypothetical shaft in rock salt, a large hollow cylinder of rock salt subjected to external pressure while still in the floor of a drift at Avery Island, LA, a laboratory-scale hollow cylinder subjected to external pressure, and a model pillar of salt subjected to axial load. Measured creep responses are available for all of these experiments except the hypothetical shaft. In all cases, deformations computed with the UCP model are much larger than the ESC predictions and are in better agreement with the data. The RESC model also produces larger deformations than the ESC model, and for the South Drift, the RESC predictions agree well with measured closures.

Morgan, H.S., and R.D. Krieg. 1990. "Investigation of an Empirical Creep Law for Rock Salt that Uses Reduced Elastic Moduli," *Rock Mechanics: Contributions and Challenges, Proceedings of the 31st US Symposium Golden, CO June 18-20, 1990.* Eds. W.A. Hustrulid and G.A. Johnson. Brookfield, VT: A.A. Balkema, 965-972.

ABSTRACT: Rock salt was predicted initially to creep at rates about one-third to one-fourth of those measured rates in situ at the Waste Isolation Pilot Plant (WIPP). Dividing Young's modulus E by 12.5 produced an empirical "fix" to the models; the modeled effects subsequently produced surprisingly good fits to field measurements of creep in several different WIPP room configurations. A hypothetical shaft was modeled to investigate the calculated results while varying the radius over which this empirical "fix" was applied. A near-field damage hypothesis, developed on the basis of observed underground features, is not matched by restricting the empirical "fix" to the area near the shaft surface. A far-field straining hypothesis does not seem valid, as almost all surrounding salt must be assigned the revised modulus before approaching the effects calculated with $E/12.5$. The empirical model with $E/12.5$ closely models a laboratory stress relaxation test of rock salt. A unified creep plasticity model, revised to fit both laboratory stress relaxation and creep, produces better closures and closure rates for the shaft problem than the unmodified reference model. The in situ behavior of salt may be better modeled if unloading or relaxation tests are used in addition to constant stress creep tests. Further tests are required as only one relaxation test has been used. Other

creep models should also be checked to determine if unloading tests improve their predictive capability. DWP

Morgan, H.S., and C.M. Stone. 1985a. *Pretest Reference Calculation for the Overtest for Simulated Defense High Level Waste (WIPP Room B In Situ Experiment)*. SAND85-0213. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A pretest reference calculation for the Overtest for Simulated Defense High-Level Waste (DHLW) or Room B experiment is presented in this report. The overttest is one of several large-scale in situ experiments currently under construction near Carlsbad, NM at the site of the Waste Isolation Pilot Plant (WIPP). Room B, a single, isolated room in the underground salt formation, is to be subjected to a thermal load of approximately four times the areal heat output anticipated for a future repository with DHLW. The load will be supplied for a period of three years by canister heaters placed in the floor. Room B is heavily instrumented for monitoring both temperature increases due to the thermal loading and deformations due to creep of the salt. Data from the experiment are not available at the present time, but the measurements will eventually be compared to the results presented here to assess and improve thermal and mechanical modeling capabilities for the WIPP. The thermal/structural model used here represents the state of the art at the present time. A large number of plots are included since an appropriate result is presented for every Room B gauge location.

Morgan, H.S., and C.M. Stone. 1985b. *Pretest Reference Calculation for the 18-W/m² Mockup for Defense High-Level Waste (WIPP Room A In Situ Experiment)*. SAND85-0807. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A pretest reference calculation for the 18-W/m² Mockup for Defense High-Level Waste (DHLW) or Room A experiment is presented in this report. The mockup is one of several large-scale in situ experiments currently under construction near Carlsbad, NM, at the site of the Waste Isolation Pilot Plant (WIPP). The 18-W/m² test is an in situ experiment developed to simulate the Reference Repository Conditions (RRC) for DHLW in salt. The test consists of three long, parallel rooms (A1, A2, A3) which are heated by canister heaters placed in the floor of each room. These heaters produce thermal loading which simulates an areal heat output of 18-W/m² for Room A2, which is the focus of the experiment. This load will be supplied for a period of three years. Rooms A1, A2, and A3 are heavily instrumented for monitoring both temperature increases due to the thermal loading and deformations due to creep of the salt. Data from the experiment are not available at present time, but the measurements for Room A2 will eventually be compared to the results for Room A2 presented here to assess and improve thermal and mechanical modeling capabilities for the WIPP. The thermal/structural model used here represents the state of the art at the present time. A large number of plots are included since an appropriate result is presented for every Room A2 gauge location.

Morgan, H.S., and C.M. Stone. 1985c. *Pretest Reference Calculation for the 6.1 Meter (20 ft) Wide Drifts of the Geomechanical Evaluation (WIPP Room G In Situ Experiment)*. SAND85-0893. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A pretest reference calculation for the Geomechanical Evaluation or Room G experiment is presented in this report. The Geomechanical Evaluation is one of several large-scale in situ tests currently under construction near Carlsbad, NM, at the site of the Waste Isolation Pilot Plant (WIPP). The Room G experiment consists of isolated, two-dimensional

drifts with different room spans, an isolated drift intersection, and a wedge pillar. The primary purpose of the experiment is to provide data for validating computational modeling capabilities used in analyzing nuclear waste repositories in salt. The calculation presented here addresses only one portion of the test, namely isolated drift configurations which are initially 6.1-m (20 ft) wide by 3.05-m (10 ft) high. The Geomechanical Evaluation is heavily instrumented for monitoring deformations due to creep of the salt. Data from the experiment are not available at the present time but the measurements for Room G will eventually be compared to the results presented in this report to assess and improve structural modeling capabilities for the WIPP. The model used for this calculation represents the state of the art at the present time. A large number of plots are included since an appropriate result is presented for every gauge location associated with the 6.1-m wide drifts.

Morgan, H.S., and C.M. Stone. 1985d. *Pretest Reference Calculation for the Heated Axisymmetric Pillar (WIPP Room H In Situ Experiment)*. SAND85-1146. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A pretest reference calculation for the Heated Axisymmetric Pillar or Room H experiment is presented in this report. The Heated Axisymmetric Pillar is one of several large-scale in situ experiments currently under construction near Carlsbad, NM at the site of the Waste Isolation Pilot Plant (WIPP). This test is an intermediate step in validating numerical techniques for design and performance calculations for radioactive waste repositories in salt. The test consists of a cylindrically shaped pillar, centrally located in an annular drift, which is uniformly heated by blanket heaters. These heaters produce a thermal output of 135 W/m². This load will be supplied for a period of three years. Room H is heavily instrumented for monitoring both temperature increases due to thermal loading and deformations due to creep of the salt. Data from the experiment are not available at the present time, but the measurements for Room H will eventually be compared to the calculations presented in this report to assess and improve thermal and mechanical modeling capabilities for the WIPP. The thermal/structural model used in the calculation represents the state of the art at the present time. A large number of plots are included since an appropriate result is required for every Room H gauge location.

Morgan, H.S., and W.R. Wawersik. 1989. "Computed and Measured Responses of a Thick-Walled Hollow Cylinder of Salt Subjected to Both Homogeneous and Inhomogeneous Loading," *Rock Mechanics as a Guide for Efficient Utilization of Natural Resources. Proceedings of the 30th US Symposium, West Virginia University, Morgantown, WT, June 19-22, 1989*. Ed. A.W. Khair. SAND88-2744C. Brookfield, VT: A.A. Balkema. 361-368.

ABSTRACT: Measured closures and closure rates around excavations in bedded salt at the Waste Isolation Pilot Plant (WIPP) were at least three times larger than initial predictions made with a reference creep model for rock salt. Potential sources of error include the constitutive behavior of salt in situ. Thick-walled, hollow cylinders of salt were tested in two controlled laboratory experiments as an expedient and cost effective means of narrowing the existing uncertainties. Various combinations of axial load, internal pressure, external pressure, and temperature were tested. Three different constitutive models for rock salt have been compared to the experimental data: an elastic power-law secondary creep (ESC) model, a revision of the ESC (RESC) model with greatly reduced elastic moduli (RESC') but unchanged creep parameters, and a unified creep plasticity (UCP) model.

The tests show that displacement measurement can be obtained with thick-walled cylinders that are representative of inhomogeneous, truly three-dimensional, and time-dependent stress states. Simultaneous, independent measurements of axial and diametral displacements enhance the comparison of data and predictions. Triaxial-like and three-dimensional loading minimizes

uncertainties in material properties between samples. Experience shows that pretest modeling can avoid some transients during changes between experimental stages.

Predictions for the cylinder tests agreed reasonably well with data, in contrast with the discrepancy for the WIPP excavation. It appears that rate-dependent properties of rock salt core were altered before laboratory testing and are not the same as in situ rock salt. Redistribution of deviatoric stresses with time affects in situ salt much more than in the test cylinders. The von Mises flow criterion, used in these laboratory tests, seems adequate for generalizing one-dimensional creep data for rock salt to a three-dimensional formulation. Predictions with a Tresca criterion would provide additional clarity to this issue. There was no evidence of a mean stress effect on deviatoric creep, though the effect could conceivably have been masked during the tests.

Model rates were within a factor of two of the data where samples were either unhardened or only slightly hardened. For the ESC model, this is better than the prediction for underground tests. The RESC model is similar for the cylinders, though RESC closure rates were in near perfect agreement with the WIPP excavation data. The UCP model overpredicts closure for the cylinders and is inconsistent with WIPP excavations. The discrepancies between models and data for the cylinder tests differ significantly from the discrepancies between models and WIPP excavations. DWP

Morgan, H.S., R.D. Krieg, and R.V. Matalucci. 1981. *Comparative Analysis of Nine Structural Codes Used in the Second WIPP Benchmark Problem.* SAND81-1389. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In the Waste Isolation Pilot Plant (WIPP) Benchmark II study, various computer codes were compared on the basis of their capabilities for calculating the response of hypothetical drift configurations for nuclear waste experiments and storage demonstration. The codes used by participants in the study were ANSALT, DAPROK, JAC, REM, SANCHO, SPECTROM, STEALTH, and two different implementations of MARC. Errors were found in the preliminary results, and several calculations were revised. Revised solutions were in reasonable agreement except for the REM solution. The Benchmark II study allowed significant advances in understanding the relative behavior of computer codes available for WIPP calculations. The study also pointed out the possible need for performing critical design calculations with more than one code. Lastly, it indicated the magnitude of the code-to-code spread in results which is to be expected even when a model has been explicitly defined.

Morgan, H.S., C.M. Stone, and R.D. Krieg. 1985. "The Use of Field Data to Evaluate and Improve Drift Response Models for the Waste Isolation Pilot Plant (WIPP)," *Research & Engineering Applications in Rock Masses, Proceedings of the 26th US Symposium on Rock Mechanics, Rapid City, SD, June 26-28, 1985.* Ed. E. Ashworth. SAND84-2126C. Boston, MA: A.A. Balkema. Vol. 2, 769-776.

ABSTRACT: Computed and measured room closures for an early Waste Isolation Pilot Plant (WIPP) excavation, known as the South Drift, have been compared to evaluate and improve computational models for predicting room deformation caused by salt creep. The finite element code SANCHO was used to compute the South Drift response.

Closure was measured at more than 10 different stations along the drift, beginning from the time of excavation to as much as 26 days after excavation and continuing for more than one year. The measurements demonstrate that immediate closures are very significant. If these are not taken into account, it might be concluded that strain varied considerably along the drift

and that a two-dimensional plane strain model was inappropriate. Closure data are quite uniform when adjusted for closure before an initial measurement.

One year after excavation, horizontal closure was measured at slightly less than 0.09 m, while the calculated closure is less than 0.03 m. The data and computed closures plotted on logarithmic scales of closure and time produce linear plots with differing slopes. These plots are the basis for evaluating which parameters in the mathematical model are most appropriately changed.

Closures were calculated by changing the clay seam friction coefficient from 0.4 to 0.0, reducing the strength of anhydrite layers, and by using a borehole configuration. These changes produce higher closures but the slopes are all the same. Closures were also calculated by reducing the shear modulus, reducing shear modulus and adding primary creep, increasing the constant D in the secondary creep law, and by using a two-mechanism secondary creep law. Changes in these salt parameters changed both the slope and the magnitude of the computed curves and are closer to the data. The most important observation is that changing the secondary creep constant does not improve agreement between data and the model. As none of the combinations produce good agreement with the data, there may be some important phenomenon or phenomena, yet to be identified, which is missing from the model.

DWP

Morgan, H.S., C.M. Stone, and R.D. Krieg. 1986. *An Evaluation of WIPP Structural Modeling Capabilities Based on Comparisons with South Drift Data.* SAND85-0323. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The creep response of rock salt around a long, uniform excavation of rectangular cross section has been computed with the structural finite element code SANCHO, and the results are compared with field data. The excavation, known as the South Drift, is part of the Waste Isolation Pilot Plant Facility. The geomechanical model used in the calculations is quite complex and includes constitutive models based on standard laboratory creep tests. Because closure and closure rate measurements are at least three times larger than computed values, a thorough investigation of the many parameters in the geomechanical model is presented. This investigation indicates that variations to parameters not related to the constitutive model for halite cannot produce the type of changes in the closure histories needed to produce good agreement with data. Thus, the reason for the discrepancy is attributed to the parameters in the constitutive model for halite. However, none of the halite parameters investigated could produce the measured behavior. Several areas for future study have been identified.

Morgan, H.S., C.M. Stone, and R.D. Krieg. 1987. "A Comparison of Computed and Measured Responses for a Long Isolated Excavation of the Waste Isolation Pilot Plant (WIPP) Facility," *Computers and Geotechnics*. SAND86-2358J. Vol. 3, no. 2-3, 69-104.

ABSTRACT: The creep response of rock salt around a long uniform excavation of rectangular cross section has been computed with the structural finite element code SANCHO and the results are compared with field data. The excavation, known as the South Drift, is part of the Waste Isolation Pilot Plant Facility. The geomechanical model used in the calculations is quite complex and includes constitutive models based on standard laboratory creep tests. Because closure and closure rate measurements are at least three times larger than computed values, a thorough investigation of the many parameters in the geomechanical model is presented. This investigation indicates that variations to parameters not related to the constitutive model for halite cannot produce the type of changes in the closure histories needed to produce good agreement with data. Thus, the reason for the discrepancy is attributed to the parameters in

the constitutive model for halite. However, none of the halite parameters investigated could produce the measured behavior. Several areas for future study have been identified.

Morgan, H.S., M. Wallner, and D.E. Munson. 1987. *Results of an International Parallel Calculations Exercise Comparing Creep Responses Predicted with Three Computer Codes for Two Excavations in Rock Salt.* SAND87-2125. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Creep responses computed with the ANSALT finite element code, which was developed by the Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources) in the Federal Republic of Germany (FRG), are compared to responses computed in the US with the SANCHO and SPECTROM codes for two well-defined boundary value problems. One boundary value problem is an idealization of an underground room configuration proposed as a repository for low-level nuclear waste. The other is an idealization of a room configuration designed for testing the effect of heat on the structural response of rock salt. Both room configurations represent actual excavations in bedded salt at the Waste Isolation Pilot Plant Facility near Carlsbad, NM. The SANCHO and SPECTROM solutions to the boundary value problems have already been compared and analyzed extensively in an earlier parallel calculations exercise. The study presented here is an extension of the earlier exercise and was performed as part of a bilateral agreement between the US and the FRG to exchange technology related to the development of nuclear waste repositories in rock salt. Parameters on which the comparisons are based include both displacements and stresses. A rigorous set of procedures designed to eliminate input errors was followed. The comparisons indicate only minor differences between the ANSALT, SANCHO, and SPECTROM solutions. In most cases reasons for these differences are clearly identified.

Morgan, H.S., C.M. Stone, R.D. Krieg, and D.E. Munson. 1986. "Thermal Structural Modeling of a Large Scale In Situ Overtest Experiment for [Defense] High Level Waste at the Waste Isolation Pilot Plant Facility," *Second International Symposium on Numerical Methods in Geomechanics, Ghent, Belgium, March 31, 1986.* SAND85-1926C. Cornwall, England: M. Jackson & Son Ltd. 585-594.

ABSTRACT: Several large-scale in situ experiments in bedded salt formations are currently underway at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. In these experiments, the thermal and creep responses of salt around several different underground room configurations are being measured. Data from the tests are to be compared to thermal and structural responses predicted in pretest reference calculations. The purpose of these comparisons is to evaluate computational models developed from laboratory data prior to fielding of the in situ experiments. In this paper, the computational models used in the pretest reference calculation for one of the large-scale tests, The Overtest for Defense High-Level Waste, are described, and the pretest computed thermal and structural responses are compared to earlier data from the experiment. The comparisons indicate that computed and measured temperatures for the test agree to within 10%, but that measured deformation rates are between two and three times greater than corresponding computed rates.

Moss, M. 1980a. *Stored Energy of Gamma-Irradiated WIPP Salt.* SAND80-0416. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Samples of Waste Isolation Pilot Plant (WIPP) salt exposed at 363 K to gamma radiation from a Co⁶⁰ source were annealed at constant rates of heating in a differential scanning calorimeter in order to release the stored energy. Radiation doses were 2.2, 5.4, 8.2,

11, and 13×10^9 rad, and temperature scans were conducted from room temperatures to 800 K. The specific stored energy-dose relationship deduced from 80 K/min scans could be only approximately established due to the extreme variability of the specific energy in samples of a given dose. This variability probably results from unequal amounts of impurities in the 10-25 mg samples required for the calorimeter. The energy-dose relationship is best described empirically by $\ln Q_0 \text{ (cal/g)} = (-40.6 \pm 2.6) + (1.84 \pm 0.12) \ln D \text{ (rad)}$. Temperature scans of 10, 20, 40, and 80 K/min were performed to determine the activation energy E of the annealing process. For the four more highly dosed samples, $E = 31.1 \pm 5.6$ kcal/mole. Based upon criteria established elsewhere, there appears to be no danger of the stored energy being released quickly in a nuclear waste repository of bedded salt, nor could serious consequences result from such a release by some unforeseen mechanism.

Moss, M. 1980b. "Stored Energy of Gamma-Irradiated 97% Pure Rocksalt," *American Society for Mechanical Engineers Symposium on Thermophysical Properties of Composite Materials, Chicago, IL, November 16-21, 1980*. SAND80-1616C. Albuquerque, NM: Sandia National Laboratories. New York, NY: American Society of Mechanical Engineers.

ABSTRACT: Samples of 97% pure NaCl from the Waste Isolation Pilot Plant (WIPP) Site near Carlsbad, NM, were exposed at 363 K to gamma radiation from Co^{60} source and annealed at constant rates of heating in a differential scanning calorimeter in order to release the stored energy. Radiation doses were 2.2, 5.4, 8.2, 11, and 13×10^9 rad, and temperature scans were conducted from room temperature to 800 K. The stored energy-dose relationship is best described empirically by $\ln Q_0 \text{ (kJ/kg)} = (-39.2 \pm 2.6) + (1.84 \pm 0.12) \ln D \text{ (rad)}$. Temperature scans of 0.17, 0.33, 0.67, and 1.33 K/sec were performed to determine the activation energy E of the annealing process. For the four most highly irradiated samples, $E = 113 \pm 31$ kJ/mole. The values of stored energy and activation energy for the annealing process are similar to those reported by previous investigators. These data, then, support the conclusion that there appears to be no danger of a rapid release of the stored energy in a nuclear waste repository of bedded salt, nor could serious consequences result from such a release by some unforeseen mechanism.

Moss, M., and G.M. Haseman. 1981. *Thermal Conductivity of Polyhalite and Anhydrite from the Site of the Proposed Waste Isolation Pilot Plant*. SAND81-0856. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The study of the thermal conductivity of rock salt and other geologic materials has been extended to include polyhalite and anhydrite from the WIPP-28 and AEC-7 wells, respectively, located at the site of the proposed Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. A Dynatech Model TCFCM linear heat-flow comparator was used for the measurements in the temperature range 300-528 K for the polyhalite and 300-725 K for the anhydrite. The fine-grained polyhalite crumbled above 528 K. The anhydrite changed to a lighter color upon heating, and exhibited a lower conductivity when measured again. The data were fitted to an expression for thermal conductivity, $\lambda = \lambda_{300}(300/T)^\tau$, in which λ_{300} is the conductivity at 300 K and T is the temperature in K. For polyhalite $\lambda_{300} = 1.3 \text{ W/m}\cdot\text{K}$, and $\tau = 0.35$ in the range 300-528 K. For fresh anhydrite $\lambda_{300} = 4.5 \text{ W/m}\cdot\text{K}$ and $\tau = 1.15$ in the range 300-630 K. A rerun on the same anhydrite sample yielded $\lambda_{300} = 3.5 \text{ W/m}\cdot\text{K}$ and $\tau = 1.00$ in the range 300-725 K. Another anhydrite sample, heated for 24h at 723 K, had an even lower conductivity; 2.5 and 2.1 W/m·K at 328 and 348 K, respectively. Based on results from several sources including this study, the recommended thermal conductivity parameters for thermal modeling are: polyhalite, $\tau = 0.35$, $\lambda_{300} = 1.4 \pm 0.2 \text{ W/m}\cdot\text{K}$; and anhydrite, $\tau = 1.15$, $\lambda_{300} = 4.7 \pm 0.2 \text{ W/m}\cdot\text{K}$.

Moss, M., and M.A. Molecke. 1983. "Thermal Conductivity of Bentonite/Quartz High-Level Waste Package Backfill," *Scientific Basis for Nuclear Waste Management VI, Boston, MA, November 1-4, 1982*. Ed. D.G. Brookins. SAND82-1274C. New York, NY: North-Holland. Vol. 15, 719-726.

ABSTRACT: A mixture of bentonite clay and quartz sand is being considered for use as a waste-package backfill, the material placed between a radioactive-waste canister and the repository host rock. Compacts of bentonite/quartz with weight-percent 100/0, 70/30, 50/50, and 30/70 were made at room temperature under a pressure of 100 MPa (15 psi). Upon initial heating, the thermal conductivity of the 70/30 compact rose from 1.20 W/m·K at 298 K to 1.32 W/m·K at 373 K. After further heating to 473 K, it fell to 1.10 W/m·K, reflecting the loss of interlamellar water from the bentonite. The conductivity of the now-dehydrated compact was reproducible through several heating and cooling cycles, varying from 1.15 W/m·K at 573 K to 1.03 W/m·K at 298 K. The other mixtures were qualitatively similar to the 70/30: the 100/0, 50/50, and 30/70 dehydrated compacts displayed conductivities of 0.59, 1.06, and 0.83 W/m·K, respectively, at 298 K. Measured densities ranged from 1.98 to 2.12 g/cc. Combined geometric-mean and Maxwell models for thermal conduction in composite systems predict the measured results reasonably well. An analysis of the impact of backfills on high-level waste (HLW) package design indicates that no significant thermal penalty is imposed.

Munson, D.E. 1979. *Preliminary Deformation-Mechanism Map for Salt (with Application to WIPP)*. SAND79-0076. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Through the use of theoretical and experimental results, a complete but preliminary deformation-mechanism map for salt is constructed. This map shows those mechanisms and, consequently, the constitutive equations which control the deformation of salt for all imposed conditions of stress and temperature. Five mechanisms are identified as relevant. There are defect-less flow, dislocation glide, dislocation climb creep (two variations), diffusional creep (two variations), and an undefined mechanism. When the envelopes bounding relevant experimental investigations are overlayed on the map, it is possible to determine the interplay between data. This perspective permits a more rational interpretation of high-temperature creep data. The most powerful use of the map stems from an overlay of possible stress and temperature conditions of the Waste Isolation Pilot Plant (WIPP), a proposed radioactive waste isolation project in bedded salt. It is also possible to draw from the map some general conclusions about data adequacy and constitutive equation forms that would pertain to the project from the map. Moreover, a first-cut constitutive equation for deformation of salt for the project conditions is formulated based on empirical knowledge and the two important mechanisms. The proposed equation incorporates the effects of the transient creep response and of the transition activation energy.

Munson, D.E. [1988]. "Summary of WIPP Thermal/Structural Interactions In Situ Tests," *ASME-SES Joint Mechanics Conference, Berkeley, CA, June 20-22, 1988*. SAND88-0172A. Albuquerque, NM: Sandia National Laboratories. (Abstract Only; Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A series of five large-scale in situ tests were fielded at the Waste Isolation Pilot Plant to determine the thermal/structural response of bedded salt. The tests include two in situ simulations of repository configurations. One of these tests, which simulates a high-level waste repository heated at an areal loading of 18 W/m², consists of a three room complex of 5.5 m by 5.5 m cross section rooms 91.5 m long (Rooms A1, A2, and A3). The other of these tests, which is an overtest of the high-level repository, consists of a single room (Room B) of

the same cross section and length, but is heated to about four times the thermal load of the three room complex. Two other tests are designed to be two-dimensional and address verification of in situ material behavior. One of these tests is a heated 11.0-m-diameter by 3.05-m-high axisymmetric pillar surrounded by a 11.0-m-wide room (Room H). The other of these tests is a very long isolated 6.1-m-wide by 3.05-m-high drift (Room G). The final of the five tests addresses the problem of determining, through hydrofrac tests, the virgin stress field induced by the overburden. These tests have produced data for over three years from more than 3000 remote and 700 manual instrument installations. To date, more than 6 million data readings have been obtained. The comprehensive data base generated by these tests is now in the simultaneous processes of data reduction and analysis.

Typical results from these in situ tests illustrate several important aspects of the response of bedded salt. The stress measurements suggest that the overburden stress is lithostatic; however, the influence of the underground workings on the stress field is more pervasive than originally thought. This suggests, as a corollary, that the strain fields extend further away from the drifts and rooms than pretest calculations predicted. A series of typical room closure, salt displacement, and temperature history results illustrate the exceptional quality of the in situ data. Examples of data from several test rooms are presented, with some data comparison to show the uniformity of the salt behavior and trends of the data. Comparison of the measured and predicted deformations and closures show several significant trends. First, predictions based on laboratory parameters and constitutive models underestimate the in situ closures by factors of three. Reasons for this discrepancy are summarized to indicate the possible source. Second, for more detailed analyses, known differences between horizontal and vertical closures require inclusion of bedding effects. Various methods have been explored to incorporate such bedding anisotropy. The influence of the multipass mining effects on the short- and long-term room response was measured in detail using mining-sequence closure gauges; and the subsequent analysis, including three-dimensional calculations, shows the displacement and time extent of the mining effects to be minimal. Comparison of the calculated and measured temperatures suggest imbalances caused by heat loss from the in situ test rooms. The analysis effort is now in the process of exploring the discrepancies between the ability to calculate the measured in situ response and the actual in situ measurements. Some of the attempts to understand the discrepancy have proven helpful, but the full solution is not yet available. The nature of these attempts is explained, together with the future research efforts.

In summary, the current results and implications will be evaluated. Of specific interest are the future research directions to validate the calculational methods using the in situ results. This involves finding answers to a range of current questions on material behavior and numerical methods.

Munson, D.E., and P.R. Dawson. 1979. *Constitutive Model for the Low Temperature Creep of Salt (with Application to WIPP)*. SAND79-1853. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: While numerous constitutive models have been proposed for the low-temperature creep of salt, this work is the first to develop such a model within the framework of rate-controlling mechanisms and the deformation-mechanism map. Use of this framework permitted unfolding of the rather complicated low-temperature, steady-state creep behavior into three simpler responses involving separate regimes with individual controlling mechanisms. The observed total creep rate obeys the rules of additive processes. The creep model incorporates primary (transient) creep as a simple two parameter modification to the steady-state creep equations. Application of the model is through a formulation into proper stress and strain measures for use in a large strain finite element code. Extensive analysis of available low-temperature triaxial creep data produced the appropriate material parameters, including activation energies and stress dependencies for the separate regimes. Material variations were observed to produce changes in absolute creep rate, without change in controlling mechanism.

Numerous calculations demonstrate the adequacy of the model and numerical method to simulate the results of triaxial creep experiments on southeastern New Mexico salt from the horizons proposed for the Waste Isolation Pilot Plant.

Munson, D.E., and P.R. Dawson. 1980. *Numerical Simulation of Creep Closure of Deep Potash Mines (with Application to Waste Isolation)*. SAND80-0467. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In this work, numerical simulation of the mechanical response of a deep mine opening in potash is shown to match measured room closures to within a factor of two. In this case, the calculated closure rates after 8 years are within 25 to 75% of those measured. In making the calculations, a constitutive model for creep, as determined from laboratory triaxial tests of salt and short cylinder compressive tests of potash, was incorporated into a coupled thermal mechanical fluid flow code COUPLEFLO. The model is a multimechanism formulation of thermally activated processes acting in parallel. Because the field tests were well-documented, two-dimensional configurations and because the constitutive model was uniquely determined by laboratory data, the agreement between calculations and field data for these significant time durations is a first step in verification of the simulation technique.

Application of the model and numerical methods presented here can be used to understand deformation in deep potash mines and to aid in design of the waste isolation and petroleum storage facilities.

Munson, D.E., and P.R. Dawson. 1982a. "A Work Hardening/Recovery Model of Transient Creep of Salt During Stress Loading and Unloading," *Issues in Rock Mechanics, Proceedings of the 23rd US Symposium on Rock Mechanics, Berkeley, CA, August 25-27, 1982*. Eds. R.E. Goodman and F.E. Heuze. SAND82-0801J. New York, NY: American Institute of Mining, Metallurgical and Petroleum Engineers, Vol 23, 299-306.

ABSTRACT: An empirical model is developed that accurately predicts the transient response of salt creep to incremental and decremental changes in stress and temperature. Even though the model is empirical, it is derived from a firm, theoretical framework for the micromechanical deformation processes of both steady-state and transient creep. In the model, the transient creep functions modify the steady-state creep behavior, which, in turn, is based upon creep mechanisms and the deformation-mechanism map. The model is applied successfully to experimental stress-drop results obtained for salt.

Munson, D.E., and P.R. Dawson. 1982b. *A Transient Creep Model for Salt During Stress Loading and Unloading*. SAND82-0962. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: An empirical model is developed which accurately predicts the transient response of salt creep to incremental and decremental changes in stress and temperature. Even though the model is empirical, it is derived from a firm theoretical framework based upon the deformation-mechanism map for the micromechanical deformation processes and treats both steady-state and transient creep. In the model, transient functions modify the steady-state creep behavior. The description considers hypothetical potential functions in order to obtain strain rate versus strain functions for the workhardening and recovery that occurs during transient creep.

Conventional creep tests or stress-drop tests are analyzed using new methods for the complete evaluation of all parameters of the model. Then, the model is applied to stress-drop

experimental results for complete recovery. Parameters for the model are also developed for southeastern New Mexico salt and are used to describe experimental results from tests that have complex loading and unloading histories. The model predictions compare well with the experimental results.

Munson, D.E., and P.R. Dawson. 1984. "Salt Constitutive Modeling Using Mechanism Maps," *The Mechanical Behavior of Salt: Proceedings of the First Conference, Pennsylvania State University, University Park, PA, November 9-11, 1981*. Eds. H.R. Hardy, Jr. and M. Langer. SAND81-2196C. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 717-737.

ABSTRACT: Numerous constitutive models have been proposed for the low temperature creep of salt. This work was the first to develop such a model within the framework of a deformation-mechanism map. Use of this framework permits unfolding of the rather complicated low temperature steady-state creep behavior into three simple responses involving separate regimes with individual controlling mechanisms. The constitutive model developed in this report incorporates primary (transient) creep as a two parameter modification to the steady-state creep equations. The constitutive model presented can be applied to deep mines and, more importantly, to design of the petroleum storage and radioactive waste isolation facilities.

Munson, D.E., and K.L. DeVries. 1990. "Progress in Validation of Structural Codes for Radioactive Waste Repository Applications in Bedded Salt," *GEOVAL 90, Stockholm, Sweden, May 14-17, 1990*. SAND89-2176C. Paris, France: Organisation for Economic Co-Operation and Development. 522-529.

ABSTRACT: Over the last nine years, coordinated activities in laboratory data base generation, constitutive model formulation, and numerical code capability development have led to an improved ability of thermal/structural codes to predict the creep deformation of underground rooms in bedded salt deposits. In the last year, these codes have been undergoing preliminary validation against an extensive data base collected from the large-scale underground structural in situ tests at the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. This validation exercise has allowed the prediction capabilities to be evaluated for accuracy. A summary of the predictive capability and the nature of the in situ data base involved in the validation exercise is presented here. The WIPP validation exercise has proven to be especially productive.

Munson, D.E., and A.F. Fossum. 1986. "Comparison Between Predicted and Measured South Drift Closures at the WIPP Using a Transient Creep Model for Salt," *Rock Mechanics: Key to Energy Production, Proceedings of the 27th US Symposium on Rock Mechanics, University of Alabama, Tuscaloosa, AL, June 23-25, 1986*. Ed. H.L. Hartman. SAND85-2238C. Littleton, CO: Society of Mining Engineers, Inc. 931-939.

ABSTRACT: The US Department of Energy is constructing and operating the Waste Isolation Pilot Plant (WIPP), a research and development facility near Carlsbad, NM, to determine whether or not defense-generated, high-level radioactive waste can be stored safely in bedded salt. The goal of the WIPP modeling program is to develop the capability to predict room responses from one site to another without a priori knowledge of the actual room responses. Data from one of the early WIPP excavations, called the South Drift, have already been used to form an initial evaluation of computational models for predicting room closures as a result of salt creep (Morgan et al., 1985). A significant unresolved discrepancy existed between

predicted and measured room closures. It was suggested that future studies address alternate forms of the constitutive law. In this paper, an alternate form of the creep model for salt is used that is founded upon the deformation-mechanism map for the micromechanical deformation processes. This model embodies both steady-state and transient creep. Also, quasi-static plasticity is incorporated into the complete constitutive model for salt. The conclusion is drawn that the combination of the mechanistic creep model, plasticity, and flow potential can approximate the late time South Drift deformation. Further improvement of the model fit of plasticity in the future is expected to further improve the simulation.

ANNOTATION: The reference by Morgan et al., (1985) is included in the bibliography.

Munson, D.E., and R.V. Matalucci. 1984. "Planning, Developing, and Fielding of Thermal/Structural Interactions In Situ Tests for the Waste Isolation Pilot Plant (WIPP)," *Waste Management 84, Waste Isolation in the US, Technical Programs and Public Education, March 11-15, 1984*. Ed. R.G. Post. SAND83-2048C. Tucson, AZ: University of Arizona. Vol. 1, 317-333.

ABSTRACT: Large-scale, well-instrumented underground tests to determine in situ thermal/structural response of bedded salt are being constructed in the Waste Isolation Pilot Plant (WIPP) Facility in southeastern New Mexico. These tests are an essential component of a broad research and development program to resolve thermal/structural issues, to validate long-term prediction methods, and to develop a design basis for a future repository. They are the result of an extensive planning and evaluation procedure to determine the appropriate test configuration. All details of the tests, including background, decisions, design, site operations, and testing organization are explained. These procedures may be useful in development of other in situ tests.

Munson, D.E., J.R. Ball, and R.L. Jones. 1990. "Data Quality Assurance Controls Through the WIPP In Situ Data Acquisition, Analysis, and Management System," *High Level Radioactive Waste Management, Las Vegas, NV, April 8-12, 1990*. SAND88-2845C. La Grange Park, IL: American Nuclear Society. Vol. 2, 1337-1350.

ABSTRACT: Assurance of data quality for the in situ tests fielded at the Waste Isolation Pilot Plant (WIPP) is of critical importance. These tests supply the information for development and verification of the technology required for construction of a radioactive waste repository in bedded salt. The tests are some of the largest ever fielded in an underground facility. To assure that the extensive output generated by the tests is compatible with the high standards of quality required, a major project task was undertaken for the acquisition, control, and preservation of all the associated in situ test data bases, with the principal emphasis on the very large thermal/structural in situ tests. In order to accomplish this task, the WIPP In Situ Data Acquisition, Analysis, and Management (WISDAAM) System was put into place. The system provides for quality control of the test data bases and certified test data throughout the duration of the tests.

Munson, D.E., K.L. DeVries, and G.D. Callahan. 1990. "Comparison of Calculations and In Situ Results for a Large, Heated Test Room at the Waste Isolation Pilot Plant (WIPP)," *Rock Mechanics: Contributions and Challenges, Proceedings of the 31st US Symposium, Golden, CO, June 18-20, 1990*. Eds. W.A. Hustrulid and G.A. Johnson. SAND89-2268C. Brookfield, VT: A.A. Balkema. 389-396.

ABSTRACT: The closure measurements from a large scale, heated, in situ experimental room in salt are compared to numerical calculations using the most recent predictive technology, with very good agreement, and limited only by the unmodeled roof fracture and separation.

Munson, D.E., A.F. Fossum, and P.E. Senseny. 1989a. *Advances in Resolution of Discrepancies Between Predicted and Measured In Situ WIPP Room Closures.* SAND88-2948. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: An extensive reevaluation has been made of several major aspects of the simulation of the structural response of salt to improve the ability to represent actual deformations. As a result of the effort, it is now evident that the Tresca flow potential represents the behavior of salt. The previously used von Mises flow potential does not appear to be appropriate. The multimechanism steady-state, workhardening/recovery transient model now has been modified to be more representative of salt creep. Reevaluation of material parameters, based on new creep data and a better conceptual understanding of construction of the virgin state parameters, has resulted in significant improvement in the material parameters available for calculation. In addition, reevaluation of the coefficient of friction on clay seams was found necessary. Actual underground observations also suggested a revised stratigraphic sequence at the Waste Isolation Pilot Plant (WIPP) Facility horizon. The combination of the above improvements, when incorporated into a numerical simulation of the closure response of an underground test room (Room D), produced excellent agreement between calculated and measured closures. The agreement between the calculated and measured vertical closures is within 2% for the nearly 4.4 years represented by the experimental data. Agreement between the calculated and measured horizontal closures is not quite as good, with the calculation overpredicting the observed closure by 18%. However, based on these calculations, the approach presented here appears to have resolved much of the earlier discrepancy between calculated and measured closures.

Munson, D.E., A.F. Fossum, and P.E. Senseny. 1989b. "Approach to First Principles Model Prediction of Measured WIPP In Situ Room Closure in Salt," *Rock Mechanics as a Guide for Efficient Utilization of Natural Resources, Proceedings of the 30th US Symposium on Rock Mechanics, West Virginia University, Morgantown, WV, June 19-22, 1989.* Ed. A.W. Khair. SAND88-2535C. Boston, MA: A.A. Balkema. 673-680.

ABSTRACT: The discrepancies between predicted and measured Waste Isolation Pilot Plant (WIPP) in situ Room D closures are markedly reduced through the use of a Tresca flow potential, an improved small strain constitutive model, an improved set of material parameters, and a modified stratigraphy.

The calculated vertical and horizontal closures are within 2% and 18%, respectively, of the measured results. It seems clear that the earlier three-fold discrepancy has been markedly reduced through the incorporation of a Tresca flow criterion, transient creep response, and a modified stratigraphy.

An indication of the improvement in the calculational ability developed through the current studies is apparent by comparing these results to earlier calculational results using the original reference steady-state creep law, properties, and stratigraphy. The results using the same reference quantities, but with a 12.5 reduction in elastic moduli, form "backfitting" of in situ closure data to obtain an interim method which would better simulate the measured underground response.

It is possible to analyze the significance of each aspect of the major inputs to the improvement in the calculated creep closures. The factor that contributes most to closure is the inclusion of

transient response which, although not shown here, increases closure by about an additional 120% of that of steady-state response alone. The flow potential is also very important, where a Tresca criterion produces a 70% increase in closure over the von Mises criterion. If the stratigraphy were uniform and the coefficient of friction on clay seams were very large (i.e., no slip), the horizontal and vertical closures for a square cross section room would be identical. Thus, the separation between horizontal and vertical closures is a direct result of the bedded stratigraphy and slip at clay seams. Consequently, the relative contribution of the stratigraphy and the permitted variation in coefficient of friction produce small changes of up to about 20% in the displacement magnitudes of the calculated closures.

Munson, D.E., R.V. Matalucci, and T.M. Torres. 1988. "Implementation of Thermal/Structural Interactions In Situ Tests at the Waste Isolation Pilot Plant Facility," *The Mechanical Behavior of Salt: Proceedings of the Second Conference, Hannover, Germany, September 24-28, 1984*. Eds. H.R. Hardy, Jr. and M. Langer. SAND84-0804C. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 361-390.

ABSTRACT: Several large-scale, well-instrumented underground tests to determine the in situ thermal/structural response of bedded salt are currently being constructed at the Waste Isolation Pilot Plant (WIPP) Facility in southeastern New Mexico. These tests are an essential component of a broad research and development program to resolve thermal/structural issues, to validate long-term prediction methods, and to develop a design basis for a future repository. They are the result of an extensive planning and evaluation procedure to determine appropriate test configurations. The scale of these tests can be judged from the 3022 active remote-reading data channels, 1190 active remote-control channels, and 710 manual data inputs from more than 3700 individual gauges distributed among the six test rooms (four experiments). Implementing tests of this magnitude is a major effort in design, preparatory activities, fielding, and quality assurance controls. In this paper, the approach to fielding these tests included selecting hardware, developing appropriate technology, and eventually putting the tests into place.

Munson, D.E., T.M. Torres, and D.A. Blankenship. 1986. "Early Results from the Thermal/Structural In Situ Test Series at the WIPP," *Rock Mechanics: Key to Energy Production, Proceedings of the 27th US Symposium on Rock Mechanics, University of Alabama, Tuscaloosa, AL, June 23-25, 1986*. Ed. H.L. Hartman. SAND85-2237C. Littleton, CO: Society of Mining Engineers, Inc. 923-930.

ABSTRACT: The Thermal/Structural Interactions (TSI) in situ tests are a series of large-scale, well-instrumented tests that have been constructed at the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. As a precursor to the TSI tests, a ventilation drift (Room D) was mined, drilled, and instrumented. This room provided the contractor an excellent area to practice controlled construction methods and was a proving ground for construction, monitoring, and documentation methods. All gauges in this first room have been monitored since their initial installation, which has provided a small but representative data base. These data also were the first to be available from any TSI area for analysis. This paper discusses the construction activities in Room D and the data generated from the construction and drilling. Deformation of the room is compared briefly to numerical calculations that used a rather simple creep model as a reference. The constitutive model for salt, it appears, must be improved before it can predict the underground deformations.

Munson, D.E., T.M. Torres, and R.L. Jones. 1987. "Pseudostrain Representation of Multipass Excavations in Salt," *Rock Mechanics: Proceedings of the 28th US Symposium, University of*

Arizona, Tucson, AZ, June 29-July 1, 1987. Eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman. SAND86-2397C. Boston, MA: A.A. Balkema. 853-862.

ABSTRACT: Early-time mining sequence closure displacements show how effects of multipass excavations are accommodated in bedded salt.

Munson, D.E., T.M. Torres, and R.L. Jones. 1988. "Results of a Large, In Situ, Heated Axisymmetric Pillar Test at the Waste Isolation Pilot Plant (WIPP)," *Key Questions in Rock Mechanics: Proceedings of the 29th US Symposium, University of Minnesota, Minneapolis, MN, June 13-15, 1988.* Eds. P.A. Cundall, R.L. Sterling, and A.M. Starfield. SAND87-2257C. Brookfield, VT: A.A. Balkema. 641-651.

ABSTRACT: Extensive structural creep and thermal histories of a heated, axisymmetric, underground salt pillar are presented and analyzed through pseudostrains. In situ data are then compared to laboratory fracture and to two-dimensional, numerical, pretest reference calculations.

Munson, D.E., R.L. Jones, D.L. Hoag, and J.R. Ball. 1987. *Heated Axisymmetric Pillar Test (Room H): In Situ Data Report (February 1985 - April 1987), Waste Isolation Pilot Plant (WIPP), Thermal/Structural Interactions Program.* SAND87-2488. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Data are presented from the Heated Axisymmetric Pillar Test, a very large-scale, in situ test fielded underground at the Waste Isolation Pilot Plant. These data include selected fielding information, test configuration, instrumentation activities, and comprehensive results from a large number of gauges. The results give measured data from room closure gauges, extensometers, stressmeters, thermocouples, fluxmeters, and power gauges emplaced in the test. The test began in February 1985 and continues to the present. Data in this report cover the period from February 1985 to April 1987 and will be updated as necessary in future reports.

Munson, D.E., R.L. Jones, D.L. Hoag, and J.R. Ball. 1988. *Mining Development Test (Room D): In Situ Data Report (March 1984 - May 1988), Waste Isolation Pilot Plant (WIPP), Thermal/Structural Interactions Program.* SAND88-1460. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Data are presented from the Mining Development Test (Room D), an experiment of opportunity that was fielded underground at the Waste Isolation Pilot Plant. The room was initially intended to provide only ventilation during construction of the planned tests; however, because it had the same dimensions as other actual test rooms, it provided an opportunity to develop mining, instrumentation, and data acquisition methods at an early stage of the project. The data include selected fielding information, test configuration, instrumentation activities, and comprehensive results from a small number of extensometer and room closure gauges installed in the test room. The test began in March 1984 and continues to the present. Data in this report cover the period from March 1984 to May 1988 and will be updated as necessary in future reports.

Munson, D.E., R.L. Jones, J.R. Ball, R.M. Clancy, D.L. Hoag, and S.V. Petney. 1990. *Overtest for Simulated Defense High-Level Waste (Room B): In Situ Data Report (May 1984*

- February 1988), *Waste Isolation Pilot Plant (WIPP), Thermal/Structural Interactions Program*, SAND89-2671, Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Data are presented from the Overtest for Simulated Defense High-Level Waste (DHLW), a very large-scale, in situ test fielded underground at the Waste Isolation Pilot Plant. These data include selected fielding information, test configuration, instrumentation activities, and comprehensive results from a large number of gauges. The results give measured data from room closure gauges, extensometers, stressmeters, thermocouples, fluxmeters, and power gauges emplaced in the test. The test began with excavation of the room in May 1984 and continues to the present. Data in this report cover the period from May 1984 to February 1988 and will be updated as necessary in future reports.

Myers, J., W.E. Coons, R. Eastmond, J. Morse, S. Chakrabarti, J. Zurkoff, I.D. Colton, and I. Banz. 1986. "The Waste Isolation Pilot Plant Performance Assessment Program," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 2-6, 1986*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 203-209.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Performance Assessment Program involves a comprehensive analysis of the WIPP Project with respect to the recently finalized Environmental Protection Agency (EPA) regulations regarding the long-term geologic isolation of radioactive wastes. The performance assessment brings together the results of site characterization and underground experimental and environmental studies into a rigorous determination of the performance of the WIPP as a disposal system for transuranic (TRU) radioactive waste. The program consists of scenario development, geochemical, hydrologic, and thermomechanical support analyses and will address the specific containment and individual protection requirements specified in 40 CFR 191 Subpart B. Calculated releases from these interrelated analyses will be reported as an overall probability distribution of cumulative release resulting from all processes and events occurring over the 10,000 year post-closure period. In addition, results will include any doses to the public resulting from natural processes occurring over the 1,000 year post-closure period. The overall plan for the WIPP Performance Assessment Program is presented along with approaches to issues specific to the WIPP Project.

National Research Council. Board on Radioactive Waste Management. Panel on the Waste Isolation Pilot Plant. 1983. *Review of the Criteria for the Site Suitability, Design, Construction, and Operation of the Proposed Waste Isolation Pilot Plant (WIPP). Interim Report: July 1, 1978 to July 31, 1982.* DOE/NE/93023-3. Washington, DC: National Research Council, Board on Radioactive Waste Management.

ABSTRACT: The panel on the Waste Isolation Pilot Plant (WIPP) reviewed information (mainly available through July 1982) concerning five main areas: site selection and characterization; in situ tests and experiments; waste-acceptance criteria; design and operation of facilities; and performance assessment. The WIPP panel commented analytically on these aspects rather than summarizing activities.

Under site selection and characterization, the panel found that resources might be safely extracted from outer zones without harm, but any proposal should be examined individually as the integrity of the repository is the first consideration. The site is likely to remain tectonically quiescent during the period of interest and evaporite deformation is not a credible risk. Karst is not likely to disturb the repository site for more than a million years, and the threat of forming new breccia pipes at the site is practically nonexistent. The Bell Canyon Formation cannot support flow to form breccia pipes or interstratal dissolution. Large-scale strata-bound dissolution is not supported as a threat to a repository, but countering evidence is not conclusive. Brine reservoirs in the Castile are most likely isolated pockets of fluid which are neither recent nor from distant sources. If pressurized brines exist directly under the WIPP Site, "this should not adversely affect the operating facility, and there is insufficient justification to delay progress on the WIPP." The panel recommends the US Department of Energy obtain the right to deny mineral or hydrocarbon extraction from all zones unless it can be shown it poses no threat. Strata-bound dissolution should be evaluated by making firmer estimates of salt deposited and removed and by studying water flow and residues in anhydrite beds. Hydrologic holes should be located to help determine the influence of fractures or lineaments on the Rustler hydrology.

The in situ tests and experiments, including high-level waste, are an important aspect of WIPP. Operational handling and emplacement experience with waste packages is needed. The research and development (R&D) program should remain flexible to factor in new results, and the scientific community should be solicited for ideas and participation. Procedures for handling high-level waste in experimental areas may not be needed for transuranic (TRU) waste. Laboratory tests should supplement in situ testing.

Combustible materials should be embedded in noncombustible material. Waste acceptance criteria related to biological gas generation are based on a superficial analysis. Sulfate in the rocks may make hydrogen sulfide the major gas product. The quality assurance system is inadequate because it does not require on-site verification of package contents. Standardized waste packages should be adopted as soon as feasible. The mixture of wastes should be incapable of self-sustaining combustion in a current of air. Deficient procedures for fighting transient underground fires should be remedied. The humidity of still air and the pH of salt are significant quantities for degradation processes. Restrictions on organic material proportions should be dropped if measured relative humidity is less than 60%. Microorganisms will need to be evaluated if humidity is higher than 60%. State of the art equipment will be required for nondestructive verification of waste compliance with criteria. Practical alternatives are required for packages which do not comply. Waste-acceptance criteria are needed for high-level waste for experimental programs.

The design of an operation plan with storage areas to the south and experimental areas to the north is commendable. The layout of eight panels of storage rooms and barrier pillars is effective, provided barrier penetrations are adequately sealed. Seal details have not been

provided. The four-shaft design has greater redundancy and flexibility than the current three-shaft system. The panel has not seen an adequate evaluation justifying the three-shaft system, which is more typical of conventional mining practice than of nuclear industry practice. Mechanisms for transferring site preliminary design validation information must be established. Far-field salt displacement from long-term closure of excavations must be shown not to significantly increase permeability of the bulk of the salt. Sealing should be shown to be sufficient to preclude unacceptable increases in hydraulic conductivity across the repository horizon. Underground diesel use should be re-examined. Changes in facilities configurations need to be elaborated in terms of operational safety, efficiency, and nuclide releases.

Calculated doses are within limits for workers and far below normal background radiation for the public. Long-term release scenarios have not been verified experimentally but appear to set outside limits to credible releases. Hydrologic programs must continue to define rates and directions of flow. The probability of karst-type flows in the Rustler east of Nash Draw and effect on radiation dosages need to be determined.

National Research Council. Board on Radioactive Waste Management. Panel on the Waste Isolation Pilot Plant. 1984. *Review of the Scientific and Technical Criteria for the Waste Isolation Pilot Plant (WIPP)*. DOE/DP/48015-1. Washington, DC: National Academy Press.

ABSTRACT: The panel has evaluated the scientific and technical adequacy of work being done on the Waste Isolation Pilot Plant (WIPP) Project. The panel concluded that the scientific work has been carried out with a high degree of professional competence. The panel notes that the geology revealed by shaft sinking and excavation of drifts, and the preliminary measurements, generally confirm the geologic expectations derived from surface explorations and bore holes. The purity and volume of the salt, the absence of brine pockets at the repository horizon in the areas excavated, the absence of breccia pipes and of toxic gases, and the nearly horizontal bedding of the salt indicate that a repository can be constructed that will meet the geologic criteria for site selection. Thus, the important issues about the geology at the site have been resolved, but there remain some issues about the hydrology and design of the facility that should be resolved before large-scale transuranic (TRU) waste emplacement begins.

Some engineering aspects of the many WIPP studies by the US Department of Energy (DOE) and its contractors have not yet reached the final stage, so the panel's conclusions on these matters are not final. The final design will need to incorporate the findings of the experimental program and construction activities, or it will have to be shown that findings in the experimental program, if different than predicted (e.g., the larger amounts of water in MB-139, unexpected rates of closure in the drifts, and the permeability of the backfilled drifts), will not affect the safety of the repository.

The packaging of waste at the originating sites, transport to the site, transport vehicles, and disposal of heat-generating waste are beyond the scope of this study and are not dealt with in this report.

The health and safety consequences of the postulated repository failure mechanisms appear to be so minimal that simplifications in design may be justified, and cost-effectiveness studies should be carried out to determine whether they would be acceptable. However, the probability and the consequences of potentially rapid flow of brine solutions, containing radionuclides, through more permeable formations have not been completely determined. Once these have been resolved, conventional safety considerations (e.g., the number of shafts and packaging of waste for highway transport) might determine the optimum design. DWP

Neill, R.H. 1984. *Disposal of Radioactive Wastes (Disposicion De Desechos Radioactivos)*. Presented Before the Sociedad Mexicana de Seguridad Radiologica, Mexico City. Santa Fe, NM: Environmental Evaluation Group. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: In contrast to mathematical extrapolations of dose and effect relationships, the fundamental principle for radiation exposure is ALARA—as low as reasonably achievable. The exposure from radioactive waste disposal is less than from other sources, but there is considerable apprehension about disposal. The most promising method is deep geological disposal. Barriers in the total system range from the waste form to the total geological system. Human intrusions and natural events are the most plausible release scenarios. The geological information is most important in evaluating the long-term stability and validity in calculating potential exposure.

DWP

Neill, R.H. 1988. "Ten Years of State Evaluation of a Nuclear Waste Repository," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 377-382.

ABSTRACT: The Environmental Evaluation Group (EEG) was established in 1978 to independently evaluate the Waste Isolation Pilot Plant (WIPP) Project for the State of New Mexico in order to protect public health and safety and ensure that there is minimal environmental degradation from the project. In October 1988, WIPP will become the first engineered geological repository to dispose of nuclear waste. By concentrating on objective technical evaluation, the EEG has been able to improve the location, design, operations, and safety of the project. The evaluation has consisted of independent analyses of scientific data on site characterization, breach scenario modeling, transportation risks and safety, design parameters, operational risks and safety, waste certification, and mining. The US Department of Energy (DOE) has accepted EEGs suggestions on site relocation, transportation cask redesign, limitations on the kind of waste allowed at WIPP, waste certification procedures, additional site characterization, compliance with regulatory standards, operational procedures, and radiological monitoring. EEGs work has also helped in providing a proper perspective and sound foundation to the sometimes emotional debate on actual or perceived risks from a highly visible project. It has thus been possible to resolve contentious issues based on scientific investigations and analyses. As WIPP moves into an operational phase in 1988, EEG will continue to closely monitor the health and safety aspects of the project.

Neill, R.H., and L. Chaturvedi. 1989. "Technical and Programmatic Evaluation of WIPP," *Waste Management 89, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 26-March 2, 1989*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 1, 253-259.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) has been constructed to be a repository for transuranic (TRU) radioactive wastes generated from the US defense activities. The US Department of Energy (DOE) had planned to start shipping waste to WIPP in October 1988, but the physical plant was not ready, the shipping container was not certified, a number of regulatory requirements were not completed, and the justification for temporary emplacement of waste had not been developed. DOE is now moving swiftly towards completing a number of these requirements. A critical factor, however, remains the lack of demonstrable progress towards showing compliance with the Standards (40 CFR Part 191) for long-term integrity of

the facility. Without such compliance, the facility cannot be used for the purpose for which it has been built, that is, to permanently dispose of the defense TRU radioactive waste.

Neill, R.H., J.K. Channell, L. Chaturvedi, M.S. Little, K. Rehfeldt, and P. Spiegler. 1983. *Evaluation of the Suitability of the WIPP Site*. EEG-23. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Environmental Evaluation Group (EEG) has concluded that the Los Medanos site for the Waste Isolation Pilot Plant (WIPP) Project has been characterized sufficiently to warrant confidence in the validation of the site for the permanent emplacement of approximately 6 million ft³ of defense transuranic (TRU) waste. The maximum surface dose rate for the unshielded remotely-handled transuranic (RH-TRU) waste canisters is assumed to be 100 rem/hr with a maximum radionuclide concentration of 23 curies/L. The site and preliminary design validation (SPDV) program has confirmed the subsurface geological conditions at the site. EEG has identified further geological and hydrological work to improve confidence in the worst case scenario models of possible breaches of the repository. Some of the additional information will be necessary to assure compliance with future Environmental Protection Agency (EPA) standards.

EEG recommends several commitments be obtained from the Department of Energy (DOE) before beginning full facility construction. The DOE should agree to comply fully with the EPA standard when it is provided. The maximum surface-dose rate for unshielded RH-TRU waste canisters will be 100 rem/hr with a maximum radionuclide concentration of 23 curies/L. No potash mining should be allowed in zones I-III. Deviated drilling may be allowed under the site at depths greater than 6000 ft. Institutional control should be maintained for at least 100 years. Studies recommended by the State should be provided by the DOE by July 1985.

The EEG recommends the following studies: investigate the structural depression on Salado marker beds about 2 mi north of the shafts, computer modeling of Rustler groundwater flow, and hydrological testing. Hydrology tests should include a long duration pumping test at H-3; measurement of anisotropy at H-1, H-2, and H-3; convergence tracer tests at H-1, H-3, and H-4; and convergence tracer test at H-6 with sorbing tracers. The EEG recommends the DOE conduct nine studies already planned or in progress. DWP

Neill, R.H., J.K. Channell, C. Wofsy, and M.A. Greenfield, eds. 1979. *Radiological Health Review of the Draft Environmental Impact Statement (DOE/EIS-0026-D) Waste Isolation Pilot Plant, US Department of Energy*. EEG-3. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The Environmental Evaluation Group (EEG) has evaluated the radiological health, safety, and environmental aspects of the *Draft Environmental Impact Statement (DEIS)* by checking calculations, evaluating assumptions and methodology, considering possible omissions, evaluating conclusions, and recommending additional action. The radiation doses calculated by the EEG are in general agreement with the *DEIS* and are "no more than a fraction of existing radiation doses to the public." The EEG recommends the Waste Isolation Pilot Plant be subjected to the licensing procedures of the Nuclear Regulatory Commission.

Dose effects have been calculated instead of health effects, which are more informative. Health effects should be addressed in the *Final Environmental Impact Statement (FEIS)*. The assumptions used for transportation accidents and releases, including sabotage, may not be conservative. The radiological consequences cannot be fully evaluated until waste acceptance criteria are fully developed. The *FEIS* should include further information about site characteristics and analysis of brine reservoirs, deep dissolution, breccia pipes, groundwater

flow rates and flow paths, and the effect of impurities on the characteristics of rock salt at the repository horizons. Site selection criteria were developed in the absence of regulatory requirements and need to be examined by other agencies and groups to establish that they are reasonable and adequate. Some assumptions for operational accidents may underestimate the release of radioactivity. Details of plans and wastes need to be available before the potential exposure from the experimental waste program can be determined. Additional scenarios and calculations are appropriate to evaluate the long-term release of radioactivity. The hazards from retrieval of radioactive wastes should be examined in detail. The advantages and feasibility of site control for periods longer than 100 years should also be evaluated, as an uncontrolled site would be subject to human activity that could violate site integrity. DWP

Nelson, J.W., and P.C. Kelsall. 1984. "Prediction of Long-Term Creep Closure in Salt," *Rock Mechanics in Productivity and Protection, Proceedings of the Twenty-Fifth US Symposium, Evanston, IL, June 25-27, 1984*. Eds. C.H. Dowding and M.M. Singh. New York, NY: Society of Mining Engineers of AIME. 1115-1125.

ABSTRACT: Predictions of creep closure for periods ranging up to more than 1,000 years are needed for designing a radioactive waste repository in a salt formation. Such long-term predictions must be based on the use of laboratory and field test results extrapolated by numerical modeling. Laboratory test results are presented which show highly variable creep behavior for salts from different sites as well as salts from the same site. Comparisons of measured creep closures against predicted closures are presented for two deep bore holes in Louisiana salt domes and for an exploratory shaft and drift in southeastern New Mexico bedded salt (Waste Isolation Pilot Plant). These data illustrate the significant uncertainties involved in long-term closure predictions and indicate the critical need for site-specific, in situ closure measurements over extended periods of time for repository design.

Netherland, Sewell & Associates. 1974. *Evaluation of Hydrocarbon Potential AEC Study Area, Southeast New Mexico*. ORNL/SUB-74/38284. Oak Ridge, TN: Oak Ridge National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The hydrocarbon potential of 3 mi² (SE/4 of section 35 and S/2 of section 36, T21S, R31E; section 1 and E/2 of section 2, T22S, R31E; SW/4 of section 31 of T21S, R32E; and W/2 of section 6, T22S, R32E) was evaluated. No economically recoverable oil and gas exist within the study area or in the immediately adjoining acreage. The oil and gas lease options have no value to an operator with full knowledge of the geology, as he would also conclude that no oil and gas are economically recoverable in the study area. An operator who drills trends without full knowledge of the geology might pay a cash bonus of as much as \$40 to \$50/acre for leasing rights. The value of oil and gas rights is estimated to be approximately \$100/acre (about 2 1/2 times the leasing values above) to the owner derived "not from the finding and producing of oil and gas, but from some operators' 'hoping' to find oil and gas and their willingness to pay a 'cash bonus' for the lease or contractual right to conduct exploratory drilling toward that end." DWP

Netherland, Sewell & Associates. 1975. *Updated Evaluation of Hydrocarbon Potential ORNL Study Area, Southeast New Mexico*. ORNL/SUB-75/70344. Dallas, TX: Netherland, Sewell & Associates. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: During the year since the original report on hydrocarbon potential of a 3 mi² area, 16 new wells have been drilled in the vicinity. The results confirm earlier conclusions "that no economically recoverable oil and gas exists within the limits of the ORNL [Oak Ridge National Laboratory] study area or under the acreage immediately adjoining the study area." Three structural highs, carrying through from shallow Permian age beds to Siluro-Devonian beds, were confirmed across the central part of the area. Hydrocarbon production is limited to porous zones on the crests of structural highs. No oil or gas has been found in synclinal troughs such as at the study area. The nearest leasing is about 12 mi southeast of the study area with prices in the range of \$125/acre. ". . . we believe there has been a modest decrease in the value of the minerals in this area during the past year." DWP

Neuman, S.P., G.R. Walter, H.W. Bentley, J.J. Ward, and D.D. Gonzalez. 1984. "Determination of Horizontal Aquifer Anisotropy with Three Wells," *Ground Water*. Vol. 22, no. 1, 66-72.

ABSTRACT: Existing methods for the determination of horizontal aquifer anisotropy by means of pumping tests requires a minimum of four wells; one for water withdrawal and three for drawdown observations. This paper shows how the same methods can be used to determine anisotropy with as few as three wells, if at least two of them can be pumped in sequence. A field example is included. A method of analyzing data from more wells than the above minimum, by least squares, is also described.

Niou, S., and D.E. Deal. 1989. "Migration of Brine and Nitrogen in Creeping Salt," *Waste Management 89, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 26-March 2, 1989*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 1, 329-335.

ABSTRACT: Although the excavations in bedded salt at the Waste Isolation Pilot Plant (WIPP) are, for all practical purposes, dry, small amounts of brine have been observed to weep from exposed surfaces in the repository horizon and seep into drill holes in the underground excavations. As part of the Brine Sampling and Evaluation Program (BSEP) at the WIPP, this study has been made to formulate the complex problem of brine and nitrogen flow through deforming salt as completely as possible. The derived equations are coupled where appropriate in order to describe the natural phenomena. The main objective of this paper is to suggest a method by which the formulation might be solved in order to estimate the brine inflow rate into the excavated rooms at the WIPP repository level. The suggested solution method requires the modification and combination of two finite-element codes which may necessitate a large amount of computer memory for data storage.

Niou, S., and J.M. Pietz. 1987a. *A Statistical Inverse Analysis of the H-3 Multipad Pumping Test*. Albuquerque, NM: International Technology Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The H-3 multipad pumping test of October to December 1985, was analyzed using a new statistical groundwater inverse code with three goals: characterize the Culebra Dolomite Member by assigning regionalized values of transmissivity and storativity along with associated uncertainties; utilize all H-3 pumping test data to the extent possible; and judge the suitability of the method. The code, called INVERT, produces probabilistic distributions of transmissivity and storativity which can be used in stochastic models of radionuclide transport. Maximum likelihood methods are used to calculate transmissivity and storativity from test data.

Quantified uncertainties in the data put into the code are carried through the calculations and are reflected in confidence limits for the final parameter estimates.

The statistical methods used in INVERT are highly applicable to analysis of pumping tests for risk assessment. Hydraulic parameters must be extracted from observed data, which at the very least contain measurement errors. Extensive hydraulic testing and construction activities have created nonstatic Culebra heads. Culebra data reflect these changing heads, and therefore the data contain additional errors. Use of a statistical method for Waste Isolation Pilot Plant (WIPP) Site pumping analysis is further motivated by the fact that Environmental Protection Agency (EPA) regulations applicable to the WIPP require a probabilistic assessment of long-term repository performance. INVERT yields the requisite probabilistic distributions of Culebra hydraulic parameters which could be used in probabilistic radionuclide transport models. DWP

The conclusions from the analysis are:

1. INVERT calculated most probable transmissivity and storativity values, the quantified error in the data, and a zone pattern for the Culebra. This zone pattern reflects the responses from the H-3 test data and also results from previous studies. Using the parameters estimated by the program, the match to the observed data was reasonable.
2. A fracture zone connects H-3 with DOE-1 and H-11. A high transmissivity zone connecting H-3 with P-17 may be an extension of this zone. A zone of high transmissivity around the WIPP shafts and WIPP-21 is probably caused by construction and leakage at the shafts. Assigning WIPP 21 to the latter zone is uncertain.
3. 95 percent confidence limits calculated for Culebra transmissivities were best for H-1, H-2, H-3, H-11, and DOE-1.
4. Data from WIPP-12, WIPP-13, WIPP-19, WIPP-21, and WIPP-22 were distorted by well development. WIPP-12 and WIPP-13 were omitted from the analysis. Confidence in the responses at WIPP-19, WIPP-21, and WIPP-22 was low. Leakage from the waste handling shaft may have affected WIPP-21 and WIPP-22.
5. Uncertainties in the responses for wells such as P-14, P-15, H-6b, H-5b was high. Instrument malfunctions and simultaneous construction activities thwarted the goal of maximum data utilization.
6. Reliability of the calculated parameters and the definition of parameter zones can be improved with more pumping test data.
7. Several regions around the WIPP Site lack Culebra monitoring wells.

Niou, S., and J.M. Pietz. 1987b. "Coupled Brine Migration and Stress Analysis for Repository Room Saturation in Bedded Salt," *Rock Mechanics: Proceedings of the 28th US Symposium, University of Arizona, Tucson, AZ, June 29-July 1, 1987*. Eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman. Boston, MA: A.A. Balkema. 601-608.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a transuranic (TRU) nuclear waste repository mined out of Permian age, bedded salt in southeastern New Mexico. Since excavation, small amounts of brine have been seeping into repository rooms under the influence of large pressure gradients. During the isolation period, the accumulation of brine in the room involves the coupled mechanisms of brine flow, salt creep, and room contents consolidation and pressurization. This preliminary analysis tested the qualitative importance of the coupled mechanisms using an idealized room geometry and available salt property data from the WIPP Site. A computer code, COUPLE, uses finite differences to solve the brine flow equation assuming Darcy's Law, with iteration used to establish compatibility between the coupled equations. Results show that mechanical characteristics of the waste and repository room air leakage strongly effect brine flow rate, but that brine flow rate was insensitive to the small changes in salt porosity and permeability.

Nowak, E.J. 1978. "The Migration of Eu through Geologic Media," *EOS Transactions, American Geophysical Union*, SAND78-1746J. Vol. 59, no. 12, 1224. (Abstract Only).

ABSTRACT: The rates of migration of long-lived radionuclides by fluid flow through geologic media depend in part on their propensities to be absorbed by the media. This absorption characteristic is often expressed as a distribution coefficient, K_d . Europium (Eu) was used as a simulant for the transuranics (TRUs) in these initial absorption measurements. The aqueous phases were concentrated brines that are typical of the salt deposits in the Los Medaños area of southeastern New Mexico. The solid phase in the absorption measurements were clays and geologic media of the same geologic area. The Eu concentration and the pH of the liquid phase were measured before and after contact with the solid media in both batch and flow experiments. A major dependence of absorption on pH was found. The values for K_d varied from $\sim 10^5$ mL/g at pH ~ 7 to ~ 10 mL/g at pH ~ 4 , and this effect obscured any differences among different solid phase compositions. Further investigation of the liquid phase revealed that the Eu was associated with a precipitate of particles having diameters that were > 0.8 and < 40 μm at the larger values of pH. At the smaller values of pH, either the particles were smaller than 0.8 μm or the Eu was in solution. Related batch and flow experiments showed that the particles which were present at high pH values were occluded by solid media, while at low values of pH, Eu was absorbed by another slower process.

Nowak, E.J. 1980a. "The Backfill as an Engineered Barrier for Nuclear Waste Management," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium, Boston, MA, November 27-30, 1979*. Ed. G.J. McCarthy. SAND79-0990C. New York, NY: Plenum Press. Vol. 2, 403-410.

ABSTRACT: This paper presents results from an experimental backfills barrier development program. The swelling, plastic flow and relative impermeability of bentonite and hectorite were observed and measured after wetting them with concentrated brines. Measurements of stable values of pH > 6.5 for the interstitial brines in wetted bentonite and hectorite confirmed conditions favorable for precipitation and sorption of transuranics (TRUs). Values of $K_d > 2000$ mL/g were measured for Pu and Am. Calculated estimates of the effectiveness of a 1-ft-thick backfill barrier are presented. They show that the breakthrough of Pu and other transuranics (TRUs) ($K_d = 2000$ mL/g) can be delayed for 10^4 to 10^5 years. The breakthrough of most fission products ($K_d = 200$ mL/g) can be delayed for 10^3 to 10^4 years, sufficient time for them to decay to very low concentrations. A backfill barrier can contribute significantly to a radioactive waste isolation system.

Nowak, E.J. 1980b. *The Backfill Barrier as a Component in a Multiple Barrier Nuclear Waste Isolation System*. SAND79-1109. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Quantitative estimates of the potential effectiveness of backfill barriers based on a linear sorption model are presented. Using getters such as clays (known sorbents), a backfill approximately 1-ft-thick can delay the breakthrough of transuranics (TRUs) by 10^4 to 10^5 years. A delay of 10^3 years is possible for major cationic fission products. These delays can be achieved provided that: the distribution coefficient (K_d , a measure of affinity for sorbed species) for the barrier material is equal to or greater than 2000 mL/g for TRUs and 200 mL/g for fission products; the interstitial groundwater velocity through the barrier is limited to 1 ft/year or less; the effective porosity of the barrier is equal to or less than 0.1; and the physical integrity of the barrier is maintained (no channels or cracks). Mixtures containing expanding clays such as smectites and other getters are expected to satisfy these criteria.

Nowak, E.J. 1980c. *Radionuclide Sorption and Migration Studies of Getters for Backfill Barriers*. SAND79-1110. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Bentonite and hectorite clay minerals were chosen for study and development as potential backfill materials for testing in the proposed Waste Isolation Pilot Plant (WIPP), a radioactive waste repository and test facility in bedded salt. This choice of materials was based on initial screening results which are presented and on the predicted physical properties of these materials. These properties were verified experimentally in concentrated brines specific to the WIPP Site. Distribution coefficients, K_d , were calculated from batch sorption measurements on bentonite and hectorite in the nearly saturated brines A and B. The resulting K_d values were in the range of $(1-5) \times 10^3$ mL/g for europium; $(2-40) \times 10^3$ mL/g for plutonium(IV); and $(4-16) \times 10^3$ mL/g for americium(III). A silica- and calcite-containing sand mixed with bentonite and hectorite acted as a sorber of americium(III) but was merely an inert diluent for plutonium(IV). Perchnetate anions (TcO_4^-) sorbed on activated charcoal with K_d values in the range of $(0.2-0.4) \times 10^3$ mL/g. Perchnetate, cesium, and strontium ions in brine were not sorbed appreciably by bentonite or hectorite. Although experimental evidence is given for a possible role of solubility in the sorption of europium on getters, other data presented here and evidence from the literature are inconsistent with a simple single reaction sorption mechanism. It is concluded that a backfill containing bentonite on hectorite and activated charcoal is potentially an effective barrier to the migration of Eu(III), Pu(IV), Am(III) cations and, with further development, to the migration of TcO_4^- anions as well.

Nowak, E.J. 1981a. "Composite Backfill Materials for Radioactive Waste Isolation by Deep Burial in Salt," *Scientific Basis for Nuclear Waste Management, Proceedings of the Third International Symposium, Boston, MA, November 17-20, 1980*. Ed. J.G. Moore. SAND80-1377C. New York, NY: Plenum Press. Vol. 3, 545-552.

ABSTRACT: Bentonite and hectorite were found to sorb Pu(IV) and Am(III) from concentrated brines with distribution coefficients $K_d > 3000$ mL/g. The permeability of bentonite to brine was less than 1 microdarcy at a confining pressure of 18 MPa, the expected lithostatic pressure at the 800-m level in a salt repository. Getters for sorption of TcO_4^- (charcoal, $K_d \geq 300$ mL/g), I^- (charcoal, $K_d \geq 30$ mL/g), Cs (mordenite, $K_d \geq 30$ mL/g), and Sr (sodium titanate, $K_d \geq 100$ mL/g) from brines were identified. Their sorption properties are presented. Thermal conductivity results (>0.5 W/mK) and evidence for bentonite stability in brines at hydrothermal conditions are also given. It is shown by calculated estimates that a 3-ft-thick mixture of bentonite with other getter materials could retain Pu, Am, and TcO_4^- for $> 10^4$ years and I^- for $> 10^3$ years. Another tailored mixture could retain Cs for ~600 years, Sr for ~700 years, TcO_4^- for ~4000 years, and I^- for ~400 years. The backfill can offer a significant contribution to the isolation capability of a waste package system.

Nowak, E.J. 1981b. "Backfill Barriers for Nuclear Waste Repositories in Salt," *Proceedings of the International Seminar on Chemistry and Process Engineering for High-Level Liquid Waste Solidification, Julich, Germany, June 1, 1981*. Eds. R. Odoj and E. Merz. SAND81-0377A. Vol. 2, 784-791. (Available from National Technical Information Service, Springfield, VA).

ABSTRACT: A backfill surrounding a waste form and canister can be an effective chemical and physical barrier to the migration of radionuclides. It can also chemically modify groundwater or brine to minimize their potency for corrosion and leaching. Interactions among the waste form, canister, other engineered barriers, groundwater or brine, heat, and nuclear radiation can affect waste package performance. Backfill materials were evaluated for containment of radionuclides, chemical modification of brine, and sensitivity to hydrothermal

conditions. Experimental conditions were relevant to nuclear waste isolation in bedded salt. They were based on geologic conditions at the site of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico, USA.

Brines were synthesized to represent water in contact with either potash-containing horizons near the WIPP Site, brine A, or water in contact with the halite of the WIPP horizons, brine B. Brine A contains 1.8 M NaCl, 0.8 M KCl, and 1.4 M MgCl as major constituents. The single major constituent of brine B is 5 M NaCl. Both brines contain 0.02 to 0.03 M Ca⁺⁺ and 10⁻⁵ to 10⁻⁴ M Cs⁺ and Sr⁺⁺.

Bentonite saturated with water has desirable physical and sorption properties for a backfill material. However, the mechanistic complexity of these properties requires that site- and material-specific studies be done for a repository in salt. At 18 MPa confining pressure (lithostatic pressure at a depth of 800 m), the measured permeability of a commercial bentonite sample to brine A was <1 microdarcy. That value is small enough to prevent significant convective transport of radionuclides relative to transport by molecular diffusion. Bentonite was also found to buffer WIPP brines at pH = ~6.5 to 7.5 at 25°C over a wide range of clay-to-brine ratios. In batch sorption experiments, bentonite sorbed Pu(IV) and Am(III) from WIPP brines with empirical distribution coefficients (K_d) $\geq$ ~10³ cm³/g.

Bentonite was found to be an inadequate sorber of the fission products TcO₄⁻, I⁻, Cs⁺, and Sr⁺⁺ from WIPP brines. New batch sorption experiments with WIPP brines have identified an activated charcoal which sorbs TcO₄⁻ with K_d = ~1000cm³/g and I⁻ with K_d = ~50cm³/g. A synthetic mordenite sorbed Cs⁺ with K_d = ~30cm³/g and a synthetic titanate sorbed Sr⁺⁺ with K_d = ~1000cm³/g.

Tailored mixtures of these sorbers could be effective backfills that contribute to the capability of the waste package for total containment during the first ~10³ years after emplacement and for controlled release thereafter. Calculated estimates of radionuclide retention times are shown for retarded diffusion through two backfill compositions. Calculated steady-state release rates for the same compositions in terms of concentrations (C_o) of radionuclides released from the waste form are also shown.

Measurements of hydrothermal reactions between backfill materials and brines have been initiated. Bentonite was contacted with brine B at 250°C for 11 days. The liquid phase was analyzed and the solid phase was characterized by powder x-ray diffraction and by transmission electron microscopy with electron diffraction and energy dispersive analysis. Initially present chlorite, clinoptilolite, and illite were no longer detectable. Brine samples taken during and after the run were mildly acidic (pH 4 to 7) after cooling. It was concluded that the montmorillonite component became better ordered without major recrystallization and should remain stable under the experimental conditions.

In summary, backfill mixtures surrounding the waste form and canister can provide a neutral or slightly acidic, potentially reducing (due to charcoal) environment, prevent convective aqueous flow, and act as an effective radionuclide migration barrier. Bentonite is likely to remain hydrothermally stable but potentially sensitive to waste package interactions which could alter the pH, the ratio of dissolved ions, or the sorption properties of radionuclide species. Effects of irradiation from high-level waste should be investigated.

Nowak, E.J. 1982a. *The Diffusion of Cs (I) and Sr (II) in Liquid-Saturated Beds of Backfill Materials*. SAND82-0750. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Diffusion rates of cesium and strontium in brine-saturated uncompacted backfill mixtures were measured to verify the magnitudes of retardation that were estimated from batch sorption data. Cesium retardation in backfill mixtures containing 40 wt. % mordenite

agreed well with the theoretical predictions assuming linear equilibrium sorption with an average K_d value of 20 mL/g. Strontium retardation by 10 wt. % sodium titanate was adequately characterized by $K_d = 43$ mL/g, but evidence for a more complex retardation mechanism was found. The corresponding K_d values calculated from batch sorption data are 13 mL/g for both cesium and strontium. The observed retardation was larger than predicted from batch sorption data; batch data are applicable for predicting adequate retardation of cesium and conservative for predicting retardation of strontium by backfill mixtures containing mordenite and sodium titanate. The techniques employed here for obtaining and analyzing diffusion data are useful for further studies of diffusion in brine-saturated backfill materials.

Nowak, E.J. 1982b. "The Backfill as an Engineered Barrier for Radioactive Waste Management," *Nuclear Technology*. SAND82-2158J. Vol. 59, no. 3, 389.

ABSTRACT: Backfill material between waste forms and the host rock contributes to waste isolation in a radioactive waste repository system. Backfills can also fill access shafts and tunnels. A "minimum backfill" is placed around waste forms or waste containers to fill minimum clearance gaps. A "backfill barrier" is an engineered layer of tailored backfill designed both to retard radionuclide migration and to fill voids. Backfill barriers have also been called "overpacks."

Several facets of backfill research are critical to backfill barrier design. Backfill materials should be selected and developed from an understanding of the chemistry of radionuclide species and their retardation or immobilization. Rates of radionuclide mass transport in backfill materials must be measured. Backfill materials may also be chosen to adjust groundwater chemistry for minimum leaching and corrosion of waste forms and waste package materials. Evidence is needed to show long-term stability of backfill materials in repository environments. Finally, applied research in these areas should be guided by clear backfill performance requirements.

Critical facets of backfill research are addressed by the papers in this issue.

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Nowak, E.J. 1983a. "Diffusion of Radionuclides in Brine-Saturated Backfill Barrier Materials," *Scientific Basis for Nuclear Waste Management VI, Boston, MA, November 1-4, 1982*. Ed. D.G. Brookins. SAND82-1258C. New York, NY: North-Holland. Vol. 15, 735-744.

ABSTRACT: The diffusion of cesium(I), strontium(II), pertechnetate, and europium in brine-saturated backfill materials was measured. Plastic diffusion cells containing cylindrical diffusion columns were used for low-density backfill materials. The diffusion of gamma emitters was followed by a gamma scanning technique. Metal diffusion cells constructed entirely from Hastelloy C-276 were used for the diffusion of pertechnetate in highly compacted bentonite. Apparent distribution coefficients calculated from diffusion data are: 0.02 m³/kg for cesium(I) in 40 wt.% mordenite and 60 wt.% bentonite; 0.04 m³/kg for strontium(II) in 10 wt.% sodium titanate and 90 wt.% bentonite; 0.5 m³/kg for pertechnetate in 70 wt.% charcoal and 30 wt.% bentonite; and 3 m³/kg for europium in 100% bentonite. Backfill effectiveness estimates based on batch sorption measurements were supported by these results; however, the diffusion results for europium did not agree well with a model for diffusion retarded by linear sorption. The first measurements of pertechnetate diffusion in highly compacted bentonite suggest that anion exclusion may play a role in reducing mass transport rates of anions in this material. Needs for diffusion measurements that take into account site-specific materials interactions are described.

Nowak, E.J. 1983b. "Diffusion of Colloids and Other Waste Species in Brine-Saturated Backfill Materials," *Scientific Basis for Nuclear Waste Management VII*, Boston, MA, November 14-17, 1983. Ed. G.L. McVay. SAND83-1343C. Brookfield, VT: A.A. Balkema. Vol. 26, 59-68.

ABSTRACT: The diffusion of plutonium (IV) and pertechnetate and the migration of colloidal gold in brine-saturated bentonite was measured. High ionic strength brine characterizes potentially intruding groundwater for radioactive waste repositories in salt. Plastic diffusion cells containing cylindrical diffusion columns were used for low density bentonite. Metal diffusion cells constructed entirely from Hastelloy C-276 were used for the diffusion of pertechnetate in highly compacted bentonite. Apparent distribution coefficients calculated from plutonium diffusion in two columns of low density bentonite are $2 \text{ m}^3/\text{kg}$ and $3 \text{ m}^3/\text{kg}$. These values are in good agreement with the value of $3 \text{ m}^3/\text{kg}$ that was calculated from previous batch sorption data. Pertechnetate anions migrated out of a brine-saturated high-density bentonite diffusion column at rates that are too large to be rationalized with a simple diffusion theory. Additional measurements that take into account possible channeling of pertechnetate are required. Colloidal gold was excluded from low density brine-saturated bentonite, but colloidal gold may have channeled between the bentonite and the wall of the diffusion cell. These results support the effectiveness of brine-saturated bentonite as an engineered barrier to plutonium. The results also highlight the need for additional measurements of pertechnetate and gold transport in bentonite. Needs for transport measurements that take into account site-specific materials interactions are also described.

Nowak, E.J. 1985. "Diffusion of Plutonium in Compacted, Brine-Saturated Bentonite," *Scientific Basis for Nuclear Waste Management VIII*, Boston, MA, November 26-29, 1984. Eds. C.M. Jantzen, J.A. Stone, and R.C. Ewing. SAND84-1118C. Pittsburgh, PA: Materials Research Society. Vol. 44, 351-358.

ABSTRACT: Diffusivities were measured for plutonium in brine-saturated compacted Wyoming bentonite. Complexities of the solution chemistry and retardation of transuranics (TRUs) necessitate diffusion studies under conditions that are specific for repository host rock types, in this case salt. Diffusivity values in the range of 10^{-15} to $10^{-14} \text{ m}^2/\text{sec}$ were obtained for bentonite at a packing density of $1800 \text{ kg}/\text{m}^3$. That density was obtained by compaction at 15 MPa, a typical lithostatic pressure in a repository in salt at 650-m depth. Even a 0.05-m thick bentonite-containing engineered barrier could decrease radionuclide release rates by approximately 4 orders of magnitude if the diffusivity for that radionuclide was in the observed range of 10^{-15} to $10^{-14} \text{ m}^2/\text{sec}$. These results confirm the effectiveness of uncompacted bentonite-containing materials as engineered barriers for radioactive waste isolation.

Nowak, E.J. 1986a. *Preliminary Results of Brine Migration Studies in the Waste Isolation Pilot Plant (WIPP)*. SAND86-0720. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Experiments to quantify brine migration in multi-heater, full-scale tests simulating repository environments have been underway in the Waste Isolation Pilot Plant (WIPP) since April, 1985. The brine migration experiments are part of near-field effects/waste package performance tests that simulate near-reference repository conditions ($18 \text{ W}/\text{m}^2$ thermal areal loading with 470 W/canister) for defense high-level waste (DHLW) in Room A1 and near-field overtest conditions ($1500 \text{ W}/\text{canister}$) in Room B. After 321 days, 22.0 kg and 19.7 kg of water had been collected from heated boreholes B041 and B042 in room B. Heated boreholes A1041 and A1042 in room A1 had yielded 1.8 kg and 1.6 kg after 162 days. These quantities of water are larger than the estimates for a hypothetical repository

array of 2.16 kW canisters based on previous small-scale test data and mechanistic brine transport models. They are also significantly larger than the quantities of brine that were reported for brine migration experiments in the Asse Mine of the Federal Republic of Germany. Mechanistic differences that depend on scale, thermal distribution, and site characteristics may account for this disagreement with other experiments and model calculations.

Nowak, E.J. 1986b. "Brine Migration Studies in the Waste Isolation Pilot Plant (WIPP)," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 2-6, 1986*. Ed. R.G. Post. SAND85-1987C. Tucson, AZ: University of Arizona. Vol. 2, 153-158.

ABSTRACT: An experiment to quantify brine migration in multi-heater, full-scale tests simulating repository environments is underway in the Waste Isolation Pilot Plant (WIPP). The brine migration experiment is part of near field effects/waste package interactions tests that simulate near-reference repository conditions (18 W/m² thermal areal loading with 470 W/canister) for defense high-level waste (DHLW) in Room A1 and near-field overtest conditions (1500 W/canister) in Room B. After 265 days, 16.1 kg and 17.6 kg of water had been collected from two heated bore holes in Room B. Heated bore holes in room A1 had yielded 1.1 kg and 1.3 kg after 105 days. These quantities of water are larger than our estimates for a hypothetical repository array of 2.16 kW canisters based on previous small-scale test data and mechanistic brine transport models. They are also significantly larger than the quantities of brine that were reported for brine migration experiments in the Asse Mine of the Federal Republic of Germany. Mechanistic differences that depend on scale, thermal distribution, and site characteristics may account for this disagreement with other experiments and model calculations.

[**Nowak**], **E.J.** 1986c. "WIPP: Status of Salt Consolidation Research," *Working Papers From the US/FRG Workshop on Sealing and Backfilling of a Salt Repository, Albuquerque, NM, September 23-25, 1986*. Comp. R.F. Cook. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-6-1 through II-6-4. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Moist (0.5 wt % to 2.0 wt %), crushed salt reconsolidates much more rapidly than dry, crushed salt. Initial calculations for a simplified geometry predict that in situ reconsolidation to 90% of intact salt density by room closure stresses will occur in a few tens of years. The permeability of crushed salt may decrease to microdarcy levels at that density. There is the possibility that in situ reconsolidated salt can assume the major sealing function in a few tens of years after emplacement, thus minimizing the geochemical stability requirements for other plugging and sealing materials. These results also highlight the important role for the small quantity of inflowing brine as a facilitator of salt reconsolidation.

Nowak, E.J. 1986d. "WIPP: Geochemical Stability Studies of Seal Materials," *Working Papers From the US/FRG Workshop on Sealing and Backfilling of a Salt Repository, Albuquerque, NM, September 23-25, 1986*. Comp. R.F. Cook. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-12-1 through II-12-4. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Information on the stability of grout and concrete prepared from high salt content mixtures is scarce. Evidence indicates that gradients of mobile chloride may exist in

such grouts that have been in contact with halite. Chloride gradients may serve to drive chloride transport for the formation of phases containing chloride, which may degrade important grout properties. Experiments focus on these issues and will include studies of the grout/halite interfaces. DWP

Nowak, E.J. 1989. "Issues Pertinent to Sealing of Radioactive Waste Repositories in Bedded Salt Formations," *Joint NEA/CEC Workshop on Sealing of Radioactive Waste Repositories, Braunschweig, Germany, May 22-25, 1989*, SAND89-1257, Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The following issues have been identified as pertinent to the sealing of radioactive waste repositories in bedded salt formations: an overall seal system function and strategy for waste isolation; performance requirements for the seal system; a need for redundancy; locations of long-term seals in excavations and bore holes; requirements for sealing interbeds and the disturbed rock zone (DRZ) seal stability for the required lifetime; and a need for short-term seals in addition to long-term seals.

These issues are defined in general terms, and some principals that may be useful in addressing them are presented. Although this presentation derives from experience with bedded salt, it has applicability to domal salt as well.

Nowak, E.J. and D.F. McTigue. 1986. "Brine Movement in Waste Isolation Pilot Plant (WIPP) Tests," *American Chemical Society 192nd Meeting, Anaheim, CA, September 7-12, 1986*, SAND86-1094A. Washington, DC: American Chemical Society. (Abstract Only)

ABSTRACT: Experiments are underway to quantify brine movement in the Waste Isolation Pilot Plant (WIPP), a full-scale research and development facility to demonstrate the safe disposal of defense radioactive wastes in bedded salt. It is desirable to have realistic predictions of brine movement for system evaluations and performance assessments. Cumulative quantities and collection rates were measured for water that is swept from 3 m high by 0.8 m in diameter zones in heated bore holes with flowing nitrogen. During 321 days, 19.7 kg and 22.0 kg of water had been collected at nearly constant rates of 60-80 g/day from each of two bore holes with 1500 W heaters. Bore holes with 470 W heaters yielded 1.6 kg and 1.8 kg of water during 162 days at approximately 10 g/day. These quantities of water are larger than our estimates from mechanistic models for thermally driven brine movement. Alternative models will be presented and compared with WIPP moisture-release results and brine chemistry information from other studies.

Nowak, E.J., and D.F. McTigue. 1987. *Interim Results of Brine Transport Studies in the Waste Isolation Pilot Plant (WIPP)*. SAND87-0880. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: It is important to have quantitative predictions of brine movement in a radioactive waste repository for performance assessment and for seal-design evaluations. Experiments to quantify brine transport to bore holes in multi-heater, full-scale tests simulating high-level waste repository environments have been under way in the bedded salt of the Waste Isolation Pilot Plant (WIPP) since April, 1985. Water vapor released to the test bore holes has been collected in flowing nitrogen and weighed periodically. Before heating, water was collected during several days from four test bore holes at rates in the range of 5 to 15 g/day. This result highlights the need for an isothermal model for brine movement in the

WIPP host rock salt. After heating began, the water collection rates rose to a peak, decreased, and then remained nearly constant for several hundred days. Subsequently, trends to decreasing rates have been observed. Cumulative quantities of water were 4.3 kg at 441 days from each of two bore holes in Room A1 (with a 470 W heater in each bore hole), and 36 to 38 kg at 600 days from each of the two bore holes in Room B (with a 1500 W heater in each bore hole). After the early transients, approximately 8 g/day/bore hole were collected in Room A1, and 50 to 80 g/day/bore hole were collected in Room B. These are much larger brine inflow rates than were observed during heated brine migration tests in the domal salt of the Asse Mine in the Federal Republic of Germany. Results from in situ brine transport tests in domal salt are not necessarily applicable to bedded salt.

A preliminary analysis of the results was begun with a highly idealized fluid flow model for porous media. Water collection data for unheated bore holes agreed reasonably well with the brine inflows that were calculated with this model. Agreement was attained using permeability and porosity values that are generally consistent with measured WIPP host rock properties. It was also shown that the WIPP experiments are well within the transient stage of this model. However, the temperature dependence of viscosity, when used in this model is inadequate to account for the large water collection rates in the heated bore holes. Further model development and additional experiments are needed to understand brine movement in the WIPP, with and without sources of heat. Parametric studies of time, scale, and salt composition are needed. Measurements of pore pressure at intervals within a few meters of WIPP excavations were shown by the model analyses to be important for testing mechanistic hypotheses concerning brine transport. WIPP hydrologic and disturbed zone characterization studies can also contribute to a mechanistic understanding of brine transport to WIPP excavations.

Nowak, E.J., and J.C. Stormont. 1987. *Scoping Model Calculations of the Reconsolidation of Crushed Salt in WIPP Shafts*. SAND87-0879. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Scoping model calculations show that crushed salt seal material can reconsolidate in a Waste Isolation Pilot Plant (WIPP) shaft to densities and permeabilities that are nearly equal to those for intact WIPP host rock salt. The current best estimate is that crushed salt in the lower one-third of a WIPP shaft will meet the criterion of acceptability for shaft sealing in less than 200 years. The extent of expected reconsolidation was shown to be sensitive to the rates of brine inflow from overlying water-bearing zones and from the WIPP host rock salt. Reconsolidation was also found to be sensitive to predictions of closure within the current range of uncertainty. Reconsolidation was found to be relatively insensitive to the initial void fraction within the practically achievable range (0.15 to 0.3) and to the time delay from shaft excavation to crushed salt emplacement. These results show that an effective upper shaft seal system is needed to protect the reconsolidating crushed salt from brine inflow for approximately 200 years. They also show that it is important for the evaluation of shaft seal performance to have more accurate, thoroughly tested models for brine influx from WIPP host rock and for shaft closure.

Nowak, E.J., and L.D. Tyler. 1989. "The Waste Isolation Pilot Plant (WIPP) Seal System Performance Program," *Joint NEA/CEC Workshop on Sealing of Radioactive Waste Repositories, Braunschweig, Germany, May 22-25, 1989*. SAND89-0386C. Paris, France: Organisation of Economic Co-Operation and Development. 98-110.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Seal System Performance Program addresses the sealing of all man-made penetrations. Sealing concepts for shafts, drifts, and bore holes have been developed, and candidate seal materials were identified. Ongoing

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laboratory tests and model calculations have confirmed the potential effectiveness of reconsolidated WIPP crushed salt as a primary long-term seal material. Grouts based on crushed WIPP salt appear to be viable materials for sealing anhydritic interbeds at drift and panel seal locations. In situ tests have demonstrated the viability of concrete bulkheads as temporary seal materials that preserve the integrity of the seal system until the crushed salt components have reconsolidated sufficiently. Cementitious grouts have also been tested in WIPP bore holes drilled from the surface. Scaled in situ tests of crushed salt and bentonite (as a temporary seal material to prevent downflow of water into the crushed salt in shafts) are currently underway. Large-scale seal tests and the development of models that predict the performance of seal systems are being developed from the test data.

Nowak, E.J., S.J. Finley, and C.L. Howard. 1990. *Implementation of Initial Tests in the Brine Inflow Room (Room Q) of the Waste Isolation Pilot Plant*. SAND90-0611. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The purpose of this report is to summarize for the record the objectives, planning, progress, and documentation of excavating Brine Inflow Room Q and implementing an initial set of Room Q tests. The Room Q tests were designed primarily to test the scale-up accuracy of the current brine inflow model by providing data on brine flow from the host rock salt to a large-scale excavation in the Waste Isolation Pilot Plant (WIPP). Data from these tests will also be used to reduce uncertainties in flow parameters and evaluate proposed mechanistic models. Room Q was excavated with a tunnel-boring machine. The room has the shape of a 350-ft-long cylinder with a nearly horizontal longitudinal axis, a circular cross section, and a nominal diameter of 9 ft 6 in.. A circular cross section was chosen to limit stress concentrations and thereby slow the development of a disturbed rock zone that may cause inaccurate brine inflow measurements. The initial tests were implemented to measure brine flow parameters and room closure. Pore pressure, permeability, and brine inflow were measured with 15 tools emplaced in bore holes above, below, and on the north side of the room at a station 75 ft into the host rock from the entrance to the room. These measurements were made before, during, and after Room Q was bored to obtain data on the responses in the host rock to the boring process. Closure measurements were started almost immediately after excavation progressed past each measurement station. The designs, timing, sequence, procedures, and as-built records for these tests were documented in Sandia National Laboratories WIPP Quality Assurance files and Westinghouse WIPP Engineering records.

Nowak, E.J., D.F. McTigue, and R. Beraun. 1988. *Brine Inflow to WIPP Disposal Rooms: Data, Modeling, and Assessment*. SAND88-0112. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A Waste Isolation Pilot Plant (WIPP) data base that characterizes brine movement and accumulation is summarized and analyzed. The data are interpreted in terms of a model for flow in a saturated porous medium. The model, summarized in this report, embodies the Darcy-flow assumption and storage due to linearly elastic compression of the salt and brine. Comparisons between model calculations and brine inflow rates measured in the WIPP show order of magnitude agreement for permeabilities in the range of 10^{-21} to 10^{-20} m² (1 - 10 nanodarcies). These values of permeability are in accord with independent, in situ determinations of permeability in the salt. Expected accumulations of brine in typical WIPP waste disposal rooms were calculated by numerical methods using a mathematical description for the brine inflow model. The expected brine accumulation in a disposal room was calculated to be in the range of 4 m³ to 43 m³ in 100 years. WIPP disposal rooms, filled with waste and backfill, are expected to be completely reconsolidated due to host rock creep in about 100 years, preventing further accumulation of brine. Calculations show that water-

absorbing tailored backfill materials can readily absorb the maximum expected brine accumulations in WIPP disposal rooms while maintaining adequate mechanical strength.

Nowak, E.J., J.R. Tillerson, and T.M. Torres. 1990. *Initial Reference Seal System Design: Waste Isolation Pilot Plant*. SAND90-0355. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Waste Isolation Pilot Plant (WIPP) sealing program results are embodied in the initial seal system strategy and reference design. The design provides a common basis for calculations and analyses so that results can be compared directly. The sealing strategy combines both long- and short-term seal components. Crushed salt, consolidated by creep closure of the excavations, is the principal long-term barrier to fluid flow. Short-term seal components are used until creep consolidation is sufficient. Concretes developed specifically for WIPP seals and swelling clay materials that exhibit low permeability to WIPP groundwater and brine have been chosen for the short-term components. A body of evidence exists showing the stability of these materials for the length of time they are required to function. Reference designs are described and drawings are shown for each of the principal multi-component seals. Confidence in the sealing strategy and the reference designs resulted from a combination of laboratory tests, numerical modeling, and in situ demonstrations. The sealing strategy, materials, and designs for the WIPP repository are consistent with the concepts and designs previously proposed for other national and international waste management programs. Past accomplishments and planned activities in the sealing program will produce a detailed, conceptual design for the seal system and a seal system performance model. Additional design, analysis, laboratory testing, and in situ testing are needed to assure the performance of the seal system.

NUS Corporation. 1979. *Report of Geologic Data Review for the New Mexico WIPP Site*. NUS-3324. Rockville, MD: NUS Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The NUS Corporation was contracted by Sandia National Laboratories to evaluate the validity of early site characterization studies for the WIPP Site in southeastern New Mexico. None of the NUS investigations completely met the requirements of the NUS Generic Standards for Geological Investigations, so secondary methods were used to validate the geologic data where nonconformances existed. The secondary methods included similar equipment, methods, and personnel; comparing results from similar operations; checking the reputation of contractors and consultants; examining memoranda acting as design documents and investigation controls; and redundant testing. NUS "concluded that the validity of the geologic data base obtained from 26 boreholes and 3 geophysical surveys for the Waste Isolation Pilot Plant can be substantiated." NUS performed the review during November and December 1978. DWP.

NUS Corporation. Robinson & Robinson Division. 1979. *Report of the Management of the Core Repository Relocation*. NUS Report Number 3352. Denver, CO: NUS Corporation, Robinson and Robinson Division.

ABSTRACT: The WIPP core repository was relocated in February 1979, to a new warehouse on Canal Street in Carlsbad, New Mexico. NUS Corporation designed the warehouse, developed a computerized inventory, and managed the relocation. A total of 6,510 core and cuttings boxes was inventoried and moved. The inventory list at the end of the move is included in the report. DWP

Oak Ridge National Laboratory. 1973a. *Site Selection Factors for the Bedded Salt Pilot Plant.* ORNL-TM-4219. Oak Ridge, TN: Oak Ridge National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Because of the nature of radioactive waste disposal in geologic formations, the selection of suitable sites is a unique exercise, totally different from that for any other type of facility. This compilation of the various factors that must be taken into consideration was assembled as an aid in the selection and confirmation of a site for the Bedded Salt Pilot Plant. As might be expected, most of these factors are related to geologic characteristics, which are discussed under the headings of stratigraphy, structure, hydrology, and mineral resources. Other factors concerned with geography and facility design and operations are also included.

Oak Ridge National Laboratory. 1973b. *Program Plan for the Development of the Bedded Salt Pilot Plant.* ORNL-TM-4233. Oak Ridge, TN: Oak Ridge National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The program leading to the establishment in FY83 of a pilot plant for storing radioactive wastes in bedded salt is described. This program consists of laboratory and field investigations of the factors affecting the suitability of a specific site in southeastern New Mexico; of more generally applicable problems associated with geohydrology and rock mechanics; and of considerations bearing on the operational safety of a pilot plant repository. Tasks concerned with the engineering development and design of the facility are also included.

ANNOTATION: The reference to FY83 in the abstract was the projected date for opening a pilot plant.

O'Brien, P.D., and D.W. Powers. 1976. "The Southeastern New Mexico Radioactive Waste Disposal Pilot Plant," *Proceedings of the Twenty-third Annual Southwestern Petroleum Short Course, Lubbock, TX, April 22-23, 1976.* Lubbock, TX: Southwestern Petroleum Short Course Association. 335-344.

ABSTRACT: The radioactive waste disposal pilot plant (RWDPP) in southeastern New Mexico has been revived after the Atomic Energy Commission considered and then dropped the concept of retrievable surface storage during the early 1970s. This repository is to "accommodate all categories of ERDA-generated waste and ... its design should permit later conversion for the storage of commercial wastes." The nuclear-fuel cycle produces wastes at all steps: mining and milling, processing and enrichment, fuel-element fabrication, power-plant operation, and fuel reprocessing. Part of the waste from each step, except mining and milling, is proposed for storage at the RWDPP. Most of these are alpha waste plus intermediate, cladding, and high-level waste from reprocessing.

The site is located in the northern part of the Delaware Basin in Permian age salt beds. Bedded salt is plastic, has high thermal conductivity, and is easy to mine. In addition, these deposits are well bedded, thick, at proper depth, and are relatively pure. The site appears to be located at an adequate distance from dissolution fronts in the area. The value of potential petroleum and potash resources in the area will have to be weighed against the value and

necessity of a disposal site. The current site under consideration has been selected after an initial site was determined to be structurally complex and unsuitable for easy and safe mining. The geology is being studied to determine characteristics of possible pathways, such as solutioning or tectonics, for waste to reach the biosphere.

The RWDPP is being designed with two separate storage levels for alpha wastes and high-level wastes that require shielding during handling. Experiments are being designed to determine the interaction of salt with high-level canister materials and waste forms.

The conceptual facility design is scheduled to be complete by June 1977. Construction is to begin in 1978, with the repository to begin operating in 1983. DWP

Olhoeft, G.R. 1978. *Electrical Properties of Salt Cored from Carlsbad, New Mexico*. Open File Report 78-463. Denver, CO: US Geological Survey.

ABSTRACT: Electrical properties of halite salt core from 786 m deep in borehole ERDA-9 were measured at 3% relative humidity, at a temperature of 295 K over a frequency range from 10 to 10⁶ Hz, and at direct current. The subsamples show that both the real relative dielectric permittivity and the real part of complex resistivity are highly variable and dependent on frequency. For single crystal halite, dielectric permittivity was independent of frequency, and resistivity measured at 10² Hz was nearly five orders of magnitude greater. These differences are attributed to impurities along crystal boundaries in the ERDA-9 samples. DWP

Pahwa, S.B., and J.R. Wayland. 1980. "Far Field Thermal Calculations for the WIPP Site in Southeastern New Mexico (SENM)," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium, Boston, MA, November 27-30, 1979*. Ed. G.J. McCarthy. SAND79-1013C. New York, NY: Plenum Press. Vol. 2, 817-824.

ABSTRACT: The temperatures must be evaluated for the strata surrounding heat-producing radioactive waste buried in salt at the Waste Isolation Pilot Plant (WIPP) Site. The same model for hydrologic transport can be used to study temperature increases in aquifers and at the ground surface.

Rustler water-bearing units were assigned to one unit 40-ft-thick while the Delaware Mountain Group, below the evaporites, was modeled as one 1000-ft-thick aquifer. Variable thermal test cases were assumed, with a base case over 1470 acres of 100 kW/acre at 2700 ft depth and 30 kW/acre at 2100 ft. Surface boundary conditions neglected seasonal and daily variations and combined convection and radiation heat losses with a linear convection equation.

At the repository horizons, temperatures peaked before 100 years and ranged from about 140 to nearly 300°F, depending on the loading conditions. Temperatures in the Rustler peaked after 1000 years and ranged from about 90 to about 105°F. The temperature changed about 1°F maximum at a depth 20 ft below the surface, while the change was about 0.05°F at a depth of 6 in. The calculated effects of variable salt thermal conductivity can be as great as the extremes proposed for thermal loading densities. DWP

Palacas, J.G., R.P. Snyder, J.P. Baysinger, and C.N. Threlkeld. 1982. *Geochemical Analysis of Potash Mine Seep Oils, Collapsed Breccia Pipe Oil Shows and Selected Crude Oils, Eddy County, New Mexico*. Open-File Report 82-421. [Denver, CO: US Geological Survey.]

ABSTRACT: Oil shows, in the form of oil stains and bleeding oil, in core samples from two breccia pipes, Hills A and C, Eddy County, NM, and seepage oils in a potash mine near Hill C breccia pipe are geochemically similar. The geochemical similarities strongly suggest that they belong to the same family of oils and were derived from similar sources.

The oils are relatively high in sulfur (0.89 to 1.23%), rich in hydrocarbons (average 82%), relatively high in saturated hydrocarbon/aromatic hydrocarbon ratios (average 2.9), and based on analysis of seep oils alone, have a low API gravity (average 19.4°). The oils are, for the most part, severely biodegraded as attested by the loss of n-paraffin molecules.

Geochemical comparison of seven crude oils collected in the vicinity of the breccia pipes indicates that the Yates oils are the likely source of the above family of oils. Six barrels of crude oil that were dumped into a potash exploration borehole near Hill C breccia pipe, to release stuck casing, are considered an unlikely source of the breccia pipe and mine seep oils. Volumetric and hydrodynamic constraints make it highly improbable that such a small volume of "dumped" oil could migrate over distances ranging from about 600 ft to 2.5 mi to the sites of the oil shows.

Pearson, F.J., Jr., V.A. Kelley, and J.F. Pickens. 1987. *Preliminary Design for a Sorbing Tracer Test in the Culebra Dolomite at the H-3 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site*. SAND86-7177. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The use of sorbing tracers in a field hydrologic test is a method of estimating the nuclide transport characteristics at one location in the Culebra Dolomite Member of the Rustler Formation at the Waste Isolation Pilot Plant (WIPP) Site. The Culebra is considered to be the principal continuous pathway from the site in the event of a breach of the planned nuclear waste repository. To prepare for such a tracer test, data evaluation and design calculations are necessary to estimate the principal parameters governing solute transport and the quantity and geochemical character of potential tracers. The following report represents the first step in preparing for a sorbing tracer test, namely a preliminary analysis that considers: the selection of the best location for the first test at the WIPP Site; an evaluation of a conservative tracer test at the recommended site to provide estimates of the physical solute-transport parameters; a hydrogeochemical and mineralogic characterization of the Culebra Dolomite; the rationale and recipe for the tracer-injection solution; the compilation of a list of potential sorbing and conservative tracers; and the identification of other needs before fielding the sorbing tracer test. The appendix to this report contains the thermodynamic data base used to support the geochemical model (PHREEQE) used in this study.

the Culebra Dolomite at the H-3 hydropad is the recommended site for conducting a sorbing tracer test because: the site has been well-characterized hydraulically in a number of multi-well interference tests; a convergent-flow conservative tracer test has been conducted at the H-3 hydropad, and analyzed to yield estimates of the physical solute-transport parameters (this test identified the role played by fractures in dominating solute-transport behavior at the hydropad scale); several high-quality groundwater samples have been collected from the Culebra at the H-3 site, and they have provided analyses with which to assemble a well understood geochemical characterization; the H-3 site is located down-gradient from the repository site on a probable groundwater flow path under natural gradients; and the H-3 site has appropriate hydraulic characteristics to allow the use of sorbing tracers with a wide range of partition coefficients and provide breakthrough in the allowable tracer-test operational period, assumed to be 2 to 5 years. The combination of relatively high transmissivity, extensive geologic and geochemical characterization, and down-gradient location make H-3 the optimum location for conducting the first sorbing tracer test at the WIPP Site. To bracket geochemical variability and to test transport under different hydraulic conditions, it may prove desirable to conduct a second experiment at a location where Culebra brines are more concentrated. However, this second experiment is not considered further in this report.

The H-3 hydropad complex consists of three wells arranged in an equilateral triangle with approximate 30-m sides. Each well is completed either open-hole or through perforated casing to the Culebra, which is about 7 m in thickness. Interpretation of a convergent-flow tracer test, performed at the H-3 hydropad in 1984 using two conservative organic tracers, meta-trifluoromethylbenzoate (m-TFMB) and pentafluorobenzoate (PFB), has yielded the following physical solute-transport characteristics: longitudinal dispersivity of 1.5 to 3 m, a fracture porosity of 1.9×10^{-3} , and effective matrix-block sizes ranging from 0.25 to 2.0 m. During this test, H-3b3 was the pumping well and tracers were introduced into wells H-3b1 and H-3b2. Using the above estimates, coupled with a laboratory-measured matrix porosity of 0.2, estimated tortuosities of 0.15 to 0.45, and free-water diffusion coefficients of 7.4×10^{-6} cm²/sec (m-TFMB) and 7.2×10^{-6} cm²/sec (PFB), the breakthrough curves for the two tracers were simulated using the flow and solute-transport code SWIFT II.

Design simulations for the sorbing tracer test were conducted assuming an injection of one kilogram of generic tracer and applying a range of partition coefficients of 0.1 to 50.0 mL/g for the flow path with the higher transport rate (H-3b1 to H-3b3) and 0.1 to 10.0 mL/g for the flow path with the lower transport rate (H-3b2 to H-3b3) at the H-3 hydropad. The results of these simulations were utilized to assist in the selection of sorbing tracers that would break through within the 2- to 5-year period planned for the test.

Analyses of groundwater and core samples from the Culebra at the H-3 hydropad indicate that the water samples are reasonably consistent and represent Culebra formation water. The Culebra is a gypsiferous dolomite with minor amounts of halite bounded by claystones. The

water chemistry is controlled by the mineralogy of the formation. Thermodynamic equilibrium calculations indicate that the water is in equilibrium with calcite, dolomite, gypsum, and celestite and has a pH of 7.3 to 7.4. The calculations also suggest that the water is in near-equilibrium with goethite and uraninite with an Eh of 0.05 to -0.15 volts.

Geochemical analysis of the Culebra Formation water led to the development of a recipe for the solution into which the tracer will be mixed prior to injection. The composition of the tracer solution is such that it should mimic the properties of the natural formation water and neither alter the chemistry of the matrix or formation water of the Culebra nor cause the tracer to precipitate or to become unstable under the existing reduction-oxidation (redox) conditions in the Culebra.

In considering sorbing and conservative tracers for the planned test at H-3, it was necessary to consider geochemical constraints on the injected tracers. The tracers must be able to be injected at concentrations low enough to not significantly alter the injection fluid or to provoke any reaction that could cause precipitation of the tracer before or during injection. The concentration should be high enough to define the breakthrough curve while being relatively easy to analyze. The sorbing and conservative tracers should be compatible. Radionuclide tracers are considered to be the most appropriate tracers because they require low mass input while still being extremely sensitive to detection, and they should mimic the transport characteristics of the projected waste inventory.

Radionuclide tracers most suitable for use as a sorbing tracer are either fission products or actinides. Nuclides of nickel, cobalt, strontium, uranium, neptunium, and plutonium were reviewed for suitability as possible sorbing tracers because they have partition coefficients low enough to achieve breakthrough in a two- to five-year test, and they are elements with long-lived nuclides in the projected WIPP waste inventory. Based on their half-lives, the nuclides Ni, Co, Co, Sr, Sr, Sr, U, Np, Pu, and Pu are recommended for further consideration. One important consideration will be the presence of certain fission products, such as Sr, in the probable waste inventory, and whether objections might be raised over the use of such nuclides for testing. To provide data for interpretation of the physical solute-transport parameters along the flow paths between the wells (also, to provide a comparison to parameters from the previously conducted conservative tracer test), conservative tracers should accompany the selected sorbing tracers. The most likely candidates are ^3H (tritium), ^{82}Br and ^{131}I .

Prior to fielding a sorbing tracer test, a final detailed design report will be completed. This report will describe final tracer selection, detailed design calculations, site preparation, instrumentation requirements, staffing requirements, review of safety, health, and regulatory requirements and procedures, and determination of the optimum operational conditions for the test.

ANNOTATION: This test was not fielded. No hydraulic tests using sorbing radioactive tracers have been performed at the WIPP.

Peterson, E.W. 1980. "Analysis of Borehole Plug Performance," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980*. ONWI-212. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 178-179.

ABSTRACT: A grout plug, 20 cm in diameter and 1.8-m long, was placed in an anhydrite bed at a depth of 1,370 m in borehole AEC-7. Fluid build-up, shut-in, and tracer flow tests were conducted on this plug to evaluate flow paths. A one-dimensional analysis of data, together with laboratory results, indicate "the predominant flow into the test region occurred through the cement plug/borehole interface region, with lesser contributions occurring through

the wellbore damage zone, the plug core, and the surrounding undisturbed anhydrite formation." Flow from the underlying Bell Canyon was limited to 0.6 L/day. Calculated permeability is 50 microdarcies and porosity is 0.018. If a wellbore damage zone is similar in size to the wellbore, permeability is less than 5 microdarcies. The data suggest flow occurs through a region with microstructure approximated by a porous medium. DWP

Peterson, E.W., and C.L. Christensen. 1980. "Analysis of Bell Canyon Test Results," *Proceedings of the Workshop on Borehole and Shaft Plugging, Columbus, OH, May 7-9, 1980.* SAND80-7044C. Paris, France: Organisation for Economic Co-operation and Development. 247-275. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Performance of the Bell Canyon Test (BCT) bore-hole plug has been monitored for a 7-month period. Data indicate the 2.1-m-long plug-formation system limited the Bell Canyon flow to 5×10^{-3} standard barrels per day (STB/D). Complete test results, analytical/numerical data analysis techniques, and associated plug performance evaluation assessments are included herein. Extension of conventional oil field technology to formations having the microdarcy-type permeabilities of those examined in the BCT emphasize the measurement limitations inherent within the current technology. Problems encountered in performing reliable, reproducible, microdarcy range permeability measurements are identified, data discrepancies are discussed, and the resulting impact on plug-performance assessment is defined.

Peterson, E.[W.], and S. Kelkar. 1983. *Laboratory Tests to Determine Hydraulic and Thermal Properties of Bentonite-Based Backfill Materials.* SAND82-7221. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Multiple physical and chemical barriers have been suggested as redundant containment elements for isolating high-level radioactive wastes in a repository. Backfill, including bentonite, can function to sorb migrating nuclides, to buffer the chemical conditions around the waste package, and to mechanically stabilize the waste canister. The thermal and hydraulic properties of clay, clay-sand, and clay-salt mixtures were evaluated as potential backfill materials.

Compressed pure bentonite had a measured hydraulic conductivity ranging from 0.0 ± 0.4 to $3.6 \pm 0.46 \times 10^{-13}$ m/s, depending on the compressed density. The hydraulic conductivity also increases about an order of magnitude for a 200°C temperature change, due apparently to changes in pore space geometry and clay ion conditions. Bentonite saturated with reference brine B had a measured permeability of $<4 \times 10^{-9}$ darcy. System variables are important at extremely low flow rates, and the data indicate trends rather than accurate measurements. Hydraulic conductivity of compressed composites with bentonite are higher, ranging from 5.8×10^{-13} m/s to 6.7×10^{-7} m/s. Temperature effects are varied and less pronounced in mixed compositions compared to pure bentonite. Compacted materials are more stable in the presence of brine, with higher initial dry densities. Samples that were maintained at constant volume collapsed during testing; the conductivity of these samples decreased after larger axial stresses were applied.

"Thermal conductivity of dry bentonite is strongly affected by density and mildly affected by temperatures. . . ." Thermal conductivity increased as sand or salt were added to bentonite. Values were typically greater than 1 W/mK for mixed materials. Pure bentonite typically has a thermal conductivity of about 0.6 W/mK. DWP

Peterson, E.W., and P.L. Lagus. 1979. *S³ Whole Hole Permeability Test*. La Jolla, CA: Systems, Science and Software. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The objectives of testing in the ERDA-7 borehole are to determine the permeability of the surrounding formation, assess the casing bore-hole cement bond, and provide data to design guarded straddle packer permeability tests. A single packer will be used to seal off the downhole interval to be pressurized. A nominal pressure of 100 psig will be maintained and the flow monitored until flow and pressure reach a steady-state value. The borehole pressure decay will be measured for a period equivalent to the pressurization period.

DWP

Peterson, E.W., P.L. Lagus, and K. Lie. 1987a. *Fluid Flow Measurements of Test Series A and B for the Small Scale Seal Performance Tests*. SAND87-7041. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The degree of waste isolation achieved by a repository-seal system is dependent upon the fluid flow characteristics (or permeability) of the seals. In order to obtain meaningful, site-specific data on the performance of various possible seal-system components, a series of in situ experiments called the Small-Scale Seal Performance Tests (SSSPT) are being conducted at the Waste Isolation Pilot Plant (WIPP). This report contains the results of gas-flow, tracer-penetration, and brine-flow tests conducted on concrete seals in vertical (Test Series A) and horizontal (Test Series B) configurations. The test objectives were to evaluate the seal performance and to determine if there existed scaling effects that could influence future SSSPT designs.

Peterson, E.W., P.L. Lagus, and K. Lie. 1987b. *WIPP Horizon Free Field Fluid Transport Characteristics*. SAND87-7164. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Free-field brine transport characteristics were measured in boreholes in competent halite and in Marker Bed 139 (MB139) at the Waste Isolation Pilot Plant (WIPP) Facility horizon. These data are important for plugging and sealing designs, as well as determining brine influx and buildup/dissipation of gas pressure in a repository. Both brine and gas-flow tests were conducted in boreholes using a dual-packer system.

Brine-flow tests indicate competent halite has an estimated formation pore pressure of 8.3 MPa (megapascals), while MB139 has 10.3 MPa. It is assumed that the hole does not close faster than 20 microstrains/day and there is no brine leakage along the packer to bore-hole interface or measurement system. Leakage would result in an underestimate of pore pressure. Brine flow tests indicate competent halite has a permeability of 10^{-9} darcy, while Marker Bed 139 has approximately 10^{-8} darcy permeability. These data should not be used to infer porosity.

Short gas-flow tests at 2.1 MPa pressure indicated permeabilities before brine flow tests of about 10^{-8} and 4×10^{-7} darcy, respectively, for competent halite and MB139. After brine flow tests, the formation would not accept gas during similar flow tests at 2.1 MPa. The flow paths for brine and gas must be different, given the very different gas-flow pressures and free-field pore pressure. The brine-flow test may also have closed gas-flow channels.

The data can be interpreted for free-field pore pressure and formation permeability, but the results are not conclusive. Confirmatory testing and tests measuring closure and pressure buildup are desirable.

DWP

Peterson, E.W., P.L. Lagus, and J.C. Stormont. 1986. "Permeability Measurements at the Waste Isolation Pilot Plant (WIPP)," *Waste Management 86. Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ. March 2-6, 1986.* Ed. R.G. Post. SAND85-1988C. Tucson, AZ: University of Arizona. Vol. 2, 243-248.

ABSTRACT: A series of in situ permeability measurements was conducted at the Waste Isolation Pilot Plant (WIPP) Facility horizon. These measurements were preceded by numerous laboratory permeability measurements, and measurements made from wellbores that extended from the surface through the facility horizon. The permeability of the facility horizon is a fundamental parameter, one which describes its inherent isolation capabilities and is paramount in determining its suitability for the long-term disposal of radioactive waste. Further, the permeability of the formation is important to seal design and evaluation, as flow through the total seal system is in part dependent on the permeability of the host rock. Results of a limited number of flow tests conducted to date suggest that the competent salt is essentially impermeable. However, small flows did occur along some clay/anhydrite seams. Existence of these seams may have performance assessment implications and may affect internal repository room isolation properties, as well as influence associated seal designs. Additional tests are required to fully characterize the permeability of the WIPP Facility horizon.

Peterson, E.W., P.L. Lagus, R.D. Broce, and K. Lie. 1981. *In Situ Permeability Testing of Rock Salt.* SAND81-7073. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Permeability of bedded salt was tested in situ in borehole AEC-7. Initial tests were whole-hole flow tests over large intervals between the fluid level at a 2822 ft depth and a single packer above the fluid. A series of tests used a guarded straddle-packer system to isolate 100-ft lengths of the bore hole centered at 2269 and 1869 ft. The lower zone corresponds to the contact handled (CH) waste facility horizon. Both constant pressure flow and shut-in pressure decay were measured.

Tests of the zone at 2269 ft indicate a permeability between 12 and 21 microdarcies, assuming an unsaturated homogeneous porous formation with 0.001 porosity. Constant pressure flow at 1869 ft indicated 3 microdarcies permeability, though there was no measurable pressure decay during a shut-in test. The guarded packer system shows that vertical permeability is small compared to horizontal permeability. If damage around the bore hole exists and has a cross sectional area equal to the bore hole, it has a permeability much less than 5 microdarcies.

Data are also consistent with fracture flow, which could result in penetration of the pressure front at a radial distance of 700 ft from the bore hole during the test.

These tests are limited both in depth tests and in the radial penetration of gas. Cross-hole trace/pressurization tests are recommended to measure fluid penetration distances to determine areal permeability and particle velocities for fluid migration studies. DWP

Peterson, E.[W.], P.[L.] Lagus, J. Brown, and K. Lie. 1985. *WIPP Horizon In Situ Permeability Measurements Final Report.* SAND85-7166. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Eighteen gas permeability tests were conducted underground at the Waste Isolation Pilot Plant (WIPP) to determine the permeability and porosity of the competent salt, the variation of permeability with distance from the mined surface, and the influence of interspersed clay and anhydrite seams on measured permeability. Two tests were used.

Downhole pressures were maintained approximately constant and the flow was measured. For the second test, the test region was pressurized, shut-in, and the pressure decay was monitored.

Competent salt has approximately 0.001 porosity, and permeability less than 10^{-8} darcy. Salt appears isotropic, and variability in permeability is not attributable to different types of salt. Permeability may decrease with distance from the mined surface, though the maximum measured value nearer the face was less than 10^{-6} darcy. Most clay and anhydrite zones were similar in permeability to competent salt. Confirmation tests showed large permeabilities in units above and below the center of a room apparently due to floor heave or roof sag. Zones that produced gas or accepted large gas flows could not be characterized by these tests, and they will require cross-hole flow and tracer tests. DWP

Pfeifer, M.C. 1987. *Multicomponent Underground DC Resistivity Study at the Waste Isolation Pilot Plant, Southeast New Mexico*. MS Thesis. Golden, CO: Colorado School of Mines.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) located in southeastern New Mexico, 23 mi east of Carlsbad, has been constructed to study the effects of long-term storage of nuclear waste in a bedded halite formation. The geology of the area is that of a karst environment with many dissolution structures and other deformities that must be mapped to predict the time relationship of these structures with the WIPP Site. Because of the large contrast in the electrical conductivity between crystalline salt and salt saturated water, electrical methods may play an important role in locating water-saturated zones in the halite formation. During the spring and summer of 1986, a series of underground DC resistivity surveys was performed at the site to better understand the geology near the mine. Electromagnetic data were collected as a preliminary step in determining the resistivity contrasts near the drifts. Measurements showed the rock near the drifts to have resistivities of approximately 300 to 400 ohm/m. Along with these recordings, the main experimentation consisted of using direct current electrical methods to measure four components of the electrical field: a potential voltage and three orthogonal components of the electrical field. These voltages were then converted to apparent resistivities and compared with a uniform-earth model and a three-layer model. The effect of a conductive disk in a resistive layer was then modeled to simulate a lens-shaped brine feature in the halite bed. The modeling study shows that the effect of conductive anomalous body depends on its size, orientation, and distance from the survey area.

Pfeifer, M.C., D.J. Borns, C.K. Skokan, H.T. Anderson, and J.M. Starrett. 1989. *Geophysical Methods to Monitor Development of the Disturbed Rock Zone Around Underground Excavations in Bedded Salt*. SAND89-7055. Albuquerque, NM: Sandia National Laboratories. (Abstract Only).

ABSTRACT: A zone of disturbed rock develops around underground excavations, which has direct implications on the intended long-term use of the excavations. The rate and manner of deformation depend on the interval of time after supporting room or tunnel material is removed.

Brine redistributed by the deformation and changes in porosity and permeability can be monitored by electrical methods. Conventional exploration induction tools, with effective penetration to 12 m, recorded resistivities corresponding to about 2% water content. Resistivity at depths of 1-2 m indicates about 1% water and a near-surface drying rind. DC resistivity, monitored through a grid of electrodes in the floor of a room, is well suited to monitoring the deformation of the floor.

The acoustic velocity of the rock deteriorates in pillars between room and tunnels. A seismic tomographic survey of one of the older pillars shows the interior to be acoustically

homogeneous. A low velocity zone on the surface of the pillar and less than 1-m thick was demonstrated by seismic refraction. This thickness is below the resolution of the seismic tomography survey. DWP

Pfeifle, T.W. 1987a. *Mechanical Properties and Consolidation of Potential DHLW Backfill Materials: Crushed Salt and 70/30 Bentonite/Sand*. SAND85-7208; Topical Report RSI-0282. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Material properties of proposed backfill around defense high-level waste packages are poorly known, but they are necessary to determine mechanical behavior of the waste packages. Laboratory experiments on crushed salt and 70/30 (by weight) bentonite/sand provided thermomechanical and time-dependent properties for use in numerical models. Ten unconfined compression tests were conducted on crushed salt at various densities. Tests on bentonite/sand included unconfined compression on samples at differing densities, hydrostatic compression at 20 and 100°C, hydrostatic consolidation at 20 and 100°C, and swelling.

Young's modulus for crushed salt varies from 5.3 to 12.6 GPa for densities ranging from 1,740 to 1,970 kg/m³, respectively; Poisson's ratio is about 0.35 for this same range. The unconfined compressive strength varies from 3.0 to 10.2 MPa over the range of density tested.

Results for 70/30 bentonite/sand show that Young's modulus varies from about 50 MPa to over 600 MPa for densities ranging from 1,630 to 2,010 kg/m³. Poisson's ratio is about 0.25. The unconfined compressive strength ranges from 0.15 to 2.90 MPa over the range in density. Hydrostatic compression tests show that the elastic bulk modulus linearly increases with density and is independent of temperature. The loading bulk modulus increases nonlinearly with volumetric strain (or density); it can be approximated well within empirical models. Time-dependent volume change at constant hydrostatic stress is relatively large at early time. The rate of change slows considerably with time. No temperature effect on creep is observed. Finally, maximum swell pressures of about 2 MPa occur after one day in a saturated brine.

DWP

Pfeifle, T.W. 1987b. *Backfill Material Specifications and Requirements for the WIPP Simulated DHLW and TRU Waste Technology Experiments*. SAND85-7209. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The waste package performance (WPP) experiments feature widespread use of backfill. This report presents details of the physical layouts of experiments, backfill locations, and backfill materials. Backfill materials required in the experiment are crushed salt, 70/30 (% by weight) crushed salt/bentonite, 70/30 (% by weight) bentonite/sand at low density, and sand. The crushed salt is mine-run Waste Isolation Pilot Plant (WIPP) salt, with all particles larger than 6.3 mm removed. The bentonite is a commercial granular material. The sand is also commercially available. In addition, physical properties were cited or determined for the four backfill materials. The physical properties of primary importance are grain-size and bulk density. Maximum grain-size limits were set to prevent the arching of backfill materials during emplacement. For mixed materials, grain-size distributions were matched to prevent segregation.

Approximately 450, 150, 50, and 1.3 tons of crushed salt, 70/30 crushed salt/bentonite, 70/30 bentonite/sand (low density), and sand, respectively, are needed in fielding the experiments. Requirements and specifications for materials handling equipment are sized for use in the WPP simulated defense high-level waste (DHLW) and transuranic (TRU) waste experiments. DWP

Pfifle, T.W., and P.E. Senseny. 1981. *Elastic-Plastic Deformation of Anhydrite and Polyhalite as Determined From Quasi-Static Triaxial Compression Tests*. SAND81-7063. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Constant stress-rate triaxial compression experiments were performed on specimens of anhydrite and polyhalite at low confining pressure and at two temperatures. The loading rate was $5.75 \times 10^{-2} \text{ MPa s}^{-1}$; the confining pressures were 1, 5, 10, and 20 MPa and the two temperatures were 25 and 100°C. The specimens were loaded to failure in a soft testing machine so that failure occurred at peak stress. Results from these experiments were used to construct yield envelopes, failure envelopes and stress-strain curves, and to determine mechanical properties.

Yield, determined by the onset of dilatancy, occurs at about 60% of peak stress. The effect of temperature on both the yield and failure envelopes is negligible. The polyhalite specimens were found to be about twice as strong as the anhydrite specimens.

The stress-strain data were fitted to a constitutive law having the form

$$\underline{\underline{D}} = \frac{1}{2G} \left(\underline{\underline{\dot{\sigma}}} - \frac{\nu}{1+\nu} \underline{\underline{I}} \text{tr} \underline{\underline{\dot{\sigma}}} \right) + \frac{1}{h} \underline{\underline{P}} \left(\underline{\underline{Q}} : \underline{\underline{\dot{\sigma}}} \right)$$

where $\underline{\underline{D}}$ is the rate-of-deformation tensor, $\underline{\underline{\dot{\sigma}}}$ is the Jauman rate of Cauchy stress, $\underline{\underline{I}}$ is the unit tensor, G is the shear modulus, ν is Poisson's ratio, h is the plastic hardening modulus, $\underline{\underline{P}}$ is a second order tensor that is the derivative of the plastic potential with respect to Cauchy stress $\underline{\underline{\sigma}}$, and $\underline{\underline{Q}}$ is a second-order tensor that is the derivative of the yield function with respect to $\underline{\underline{\sigma}}$. The functional forms of $\underline{\underline{P}}$ and $\underline{\underline{Q}}$ depend on the yield criterion and flow law adopted.

Two common yield criteria are employed in this study: Mises-Schleicher and Mohr-Coulomb. The corresponding plastic potentials are chosen so that dilatancy is independent of internal friction, but so that the projection of the plastic component of $\underline{\underline{D}}$ onto the octahedral plane is normal to the yield locus in that plane (normality in the octahedral plane). Because only triaxial compression experiments were performed, neither formulation could be selected as being more representative of the true material behavior.

Pfifle, T.W., and P.E. Senseny. 1985. *Permeability And Consolidation Of Crushed Salt From The WIPP Site*. Topical Report RSI-0278. Rapid City, SD: RE/SPEC, Inc.

ABSTRACT: Ten hydrostatic compression time-dependent consolidation tests were performed on crushed salt specimens fabricated from Waste Isolation Pilot Plant (WIPP) mine-run salt. Eight tests were of relatively short duration, about four days, and were performed to assess the influence of maximum grain size and moisture on the permeability and consolidation of crushed salt. Four maximum grain sizes, 9.5 mm, 4.75 mm, 2 mm, and 1 mm, and two moisture contents, dry (-0.25%) and wet (4 to 5%), were considered. Two tests were of longer duration, about 35 days, and were performed to assess the influence of time on permeability and consolidation, as well as to determine if relatively short-term tests can be used to predict long-term consolidation. All tests were performed at 25°C and a stress of 1.72 MPa, except for one long-term test, which was performed at 25°C and 3.45 MPa. Results show that maximum grain size has relatively little effect on consolidation, but that at small maximum grain size permeability is reduced. The addition of 4 to 5 (by weight) % water dramatically increases consolidation and generally reduces permeability. Permeability is also reduced with time, but is probably related to the consolidation of the crushed salt rather than to grain

surface bonding that isolates the flow path. Permeabilities measured for all tests were in the 0.5- to 3.0-darcy range. Predictions of the long-term consolidation results from the results of short-term tests are fair; however, they underestimate the measured deformation. This difference could increase with time and result in poor predictions at long times.

Pickens, J.F., V.A. Kelley, and M. Reeves. 1988. "Evaluation of the Role of Fractures in Governing Solute Transport in the Culebra Dolomite at the Waste Isolation Pilot Plant (WIPP) Site," *EOS Transactions, American Geophysical Union*. Vol. 69, no. 44, 1177. (Abstract Only).

ABSTRACT: Multiwell convergent-flow tracer tests have been conducted as part of the hydrogeologic characterization of the Waste Isolation Pilot Plant (WIPP) Site. These tracer tests have been performed in fractured regions of the Culebra Dolomite Member of the Rustler Formation to assess double-porosity transport behavior under field conditions. Without estimates of these parameters, predictions of containment transport in a fractured-rock system, such as the Culebra Dolomite, are very uncertain.

Convergent-flow tracer tests have been performed with either 3- or 4-hole arrays at three locations exhibiting fracturing and double-porosity hydraulic behavior. Transport distances were from 21 to 43 m in the 7-m thick Culebra Dolomite. The transport of the conservative organic tracers from the tracer-addition wells to the pumping well at each location was simulated using the double-porosity flow and transport model SWIFT II. Tortuosity and matrix-porosity values determined from laboratory measurements on core samples were about 0.12 and 0.15, respectively. From interpretation of the field-measured breakthrough curves, the longitudinal dispersivity, effective matrix-block size, and fracture porosity values were about 1.5, 0.5, and 0.002 m, respectively. At each tracer-test site, at least one of the flow paths exhibited strongly fracture-dominated transport.

Regional-scale solute-transport simulations using SWIFT II were also conducted, representing transport from above the repository at the center of the WIPP Site to the defined accessible environment at a distance of 3.3 km. the Culebra Dolomite, though apparently heavily fractured, appears to possess excellent double-porosity solute-retention properties under undisturbed conditions for the system conceptualization, range of properties, and interpreted regional flow regime. The transport behavior, with respect to travel time and concentration breakthrough to the accessible environment, is very similar to that of a single-porosity system with a porosity equivalent to the fracture-plus-matrix porosity. The tracer-test interpretations and regional-scale solute-transport simulations demonstrate that while fractures in the Culebra are significant in controlling transport at the local tracer-test scale, they are of minor significance over large transport distances and times. On a regional scale, computed parameter sensitivities and importance coefficients have quantified that matrix porosity and fracture flux are the most important parameters in governing transport behavior. Fracture dispersivity, fracture porosity, matrix-block length, matrix diffusivity, and matrix tortuosity exhibit a decidedly secondary importance. Calculations are ongoing to determine the role of fractures in a breach of the WIPP Facility involving more rapid flow rates and steeper flow gradients as a result of a high-pressure fluid release.

Pietz, J. 1983. "An Integral Equation Approach to Modeling Radionuclide Migration in the Backfill Barrier." MS thesis. Albuquerque, NM: University of New Mexico.

ABSTRACT: The backfill barrier is a layer of bentonite clay designed to surround buried nuclear waste canisters. In the event of groundwater intrusion and canister breach, the proposed backfill barrier would sorb the radionuclides, thus inhibiting their transportation into the biosphere.

This report describes a new one-dimensional nonlinear model for radionuclide diffusion in the backfill barrier. The single species model was developed for both laboratory and in situ configurations and a general integral equation solution is detailed. This semi-analytical method of solution uses a Green's function, quadrature of the resulting nonlinear integral equation, and Newton's method or a similar algorithm to solve for the fixed point. The nonlinear model is more realistic than previous linear models. It may also be used to elucidate the nature of the retardation mechanism. Existence and uniqueness criteria for the model are also presented in this report.

To verify the technique, the integral equation method was tested with a linear problem. To verify the integral solution for larger values of the linear isotherm K_d , very small time and space steps were required. To avoid this and to handle the large multiplicative constants expected for nonlinear isotherms, a linear isotherm of appropriate size is subtracted from both sides of the partial differential equation. The time can then be rescaled, and much larger time steps can be used. Parameters then fall within the range of those verified.

Comparisons between linear and nonlinear isotherm solutions indicated that the deviation from linear isotherm behavior need not be dramatic to cause the nonlinear solution to differ substantially from the linear. Flux calculations at the outer boundary show that the difference between linear and nonlinear release rates can be as large as an order of magnitude. Graphs of the linear isotherms fitted to the nonlinear isotherms are presented along with all flux and concentration profile solutions so that the antecedent variation from linear behavior can be appreciated. Comparisons between hollow cylinder and cartesian solutions show that the hollow cylinder model may not be necessary if the canister inner radius is about 30 cm.

The trapezoid rule and Newton-Cotes five point formulas were used for the numerical integrations. Use was made of the sifting property of the Green's function, and then the nonconvergence of the Green's function at a certain point was avoided. Green's function values were stored in a three-dimensional array and were indexed by a time difference variable. The time step size, through calculation of the Green's function, and iterations in the fixed point algorithm, controlled central processing unit time requirements. Both the time and space step size affected the error in the integrations, although no blow-up instabilities due to time or space step sizes were encountered. For non-decay, dimensionless, nonlinear isotherm solutions, run times on a CDC 6600 computer never exceeded 2 min. A listing of the cartesian and hollow cylinder computer codes is included, and recommendations for advanced work are given.

Piper, A.M. 1973. *Subrosion in and About the Four-Township Study Area Near Carlsbad, New Mexico*. Oak Ridge, TN: Oak Ridge National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The available information for a four-township area in southeastern New Mexico was examined to determine how vulnerable the candidate area and storage horizon were to dissolution and related effects. A summary of the geologic history and evidence suggests that the area may have been affected by dissolution during a long history beginning in the Permian. Most effects are related to the time of Ogallala Formation deposition and the period since.

The rates of dissolution were calculated based on assumptions about the continuity of Permian beds, continuity of Ogallala, and projected intersections of the base of Ogallala with Permian units. As the present contacts or surfaces of these Permian units differ from the projections, a horizontal change of the dissolution "front" is calculated to be about 10 to 20 mi eastward during about 12 my. The average 900-1000-ft thickness reduction means about 80 ft/my vertical dissolution rate. These projections are similar to US Geological Survey projections. The stratigraphic horizon for disposal should be better investigated on all sides of the area. The hydrologic setting of fill material in areas of solution should be further investigated.

There should be an adequate safety factor from dissolution for the area for a period from thousands to a million years. Man's activities may be more of a threat to a disposal site. DWP

Piper, A.M. 1974. *The Four-Township Study Area Near Carlshad, New Mexico: Vulnerability to Future Subrosion*. Oak Ridge, TN: Oak Ridge National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Rocks in the Guadalupian Series contain brines developed from slow, intermittent circulation before the basin was tilted. These rocks were partially flushed by fresh water from the west, and the core of the Capitan aquifer was completely flushed after tilting. Differential heads for natural conditions are inferred to indicate that the fluid flow between rocks above the Rustler and below the Castile would be downward if connected. Current, disturbed hydrologic conditions accentuate this downward potential.

Available information has been summarized that indicates six different episodes with potential for subrosion (subsurface dissolution) of evaporites in the study area: Early- to Mid-Triassic, Jurassic, Cretaceous to early-Tertiary, late-Tertiary (Ogallala Formation), Quaternary (Gatuña Formation), and Quaternary to Recent (post-Gatuña).

There is little threat from subrosion from the north or south with a moderate threat from the east. The greatest threat is from the west. Calculated rates are about 300 ft/million years (my) maximum; assuming a factor of three for pluvial maximum rates, the vertical rate should be no more than 1000 ft/my. Site selection criteria should include a depth of more than 1000 ft below the top of the Salado, an area as close to topographic/hydrologic divide as possible, and an area at least five miles from the edge of the Capitan aquifer to avoid a possible large hydraulic drive for subrosion. The greatest threat from man's activities is mainly from drillholes with inadequate casing or plugging. The candidate location will have to be assessed for this potential threat. DWP

Popielak, R.S., R.L. Beauheim, S.R. Black, W.E. Coons, C.T. Ellingson, and R.L. Olsen. 1983. *Brine Reservoirs in the Castile Formation, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. WTSD-TME-3153. Albuquerque, NM: US Department of Energy.

ABSTRACT: ERDA-6 was drilled in 1976 to test a potential site for the Waste Isolation Pilot Plant (WIPP). The structure at that site was anomalous, and the bore hole flowed pressurized brine and gas. WIPP-12, at the present site for the WIPP, was deepened in 1981 and also encountered brine. Pressurized brine was also known to have been encountered in several hydrocarbon exploration drillholes in the northern Delaware Basin. By agreement with the State of New Mexico, the Department of Energy agreed to summarize the information about the reservoirs, determine their origin, and evaluate their potential impact on the WIPP. Analyses and interpretations from geology, hydrology, and geochemistry have been integrated for this study.

Major and minor elements of the brines are interpreted as evidence that these brines were trapped as ancient seawater in porous, soft sediment, with no modern meteoric water. The evaporites of the Castile Formation were deformed and fractured after being compacted and lithified. Open fractures within anhydrite accumulated mobile brine and gas. Pressure release by occupying open fractures decreased fluid pressure to less than lithostatic but more than hydrostatic pressure. The brine reacted with carbonates to produce dolomite, reduce Mg in the brine, and enrich the brine in ^{18}O . Methane gas was generated biologically for ERDA-6 and thermogenically in WIPP-12. Both brine reservoirs may be modeled as fractured heterogeneous systems. The volumes are estimated, within an order of magnitude, to be about 630,000

barrels (ERDA-6) and 17,000,000 barrels (WIPP-12). Less than 3% of the brine would flow to the surface from the low permeability microfractures holding the brine. Fewer large fractures form an extended infiltration gallery from the microfractures, resulting in initial vigorous flow. There is no chemical or hydraulic evidence to suggest the reservoirs at different locations are interconnected. The brines appear to be in chemical equilibrium with surrounding rocks, and the brines are stagnant.

The brine reservoirs appear to be local and isolated for several reasons. Hydraulic heads differ from one reservoir to another and are higher than local groundwater heads. Gas is contained within the reservoirs. Brine and gas chemistry differ among reservoirs. Reservoirs are encountered in separate areas, though drilling is extensive. The brine, gas, and rock appear to be in chemical equilibrium.

The brines pose little or no potential for halite dissolution. There is little potential for seepage upward through the intact evaporite section because of the extremely low permeabilities of the rock and evidence these reservoirs have been isolated for a period of at least a million years.

DWP

Powers, D.W. 1980 "Geologic Processes in Evaporites in the Northern Delaware Basin," *Abstracts, Annual Meeting of the Southwest Section, American Association of Petroleum Geologists, El Paso, TX, February 25-26, 1980*, SAND79-2478A. American Association of Petroleum Geologists, 50. (Abstract Only).

ABSTRACT: Permian evaporites of the northern Delaware Basin have been studied in detail for the Waste Isolation Pilot Plant (WIPP). The WIPP is proposed for the disposal of defense radioactive waste in the Salado Formation about 30 mi east of Carlsbad.

Bore holes in the northern part of the WIPP Site confirm unusual bed thicknesses and attitudes in the Castile Formation. The Castile is ordinarily nearly flat and consists of three anhydrites and two interbedded halites with a total thickness of about 1350 ft. WIPP-13 encountered 900 ft between the top of Castile and total depth about 50 ft into the lower anhydrite. The upper anhydrite dips as much as 40 degrees and contains a small recumbent fold. The thinning and structure also occur in the lower Salado. The same stratigraphic interval in WIPP-11 is 1230-ft thick. The upper anhydrite at WIPP-11 is very thin (<80 ft) and arches; the halite below it is over 900-ft thick. The lower Salado beds arch over the Castile. The top of the Salado Formation is not arched at either bore hole. Other Castile beds in each hole vary in thickness to lesser degrees.

The major hypotheses for the origin of these features are: deposition, dissolution, and halokinesis. Laminated anhydrite does not form on 40 degree dips. Dissolution residues do not account for thin halite beds. Delicate primary halite structures in the upper Castile in WIPP-13 should not survive later massive halokinesis. Syndimentary deformation is invoked as a possible explanation; investigations continue.

Powers, D.W. 1981. "Geologic Investigations of the WIPP Site: Overview and Issues," *Environmental Geology and Hydrology in New Mexico*. Eds. S.G. Wells, W. Lambert, and J.F. Callender. New Mexico Geological Society Special Publication No. 10; SAND81-0201C. [Roswell, NM]: New Mexico Geological Society. 119-122.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is planned for the disposal of radioactive defense waste in bedded salt of southeastern New Mexico. Since 1975, the geologic investigations have progressed through preliminary site selection and geologic characterization phases; we are now primarily concerned with the long-term geological processes that may

affect the site. These processes are grouped by hydrology, dissolution, geochemical, tectonic, and climatic mechanisms.

Issues regarding isolation at the WIPP are usually grouped according to these processes or human intrusion. Combinations of human and water intrusion are the most likely ways of releasing radioactivity from the WIPP to the biosphere. The issues thus raised concern how well the hydrology is or must be known, whether resources will attract unacceptable human intrusion, and how geologic processes may enhance release of radionuclides. Analysis of these processes so far does not indicate that radioactive material will be released from the repository in significant amounts. The main issue (what are the consequences of the WIPP to the biosphere?) is satisfied, in spite of the possibility that unusual events, such as human intrusion, can occur.

Powers, D.W., and R.G. Easterling. 1982. "Improved Methodology for Using Embedded Markov Chains to Describe Cyclical Sediments," *Journal of Sedimentary Petrology*. SAND81-0471J. Vol. 52, no. 3, 913-923.

ABSTRACT: Embedded Markov chains may be used to describe rock sequences in which a lithology is not or cannot be observed following itself. Such chains lead to a transition matrix with zeroes on the main diagonal. To test the hypothesis of randomness in an embedded Markov chain, we apply Goodman's model of quasi-independence and compare it to previously used methods (which we now believe are invalid) in the geological literature. Data in the literature show quite different results (depending on the original method) when reanalyzed in this way. We present tests for homogeneity, a spatial analogue to stationarity, of multiple embedded chains, and for symmetry and Markov chain order. Matrices from vertical or laterally spaced sequences can be tested for homogeneity, and conclusions can be drawn regarding variations of processes over space. A normalized difference is proposed as an aid in interpreting the difference between observed transition frequencies and transition probabilities estimated with a model of independence or quasi-independence.

Powers, D.W., and B.W. Hassinger. 1985. "Synsedimentary Dissolution Pits in Halite of the Permian Salado Formation, Southeastern New Mexico," *Journal of Sedimentary Petrology*. Vol. 55, no. 5, 769-773.

ABSTRACT: Mining operations in the Permian Salado Formation for the Waste Isolation Pilot Plant (WIPP) reveal filled pits in halite beds, which are interpreted as synsedimentary dissolution features. The pits range from a few centimeters to as much as 1-m wide and 1-m deep, and they clearly truncate thin, underlying beds. Halite hopper crystals and possible chevron halite structures occurring in the pits and continuous, undeformed bedding in overlying units demonstrate that the pits formed and filled before deposition of the overlying unit. Pseudomorphs of halite after gypsum swallow-tail crystals are part of the evidence that the dissolution pits formed in shallow water.

Powers, D.W., and L.R. Hill. 1977. "Site Evaluation for the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico," *Transactions of the American Nuclear Society, 1977 Winter Meeting, San Francisco, CA, November 27-December 2, 1977*. Vol. 27, 436-437. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is considered a full-scale demonstration of the handling and disposal of radioactive waste in bedded salt. It is anticipated that the WIPP will be converted into a full-scale repository for energy research and development

administration defense transuranic (TRU) waste. Experimental studies with high-level commercial waste are included, but there are no plans to dispose of such waste. The site in southeastern New Mexico was chosen after a site in Kansas was abandoned for technical and political reasons. The present WIPP Site was chosen after a nearby site was rejected because of structural complications.

The main criterion for the WIPP is the same as for a repository: that no hazardous amounts of radioactivity should escape from the site. The studies in progress are to determine the existing situation and "establish baseline information for evaluation of the study area as a repository." Initial studies completed for the WIPP establish predictable stratigraphy, dip less than 1 degree, salt-bed thickness of about 100 ft or more, depth less than 3000 ft, no throughgoing bore holes within one mile, and no active or prior mining within one mile of the facility boundaries. Seismic reflection, electrical resistivity, and drilling are major field activities.

Studies of long-term geologic and hydrologic stability continue. Hydrologic programs concentrate on the present regime and possible effects due to climatic change. Salt-solution rates and locations are being examined, and a data base for radionuclide migration is being established. Regional geologic problems include an igneous dike intruded into the evaporites and breccia pipes formed by solution. Geophysical techniques, bore holes, mapping, satellite imagery, precision leveling, and laboratory studies are utilized. A report on site evaluation is scheduled for June 1978. DWP

Powers, D.W., and R.M. Holt. 1984. "Depositional Environments and Dissolution in the Rustler Formation (Permian), Southeastern New Mexico," *Abstracts with Programs, Geological Society of America, 47th Annual Meeting, Reno, NV, November 5-8, 1984*, Vol. 16, no. 6, 627. (Abstract Only).

ABSTRACT: The Rustler Formation culminates Permian evaporite deposition in the Delaware Basin. It consists of sulfates, dolomite, mudstone, argillaceous halite, and halite. The Rustler decreases in thickness from east to west in the Waste Isolation Pilot Plant (WIPP) Site area; the thinning has been attributed to dissolution.

Recent mapping of a shaft at the WIPP Site indicates that the Rustler consistently displays structures commonly associated with depositional environments. Brecciated, slumped, chaotic structures, and other features associated with dissolution/collapse were not observed. There was no evidence of karst channel development in either sulfate or carbonate units. Features from the Rustler, by lithologic association, include:

- clastics: laminar to fine beds with scour, fill, and clay drape; cross-beds; erosional surfaces and channels with lag; soft sediment deformation; rip-up clasts; fining upward units; invertebrate fossils.
- carbonates: laminated beds with scour fill; organic-rich laminated zones of probable algal origin; large climbing ripples; possible ripple cross-laminations.
- sulfates: laminar to fine beds of (?) algal origin; swallow-tail gypsum; desiccation shrinkage; enterolithic features.
- halites, argillaceous halites, and halitic mudstones: scour surfaces, displacive halite; hopper halite crystals.

The occurrence of these features in the shaft, where dissolution was presumed to have occurred, requires reevaluation of the extent of dissolution in the Rustler. The features and their stratigraphic sequence are interpreted as the result of a sabkha interacting with saline to freshwater mud flats.

Powers, D.W., and W.D. Weart. 1979. "Status of Siting for the Waste Isolation Pilot Plant," *Transactions of the American Nuclear Society, San Francisco, CA, November 11-15, 1979.* SAND79-1329A. Vol. 33, 141-142. (Abstract Only).

ABSTRACT: The Department of Energy (DOE) is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The current mission proposed for the WIPP by the DOE is: geologic isolation of defense transuranic (TRU) waste; experimental investigation of interactions between salt and various high-level waste forms; provision of an option for demonstrating isolation of a limited number (< 1000) of spent fuel assemblies.

This latter option is presently opposed by the cognizant Congressional committees and is under discussion between the DOE and Congress.

All wastes in the WIPP will be retrievable for a period of time—5 to 10 years for TRU waste and 15 to 20 years for spent fuel. The high-level waste for experiments will be retrieved upon conclusion of the associated experiments. The present schedule calls for start of construction in late 1981 and waste acceptance in 1986.

Siting or site studies for the WIPP may be grouped into three general phases: preliminary site selection or identification; site characterization; and site confirmation. When Sandia Laboratories (SNL) began work on WIPP in 1975, both rock type and general location were specified by the DOE (and prior agencies). After the initial site was shown to be unsuitable, SNL began with phase 1 and made a preliminary selection of a new site in bedded salt in New Mexico for detailed characterization. Since 1976, SNL has been primarily concerned with characterization of this site in an area known as Los Medaños. In 1978, a recommendation was made to the DOE by SNL that development of the site continue. The transition from phase 2 to phase 3 is now in progress.

Geological site characterization activities concern the present geology and hydrology of the site and surrounding region. This "snapshot" of the site shows that beds of suitable thickness, purity, structure, and stratigraphy are present at depths of about 2100 to 2700 ft, the hydrology of the site presents no operational problems, and the structure and stratigraphy of the site are acceptable. The very low level of tectonic activity in the area will alleviate design requirements for earthquake activity.

The site characterization indicates some conflict with potash and hydrocarbons within the buffer zones established for the WIPP. The estimated amount of these reserves within WIPP zones I-III, which might not be exploited if the WIPP is built, are about 3.5 million tons of potash product (K_2O); 23.5 billion cubic feet of gas; and 350 thousand barrels of distillate. These resources are small compared to US resources but may be considered as an enticement for future generations. Studies now under way may show that these resources can be developed without jeopardy to the repository and/or significant hazard to mankind. One scenario, assuming an open bore hole through the repository and conservative aquifer parameters, indicates that a hypothetical man drinking water from the exit point would, over a 50-year lifespan, accumulate a whole body dose much less than the annual whole body dose due to natural causes.

Site investigations are now concentrating on long-term geological processes to aid safety assessment. The processes of primary interest are tectonics, climatology, hydrology, and geochemistry. The effects of individual processes or combinations of processes over time must be known or sufficiently bounded to conduct a safety assessment prior to conversion to a repository. Features that are related to the processes are breccia pipes and regional salt dissolution, salt flow, and the interactions of rock and waste. The rates and conditions of formation for these features are known well enough that no obvious threat to the long-term integrity of the WIPP Site exists. Breccia pipes are solution features that have not been found

at the site; preliminary studies show these features not to be forming today, but a better understanding of their origin is required for long-term assessment. An area with apparent disturbed stratigraphy in the northern sector of the WIPP Site is still under investigation. The feature, indicated through seismic reflection surveys, appears to affect primarily the Castile Formation and is probably Permian in age. The feature will be drilled to determine the nature and age of the process that formed the feature.

There is confidence then that the site meets the criteria with the exception of some conflict with natural resources. While it is possible that future repository mining or improved understanding of geologic processes could reveal aspects undesirable for a repository, the prospects are unlikely and a recommendation can now be made to proceed with WIPP planning based on the Los Medanos site.

Powers, D.W., M. Martin, and R.M. Holt. 1988. "Siliciclastic-Rich Units of the Permian Salado Formation, Southeastern New Mexico," *Abstracts with Programs, Geological Society of America, Denver, CO, October 31-November 3, 1988*, Vol. 20, no. 7, A174. (Abstract Only).

ABSTRACT: Siliciclastic-rich beds of the Salado include muddy halite and halitic siltstones. Many of these beds are continuous over an area that is nearly comparable to the sulfatic marker beds of the Salado.

Muddy halite units can be traced in geophysical logs, cores, and underground workings over hundreds of square km. In underground workings, a muddy halite unit from the lower Salado shows considerable small-scale disruption of thin clastic units. These disrupted sediments appear similar to modern exposed halite surface deposits disrupted by precipitation. Clastic material was probably disrupted originally over the surface by influxes of brine or fresh water. The clastics settled on an irregular surface, were covered by a thin layer of halite and then were further disrupted by rainfall after desiccation. Repetition provides units with excellent gross continuity but little small-scale continuity.

Predominantly clastic beds in the upper Salado also are continuous over the hundreds of square km. The Vaca Triste Sandstone member shows bedding and channeling, as well as halite growth textures. Other sandy to silty beds in the upper Salado show evidence of clastic transport and subaerial exposure.

The great continuity and extent of these clastic beds are consistent evidence of general flooding and transport of clastics within or on top of dense brines. These beds were exposed to, and modified by, rainfall and reflooding.

Powers, D.W., S.J. Lambert, S-E. Shaffer, L.R. Hill, and W.D. Weart, eds. 1978. *Geological Characterization Report, Waste Isolation Pilot Plant (WIPP) Site, Southeastern New Mexico*, SAND78-1596. Albuquerque, NM: Sandia National Laboratories. Vols. 1-2.

ABSTRACT: The *Geological Characterization Report (GCR)* is a two-volume summary of the geological background and studies of the geology through preliminary screening to site selection and initial characterization. Chapter 1 is an executive summary (39 pages) organized by each chapter. This abstract substitutes for the long executive summary.

Chapter 2 of the GCR summarizes the history of studies of bedded salt for a repository that led to locating the WIPP Site in southeastern New Mexico. Geological and sociological criteria applied to site selection are reviewed in Chapter 2, and some of the geological methods are broadly discussed.

The regional geology (Chapter 3) of the area was prepared mainly from existing sources of information through more than 100 years of public and industry studies of the Delaware Basin and surrounding areas. Site geology (Chapter 4) integrates certain relevant information from regional geology and site-specific data from WIPP-related studies including surface studies, drilling, and seismic reflection data. The studies indicated that the geology was consistent with general criteria; unexpected conditions included deformed evaporites north of the general site area. Seismological information (Chapter 5) reviewed the historical evidence of events nearer the site, as well as continuing seismic activity southeast of the site near Kermit, TX. The activity near Kermit is believed to be related to secondary hydrocarbon recovery activity rather than active tectonic processes. The hydrological system (Chapter 6) includes the units underlying evaporites as well as shallow water bearing strata. The potentiometric levels in underlying and overlying units are comparable. Dissolution areas at Nash Draw produced the "brine aquifer" flowing southwesterly to the Pecos River. Geochemical studies (Chapter 7) range from mineralogical and petrological studies to analyses of brine chemistry including stable isotopes and uranium-disequilibrium methods. The evaporite section has been mainly stable for 200 million years or more. Pressurized brine in the Castile Formation appears to have no connection with other groundwaters and has apparently not moved significantly for about 800,000 years. Resources at the site (Chapter 8) range from surface construction materials to potash resources and possible hydrocarbons. Miscellaneous possible resources could include lithium (in brine), sulfur, gypsum, uranium, and halite. At the time of evaluation, the site area included economically mineable langbeinite reserves and possibly potash. Hydrocarbon resources have been estimated by differing methods. In all resources, the final decision regarding exclusion areas for exploitation will affect the estimates of loss of resources. Studies of thermomechanical properties of site rocks and radionuclide sorption related in Chapter 9 include some of the early data about thermal conductivity and laboratory experiments on rock mechanics. Rocks from southeastern New Mexico were demonstrated to have highly variable sorptive capacity for various radionuclides in laboratory experiments. Continuing studies for the WIPP (Chapter 10) focus on processes to assess safety, as site selection and characterization are considered largely completed. DWP

ANNOTATION: The *GCR* was conceived in late 1977 as a stand-alone document that would be a principal source of site information for the *Environmental Impact Statement* (US Department of Energy, 1980a). The *GCR* was originally titled the *Site Characterization Report (SCR)*; the title was changed for the final report because the scope of the report was more restricted than is implied by "site characterization." The *GCR* was intended as a summary of the geological background of the WIPP Site as well as the site specific studies for the WIPP through an effective date of August 1978.

The *GCR* was written, reviewed extensively, edited, printed, and distributed in the 12 months between January and December 1978. A number of individuals wrote chapters and drafts of chapters; Bechtel employees wrote many sections and provided drafting support. Sandia remained responsible for overall direction and editing, and several sections were written by Sandia employees.

The *GCR* became the first published version of a step formally incorporated into the plans for studying and reporting on investigations of proposed radioactive waste repository sites. These will be more elaborate than the two volume *GCR*; the site characterization plan (SCP) for the Yucca Mountain Project (Nevada) has been prepared in 8 volumes and in an overview comprising several thousand pages. The *GCR* also became one of the more widely cited source documents for the WIPP Project.

A successor document (Lappin, 1988a) brings certain site investigations up to date for the period 1983-1987; it includes many of the data useful in performance assessment.

An important section, written mainly by W. Weart, summarized the site selection criteria and factors applied to the WIPP Site through stages leading up to selection of the site. These

criteria are useful for screening and are to be distinguished from the decisions about establishing a repository, which will be based on performance assessment criteria.

Preece, D.S. 1986. "Three Dimensional Modeling of the Wedge Pillar Portion of the WIPP Geomechanical Evaluation (Room G) In Situ Experiment," *Rock Mechanics: Key to Energy Production, Proceedings of the 27th US Symposium on Rock Mechanics, University of Alabama, Tuscaloosa, AL, June 23-25, 1986*, Ed. H.L. Hartman. SAND86-0412C. Littleton, CO: Society of Mining Engineers, Inc. 917-922.

ABSTRACT: A three-dimensional finite-element program (JAC3D) has been used to calculate deformation and stress distribution prior to construction of the Waste Isolation Pilot Plant (WIPP) wedge pillar experiment (Room G). Along the pillar, horizontal closure of drifts increases. Vertical closure decreases away from the tip of the pillar. The drift walls shift parallel to the drift axis mostly near the wedge tip of the pillar, and the shift drops off rapidly with distance from the wedge tip. The behavior at a station where the wedge pillar is 1.7 m wide was calculated with a two-dimensional plane strain model and the results compare well with JAC3D model calculations. Vertical and horizontal closures predicted using the JAC3D are, respectively, 1.5 and 2 times the closures calculated from two-dimensional plane strain model of a single drift including stratigraphic information. Calculated stresses, assuming instantaneous drift creation, indicate failure at the pillar wedge tip. The propagation of failure is not quantified, as the model did not include a failure criterion. Predicted stresses are probably higher than is expected from realistic simulation of mining. DWP

Preece, D.S. 1987. *Pretest 3-D Finite Element Modeling of the Wedge Pillar Portion of the WIPP Geomechanical Evaluation (Room G) In Situ Experiment*. SAND87-0472. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Pretest three-dimensional finite-element calculations have been performed on the wedge pillar portion of the Waste Isolation Pilot Plant (WIPP) geomechanical evaluation experiment. The wedge pillar separates two drifts that intersect at an angle of 7.5 degrees. The purpose of the experiment is to provide data on the creep behavior of the wedge and progressive failure at the tip. The first set of calculations utilized a symmetry plane on the center line of the wedge, which allowed treatment of the entire configuration by modeling half of the geometry. Two three-dimensional calculations in this first set were performed with different drift widths to study the influence of drift size on closure and maximum stress. A cross section perpendicular to the wedge was also analyzed with two-dimensional finite-element models and the results compared to the three-dimensional results. In another set of three-dimensional calculations, both drifts were modeled but with less distance between the drifts and the outer boundaries. The results of these calculations are compared with results from the other calculations to better understand the influence of boundary conditions.

Preece, D.S., and W.R. Wawersik. 1982. "Finite Element Derived Stress and Strain Fields in Triaxial Creep Test Specimens," *EOS Transactions, American Geophysical Union*, Vol. 63, no. 45, 1095-1096. (Abstract Only).

ABSTRACT: In recent years, underground storage programs have been developed for placing nuclear wastes and hydrocarbons in salt formations. Design calculations for these programs rely heavily on material data, which are determined in triaxial creep experiments on cylindrical specimens in the laboratory. To ensure the validity of these data, finite-element simulations were carried out for standard specimens ($L:D = 2$) using a power-law creep model. Stress, strain, and strain-rate fields were computed as a function of time (sample shortening) at

constant applied effective stress in the presence of frictional restraints between the steel loading pistons and the salt. Large changes in specimen dimensions were considered to evaluate the influence of punching of the steel pistons into the sample ends. Calculated data are used to interpret transients in creep tests following changes in applied stress or temperature. The results of the finite-element simulations are also used to determine when strain rates, which are inferred from changes in sample lengths and diameters, become meaningless.

Results of the finite-element computations will be demonstrated in a color movie of the predicted changes in effective stresses with time.

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RamaRao, B.S., and M. Reeves. 1990. *Theory and Verification for the GRASP II Code for Adjoint-Sensitivity Analysis of Steady-State and Transient Ground-Water Flow*. SAND89-7143. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Calibration of a numerical model of the regional groundwater flow in the Culebra Dolomite at the Waste Isolation Pilot Plant in southeastern New Mexico has been performed by an iterative parameter-fitting procedure. Parameterization has been secured by choosing to assign the transmissivity values at a limited number of selected locations, designated as pilot points. The transmissivity distribution in the model is derived by kriging the combined pool of measured and pilot-point transmissivities. Iterating on the twin steps of sequentially adding additional pilot point(s) and kriging leads to the model of required accuracy, as judged by a weighted least-square-error objective function. At the end of calibration, it must be ensured that the correlation structure of the measured transmissivities is broadly preserved by the pilot-point transmissivities. Adjoint sensitivity analysis of the model has been coupled with kriging to objectively provide the optimal location of the pilot points during an iteration. The pilot-point transmissivities have been adjusted by modeler's judgment incorporating information, where available, on local geologic conditions and large-scale hydraulic interference tests, to minimize the objective function.

Adjoint methodology offers an efficient algorithm for calculation of the required parameter sensitivities. It separates the analysis into two distinct stages, with the first one related exclusively to the objective function, and the second one exclusively to the parameter of investigation, with the adjoint-state function from the first stage providing the link between the two stages. Implementing this philosophy, the equations of the adjoint sensitivities have been derived, keeping the partial variations with respect to pressure and parameters distinct. The adjoint-state function is interpreted to be an impulse-source response function in the transient state and a unit-source-rate influence function in the steady state. A three-dimensional finite-difference code, GRASP II, has been built to implement the adjoint sensitivity analysis, offering a wide range of options in objective functions and sensitivity parameters. The code has been extensively verified, by comparing the results with the sensitivity coefficients derived analytically and with those from a perturbation approach.

In this report, the theory and development of adjoint-sensitivity analysis and the verification of the numerical code are treated. A case study for the application of this coupled kriging-and-adjoint-sensitivity approach to calibration of the model for the site mentioned has been completed. The application demonstrates the usefulness of the present approach to calibration, particularly while handling a combination of the steady-state and transient-head data.

Ramey, D.S. 1985. *Chemistry of Rustler Fluids*. EEG-31. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: US Geological Survey (USGS) water chemistry data for the Rustler Formation in 20 test holes near the Waste Isolation Pilot Plant (WIPP) show three chemically separate fluid-bearing zones at the site that progressively merge to the west toward Nash Draw. Rustler-Salado contact fluids are nearly saturated with respect to halite; magnesium is the dominant cation east of the WIPP Site in a region that may correspond to the limit of salt dissolution. The Culebra Dolomite Member of the Rustler Formation areally exhibits three chemical zones ranging from sodium chloride brines in the east to a moderately saline calcium sulfate water to the west. The Culebra is undersaturated with respect to halite. The Magenta Dolomite Member of the Rustler Formation fluids are dominated by sodium chloride with a few wells having sulfate as the dominant anion. The water chemistry program must obtain representative

and replicable data to understand the chemical changes along the proposed flow path for Culebra groundwater. DWP

Randall, W.S., M.E. Crawley, and M.L. Lyon. 1988. *1988 Annual Water Quality Data Report for the Waste Isolation Pilot Plant, March 1988*. DOE-WIPP 88-006. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is a Department of Energy (DOE) research and development facility designed to demonstrate the safe disposal of transuranic (TRU) radioactive waste resulting from the nation's defense programs.

The Water Quality Sampling Program (WQSP) supports four major programs for the WIPP: Site Characterization, Performance Assessment, the Radiological Baseline Program, and the Ecological Monitoring Program.

Results from 24 WQSP wells sampled from January through November 1987 are presented in this report. Water quality data from two water-bearing zones have been collected. These zones are the Culebra and Magenta Dolomite Members of the Rustler Formation. Analytical results from the sampling program include field chemistry data, general water quality parameters, trace metals, Environmental Protection Agency (EPA) priority pollutants, dissolved gases and selected reduction oxidation (redox) couples.

In addition to the 24 WQSP wells mentioned above, nine private wells were sampled for primary and secondary drinking water parameters and radionuclides. Six wells were analyzed for trace metal concentrations and priority pollutants, as well as general water quality parameters and radionuclides. The water samples from the private wells came from three water-bearing zones, the Santa Rosa Sandstone of the Dockum Group, the Dewey Lake Red Beds, and the Culebra Dolomite Member of the Rustler Formation. In some instances, where no reliable well completion logs are available, it was not clear which actual water-bearing zone the well was completed in. It is hoped that with the continuing search for records and analysis of the water samples the source of the water may be determined.

The private wells and the WQSP wells are scheduled to be sampled three times before the first receipt of waste. The only exception to this is WIPP-29, which has been dropped from the overall program.

A comprehensive Water Quality Baseline report covering data from all three rounds, collected and analyzed prior to the receipt of waste, will be written and issued some time in the year 1989.

Ratigan, J.L. 1979. *Determination of Barrier Pillar Thickness in Pre-WIPP Dedicated Area*. Technical Letter Memorandum RSI-0029. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The pre-Waste Isolation Pilot Plant Dedicated Area in the lower level is laid out with two distinct experimental areas each consisting of three rooms separated by two pillars. The mechanical interaction between any experiments is assumed to be negligible. Barrier pillars with a width set at 18.3 m (60 ft) have been proposed between any two experimental areas. This study evaluates the mechanical interaction between the two experiments for various barrier pillar thicknesses.

Barrier pillars with widths of 18.3 m (60 ft), 27.4 m (90 ft), and 36.6 m (120 ft) have been evaluated. Two models were used. In model M1, the geometry of one experimental area was modeled explicitly and the other experimental area was replaced with a material that had a modified deformation modulus. Model M2 assumed one experimental area is a wide room without pillars, which is a very conservative assumption. The results indicate M1 more accurately represents the experimental area. The simulation shows "the 18.3-m (60-ft) barrier pillar is adequate in minimizing mechanical interactions to acceptable levels to satisfy the objectives of the individual experiments in the two areas." DWP

Ratigan, J.L., and L.L. Van Sambeek. 1978. *Elastic/Plastic Simulation of the Mississippi Chemical Company Room and Pillar Mining Operation*. Technical Letter Memorandum RSI-0012. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The room-and-pillar mining operation of the Mississippi Chemical Company Potash Mine in New Mexico was simulated by characterizing the rock as an elastic/plastic material. The objectives of the analysis were to simulate the mining system with a finite-element computer code (SPECTROM-11) and to determine whether horizontal instrumentation holes could be drilled in the pillars, given the stress state after mining.

Several assumptions are not representative of real conditions. These rocks are expected to behave as viscoelastic rather than elastic/plastic materials. The tensile strength and the strength of the rock at large, compressive mean stresses are overestimated. The simulation suggests that horizontal instrumentation holes will be difficult to drill due to vertical stresses in pillars, and the instruments would have to be installed near the center. The viscous character of these rocks and the failure strength need to be determined as they are significant in the simulation. DWP

Rechard, R.P., H. Iuzzolino, and J.S. Sandha. 1990. *Data Used in Preliminary Assessment of the Waste Isolation Pilot Plant (1990)*. SAND89-2408. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report documents the data available as of August 1990 and used by the Performance Assessment Division of Sandia National Laboratories in its December 1990 *Preliminary Performance Assessment of the Waste Isolation Pilot Plant (WIPP)*. Parameter values are presented in table form for the geologic subsystem, engineered barriers, bore-hole flow properties, climate variability, and intrusion characteristics. Sources for the data and a brief discussion of each parameter are provided.

Rechard, R.P., W. Beyeler, R.D. McCurley, D.K. Rudeen, J.E. Bean, and J.D. Schreiber. 1990. *Parameter Sensitivity Studies of Selected Components of the Waste Isolation Pilot Plant Repository/Shaft System*. SAND89-2030. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This status report presents preliminary analyses of flow through the rooms, drifts, seals, and shafts of the Waste Isolation Pilot Plant (WIPP). The purpose of these analyses is to evaluate the importance of various components and parameters of the transuranic waste repository. These analyses are presented to show the current status of repository/shaft system modeling, and to provide input for evaluating proposed engineered modifications to the waste and rooms to ensure compliance with the Environmental Protection Agency's *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Waste*. Detailed descriptions are given for nine

computational models of the WIPP repository for either undisturbed or human-intrusion conditions. Some models are refined versions of earlier models; others include rudimentary studies of an additional phenomenon, flow of generated gas. The models of an undisturbed repository substantiated the results of earlier models by showing that no waste leaves the vicinity of the disposal area in 10,000 years. The models that studied gas flow agreed with this position; however, the models are too rudimentary to permit conclusive statements. The five models of the human intrusion event explored the importance of parameters (e.g., waste permeability and Salado Formation heterogeneity) that influence the flow of brine through the waste, establishing a base for understanding the behavior of the waste, disposal rooms, drifts, and interbeds in the host rock.

Reed, E.L., & Associates. 1977. *Detailed Hydrologic Drilling and Testing, WIPP Study Area, Los Medanos, Southeastern New Mexico*. Midland, TX: Ed. L. Reed & Associates. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: WIPP hydrologic testing is designed to examine the stability of the Salado Formation and the potential for dispensing radionuclides through aquifers in the Rustler and Dewey Lake Formations. Hydraulic gradients and rate of fluid movement must be determined. Six test holes (H-1, H-3, P-14, P-15, P-17, and P-18) to the top of Salado exist, and holes at location H-2 are being constructed to individually test fluid-bearing zones at the top of Salado, Culebra, and Magenta. Preliminary tests show that permeabilities are extremely low and, consequently, long-term tests and monitoring will be necessary. The three-hole configuration at H-2 permits long-term studies without interference between zones and will also allow for testing single zones with closely spaced boreholes.

Recommended tests include: dual holes for injection tests and monitoring of Dewey Lake to calculate transmissivity, radioactive tracer injection and monitoring, and drilling a line of Salado-Culebra testholes between P-14 and Nash Draw to evaluate westward changes in the brine aquifer and the Culebra. DWP

ANNOTATION: The recommended tests have not been performed.

Reeves, M., V.A. Kelley, and J.F. Pickens. 1987. *Regional Double-Porosity Solute Transport in the Culebra Dolomite: An Analysis of Parameter Sensitivity and Importance at the Waste Isolation Pilot Plant (WIPP) Site*. SAND87-7105. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A high-transmissivity fracture-controlled path is assumed, for modeling purposes, to provide the means for transport of infinitely long-lived radionuclides through the Culebra Dolomite Member of the Rustler Formation to the accessible environment at the Waste Isolation Pilot Plant (WIPP) Site, following a breach that does not disturb the existing head potentials within the unit. Both matrix diffusion and sorption retard the transport. Parameter ranges and base-case values depict the uncertain properties of the Culebra while simulations with SWIFT II exhibit the corresponding ranges in travel time, the performance measure adopted for this report. Consistent with the paucity of the double-porosity data base, model assumptions are kept simple and parameter ranges relatively large. Thus, computed travel times may be unrealistic and should not be quoted apart from the model assumptions. Computed parameter sensitivities and estimated parameter importance, however, should provide valuable guidance to the current site-characterization program at the WIPP Site. The report demonstrates the importance of the rate of fluid flow within the fractures and the relative capacity of the rock matrix for the retention of radioactive contaminants. It also

demonstrates the relative unimportance of some of the matrix kinetic parameters that relate to the matrix diffusion time. The report underscores the importance of hydraulic and tracer tests, particularly in the southeast sector of the WIPP Site. Such tests would further confirm the flow and transport conceptualization, determine the extent of site heterogeneity, and reduce uncertainty in the transport properties.

Register, J.K. 1980. *Subsurface Hydrology of Strata Overlying the Salado Formation at the Waste Isolation Pilot Plant Site*. TME 3059. Albuquerque, NM: US Department of Energy. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The contact between the Rustler and Salado Formation, the Culebra Dolomite Member, and the Magenta Dolomite Member are fluid-bearing zones above the Salado Formation. Nearly saturated brines are found in Nash Draw at the Rustler-Salado contact. The Culebra Dolomite Member is highly variable in permeability; it contains water in some areas and not in others. The water in the Culebra is generally too saline for human consumption and is marginal for livestock in most areas. The Magenta Dolomite Member bears fluid in some places, but low transmissivity provides slow recharge to wells. A thin sandy zone in the Dewey Lake Red Beds in H-2 was moist but could not be tested. The H-5 complex, northeast of the site, indicated the lower 2 ft of the Santa Rosa Sandstone was saturated. The yield was below the limit of detection (0.1 gal/min). Three potash holes drilled for WIPP in the eastern part of the site indicated water-bearing zones in the Santa Rosa based on gamma-ray and neutron logs. DWP

Register, J.K. 1981a. *Brine Pocket Occurrences in the Castile Formation, Southeastern New Mexico*. TME 3080. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Castile Formation, which underlies the Salado Formation and Waste Isolation Pilot Plant (WIPP) Facility horizon, is composed of interbedded thick halite and laminar anhydrite-carbonate. The Castile and Salado have very low porosity and no permeability. "Pockets of brine and associated hydrogen sulfide gas have been encountered in the Castile Formation by various oil drilling companies and Sandia National Laboratories. . . . Of the 62 deep bore holes drilled into the Castile, 10 (16%) penetrated pressurized brine reservoirs. . . . Nine of these ten occurrences were associated with the deformation front abutting the Capitan Reef. Of these nine, eight were associated with known anticlinal structures in the Castile. The remaining [tenth] occurrence (Belco-Federal), located more centrally in the basin, about three miles southwest of the WIPP Site, was also closely related to an anticline. All brine encounters in the Castile, except AEC-7, flowed to the surface with initial rates estimated between 600 and 20,000 barrels per day. Initial downhole pressures were estimated to range from 1630 to 2322 psi."

Geochemical data from brine reservoirs differ markedly from basin aquifers, indicating no connections. The brine chemistry is consistent with dissolving halite, but is inconsistent with expected chemistry of Permian water or fluid from dehydrating gypsum. The brine residence time, based on uranium isotope disequilibrium, is more than 500,000 years.

The absence of evaporite structure lowers the possibility of intersecting a brine reservoir in a drill hole or construction of a shaft for site and preliminary design validation. DWP

Register, J.K. 1981b. *Rubidium-Strontium and Related Studies of the Salado Formation, Southeastern New Mexico*. SAND81-7072. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Salado Formation, a member of the Ochoan series, is a bedded salt deposit found in the Delaware Basin of southeastern New Mexico and west Texas. It is comprised primarily of halite and sylvite with minor amounts of sulfate minerals. Rubidium-strontium age determinations of the evaporite minerals in the Salado indicate an age of final equilibration of 214 ± 15 my. This age is fairly consistent with the geologic age of the formation, precluding substantial alkali-alkaline earth migration since deposition. Polyhalite and anhydrite samples from the Salado give Sr/Sr values of about .7078, which are consistent with reported values for Permian sea water. The rare earth element (REE) and trace-element concentrations of the polyhalite and anhydrite samples are very low, reflecting the composition of sea water.

Rubidium-strontium age determinations of the clay minerals extracted from the salt suggest a minimum age of 390 ± 77 my. This age probably represents the minimum age of the provenance of the clay minerals. The REE and trace-element concentrations, as well as the mineralogy of the clay minerals, indicate a detrital origin for the clay minerals with some clay/brine interaction. Clay minerals seem generally depleted in the light REE (relative to North American shale), which most likely were replaced by Ca^{2+} and Na^+ from the evaporitic brines.

ANNOTATION: This SAND document is reprinted from Register's MS thesis from the University of New Mexico in 1979.

Register, J.K., and D.G. Brookins. 1980. "Rb-Sr Isochron Age of Evaporite Minerals from the Salado Formation (Late Permian), Southeastern New Mexico," *Isochron/West*. No. 29, 39-42.

ABSTRACT: Isotopic work on evaporites indicates young ages for halide and sulfate minerals by K-Ar and Rb-Sr methods are due to post formation, open-system conditions. Metamorphic events or episodic and/or continuous loss of radiogenic ^{40}Ar and ^{87}Sr have been suggested. Rb-Sr isochron ages (214 ± 15 my) for 41 samples including sylvite-halite mixtures, polyhalite-rich samples, and anhydrites, agree well with K-Ar dates (average 210 my) for primary anhydrites. These dates do not support continuous or episodic loss of ^{87}Sr or ^{40}K after 200 my except near a Tertiary age igneous intrusion. The dates may reflect final potash ore formation or diagenetic-epigenetic events in the Triassic. Five samples, mainly from nine wells, fall well off the isochron line and were omitted. The Rb-Sr isochron changes to 199 ± 20 my if these data are included. DWP

Register, J.K., and C.C. Little. 1983. "Testing and Significance of Pressurized Fluid Reservoir Encounters for the Site Characterization Process for Radioactive Waste Disposal Facilities," *Waste Management 83, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, February 27-March 3, 1983*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 377-385.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Project is a US Department of Energy (DOE) research and development activity to demonstrate safe disposal of transuranic (TRU) waste from the nation's defense programs. During the past seven years, an extensive site characterization effort has been conducted in the Los Medanos area of southeastern New Mexico. A portion of the effort addressed the mode of occurrence and origin of flowing artesian brine reservoirs known to exist in the northern Delaware Basin (the WIPP Site area). Investigation of these features was performed by comprehensive geological, hydrological, and geochemical testing in two DOE bore holes that intersected reservoirs. The testing program

plan was found to be a technically sound and cost-effective method by which to develop and support hypotheses relative to the characteristics, genesis, and history of the reservoirs. Similar testing programs would be applicable to the characterization of similar features at other potential waste disposal sites in bedded salt. The interpretation of the test results indicates that the brine reservoirs in the northern Delaware Basin should have no effect on the integrity of the WIPP Facility.

Register, J.K., D.G. Brookins, M.E. Register, and S.J. Lambert. 1980. "Clay Mineral-Brine Interactions During Evaporite Diagenesis: Lanthanide Distribution in WIPP Samples," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, MA, November 27-30, 1979*. Ed. C.J.M. Northrup, Jr. SAND79-1284C. New York, NY: Plenum Press. Vol. 2, 445-452.

ABSTRACT: Clay minerals are considered for overpack materials around canisters of radioactive waste disposed of in salt beds. To examine their chemical behavior, samples of clay minerals from evaporite rocks in southeastern New Mexico were analyzed for clay type and chemistry using scanning electron microscopy (SEM) neutron activation analysis (NAA), x-ray diffraction (XRD), and supporting techniques. Interlayered chlorite-saponite is the most common clay mineral; it is interpreted as an incomplete alteration product of the interaction of Mg-rich brine with detrital, trioctahedral montmorillonite. Fourteen clay samples from water-insoluble fractions were analyzed for trace elements and lanthanides. Trace elements are higher in clay minerals than in sulfate samples, indicating both the detrital origin and insignificant loss of trace elements due to interaction with brines. Trace elements are concentrated as oxide coatings on evaporite grains or as clay mineral inclusions. Nine lanthanide elements in clay minerals are distributed in a pattern similar to pelagic sediments, but the pattern differs significantly from sea water. Clay minerals exchanged little of the lanthanides interacting with brines. Heavy rare earth elements (REEs) are enriched from clay mineral sources as chlorite-saponite formed from smectite. Sea water is not the source as its absolute concentration is about six orders of magnitude lower than the clay minerals. Light REEs are slightly depleted as they are incorporated into evaporite minerals or oxide-hydroxide coatings. The lanthanides are retained in the detrital clay phase during diagenesis. "Applied to possible overpack-brine interactions, the argument can be made for retention of both lanthanides and actinides in the overpack material closest to the canister in the presence of brine." DWP

Rehfeldt, K. 1984. *Sensitivity Analysis of Solute Transport in Fractures and Determination of Anisotropy Within the Culebra Dolomite*. EEG-27. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Data from the H-6 convergent tracer test indicate anisotropy within the Culebra Dolomite Member of the Rustler Formation due to travel along fractures as well as mixed fracture and porous flow. Because porous medium theory may be inadequate to model flow and transport in such a system, the analytic solution to solute transport in a fractured porous medium has been examined for sensitivity to various parameters. The most sensitive parameters are fracture aperture and the distribution coefficient of the porous matrix. This coefficient is valid only if diffusion into the matrix is assumed or demonstrated. The fracture aperture and spacing should be measured from shafts, cores, or outcrops, in that order of priority. Laboratory tests can be used to test matrix diffusion as would field tests in fractured areas such as H-6.

Three well tests of anisotropy at H-6 and H-4 hydropads were reexamined using the data from Ward et al. (1983), the three-well technique, and standard Jacob-semilog plot of drawdown data to obtain effective transmissivity. The H-6 data indicate the major component of

transmissivity may be north-south. The H-4 data yield a south-southwest major component. These contrast with the northwest-southeast major component presented by Gonzalez (1983). The method is easily applied with a desk-top calculator. These results indicate that "the sensitivity of the [hydrologic] model to varied anisotropy parameters should be documented."

DWP

ANNOTATION: The works by Ward et al. (1983) and Gonzalez (1983) are included in this bibliography.

Rehlinger, R., L. Brown, and D. [W.] Powers. 1980. "New Evidence for Tectonic Uplift in the Diablo Plateau Region, West Texas," *Geophysical Research Letters*, SAND79-2046J. Vol. 7, no. 3, 181-184.

ABSTRACT: Recent releveing measurements conducted by the National Geodetic Survey in west Texas and southeastern New Mexico indicate uplift of the Diablo Plateau-Salt Basin region relative to benchmarks to the northeast in the Great Plains. These new measurements confirm and enhance the previously reported interpretations of releveing data in this area. Total relative uplift measured between 1934 and 1977 reaches 19 ± 3 cm. Combining this new information with leveling data from 1934, 1943, and 1958 along this same route indicates that: the uplifted area extends 120 km in the east-west direction (there is presently no control on any north-south component of tilting), with maximum relative uplift occurring approximately 12 km west of the boundary between the Diablo Plateau and Salt Basin graben; and on the time scale between measurements (~20 yrs), uplift appears to be occurring more or less continuously, although not at a constant rate. The progressive deformation indicated by the releveing measurements, the large magnitude relative to possible leveling errors, and the spatial dimensions of the uplift rule out systematic errors or near-surface effects (water table variations, sediment compaction, etc.) as an explanation and favor a tectonic origin. Intracrustal magmatic activity or some form of preseismic deformation (dilatancy, fault creep at depth, etc.) appear to be the most reasonable explanations in view of presently available geologic and geophysical information.

The pattern of uparching is perturbed at the Salt Basin graben, indicating 4.2 ± 0.3 cm of subsidence relative to its margins between 1958 and 1977. This subsidence could be related to the regional tectonic uparching, although near-surface, nontectonic effects cannot be excluded.

Reith, C.C., and G.R. Daer. 1985. *Radiological Baseline Program for the Waste Isolation Pilot Plant. Program Plan*. WTSD-TME-057. Carlsbad, NM: US Department of Energy.

ABSTRACT: This document is the Radiological Baseline Plan (RBP) for the Waste Isolation Pilot Plant (WIPP) Project. The primary purpose of the RBP is to acquire baseline data describing background levels of radiation and radionuclides among the WIPP environments prior to the underground emplacement of radioactive wastes. The RBP will be succeeded by the Operational Radiological Monitoring Program (ORMP) in which the environment around the WIPP Site will be sampled for radiation and radionuclides associated with waste emplacement or other WIPP operations.

The RBP consists of five subprograms: (1) Atmospheric baseline, wherein airborne particulates will be sampled at various locations around the WIPP site. (The atmospheric pathway has been identified as the primary pathway for radionuclide transport between the WIPP facility and man.) (2) Ambient radiation, wherein penetrating gamma radiation around the WIPP will be sampled with an aerial gamma survey, a continuous exposure-rate meter, and an array of 38 dosimeters. (3) Terrestrial baseline, wherein soil samples will be collected from all dosimetry

locations to be archived or analyzed for radiological parameters. (4) Hydrologic baseline, wherein surface water and bottom sediments will be sampled and analyzed for radiological parameters. Groundwater from nearby wells will also be sampled and analyzed. (5) Biotic baseline, wherein radiological parameters will be analyzed in key organisms along potential radionuclide pathways leading to man.

The data in the RBP will facilitate the interpretation of data from the ORMP by indicating whether conditions during WIPP operations represent a significant departure from baseline (preoperational) conditions.

Reith, C.C., and E.T. Louderbough. 1986. "The Dispersal and Impact of Salt from Surface Storage Piles at the Waste Isolation Pilot Plant," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 2-6, 1986*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 129-134.

ABSTRACT: A comprehensive program of ecological studies occurs at the Waste Isolation Pilot Plant (WIPP) in an effort to detect and quantify impacts of excavated salt, which is stored on the surface in two piles: one having originated in 1980, the other in 1984. Both piles are surrounded by berms, which channel runoff to holding ponds, so nearly all dispersal is due to the resuspension, transport, and deposition of salt particles by wind.

Ecological parameters that have been monitored since 1984 include: visual evidence (via photography), soil properties, microbial activity, leaf-litter decomposition, seedling emergence, plant foliar cover, and plant species diversity. These are periodically assessed at experimental plots near the salt piles and at control plots several kilometers away.

Concentrations of soluble ions, particularly sodium and chloride, in surficial samples have been most effective by salt impacts. These parameters have been significantly higher at experimental plots than at control plots, with differences being greatest in spring. Seasonal patterns suggest that salts are dispersed and transported mostly during spring, when winds are strongest, but are leached downward through the sandy soil during summer, which is the local wet season. In no case do salt levels in the soil approach published thresholds for potential plant inhibition. Other ecological parameters reveal no consistent evidence of salt impacts. Microbial activity and leaf-litter decomposition are the same between experimental and control plots. The same is true for vegetation parameters, except for foliar cover, which is slightly reduced in plots adjacent to the salt piles. Sustained monitoring will be necessary to identify subtle or cumulative impacts of salt on the local ecosystem.

Reith, C.C., E.T. Louderbough, R.J. Eastmond, and A.L. Rodriguez. 1985. *Ecological Monitoring Program at the Waste Isolation Pilot Plant, First Semiannual Report*. WTSD-TME-058. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant.

ABSTRACT: The ecological monitoring program was begun in May 1984 "to detect and quantify possible near-field impacts of WIPP construction activities on the local ecosystem. These impacts include: alteration of natural habitat; deposition of salt and fugitive dust; and increase in noise and human activities in and around the installation." This first semi-annual report covers July through December 1984.

Ecological parameters are monitored at six permanent study plots in the oak-sage-mesquite community around the site as part of seven subprograms: environmental photography; soil survey; soil microbial studies; vegetation survey; vertebrate census; environmental water quality; and meteorological monitoring. Aerial photograph interpretation indicates that surface disturbance and habitat change from construction is about 83% of the projected total.

Chloride concentration in surface soils is increased downwind from the northwestern salt storage pile, but is well below toxicity. Plant and microbial parameters appear unaffected by the elevated chloride. Ambient air temperatures are somewhat higher at WIPP relative to other stations in southeastern New Mexico; this may be due to topographic effects. No other site-related changes were evident during this period, but monitoring will continue. DWP

Reith, C.C., K. Prince, T. Flscher, A.L. Rodriguez, D. Uhland, and D. Winstanley. 1986. *Annual Site Environmental Monitoring Report for the Waste Isolation Pilot Plant, Calendar Year 1985.* DOE-WIPP-86-002. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: During 1985, ecological parameters were monitored under a continuing program. An important activity beginning in 1985 was the radiological baseline program to establish a preoperational baseline against which operational radiation measurements can be assessed. This program will continue until 1988 when radioactive waste is delivered to the Waste Isolation Pilot Plant (WIPP). The program consists of five subprograms: the atmospheric radiation baseline; the ambient radiation baseline; the terrestrial radiation baseline; the hydrologic radiation baseline; and the biotic baseline. Samples were analyzed for activities of naturally occurring and transuranic radionuclides. The data will be used to establish a preoperational data base. Radiological measurements fall within the expected range of natural radiation data in national guidance documents. An extensive quality assurance program was applied to validate procedures, analyses, and data handling.

Environmental photography of the site and vicinity has been acquired about every six months, covering the site and vicinity along north-south flight lines. There are no apparent changes in soil microbial activity due to salt movement from surface stockpiles. Changes in soil parameters near salt stockpiles have been ephemeral, occurring mainly during the spring when it is most windy and declining during the later wetter period. Raptor studies reveal slightly lower nest success for Harris hawks near the WIPP. DWP

RE/SPEC, Inc. 1986. *Test Plan: Acoustic Emissions Monitoring in the Wedge Pillar of the Geomechanical Evaluation In Situ Test (Room G).* RSI-0291. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Geomechanical Evaluation in situ test (Room G) is an intermediate step in validating numerical techniques for design and performance calculations. These calculations will be used to advance our knowledge of complex geometric situations and to investigate yielding and failure modes for salt. This test plan addresses the use of acoustic emissions (AE) to detect the onset and the location of yielding and fracturing in the wedge-shaped pillar and the use of ultrasonic velocity (V_p) to characterize the salt.

The isolated salt wedge pillar consists of an initial drift section 10 feet (3.05 m) tall by 20 feet (6.1 m) wide or an optional 15 feet (4.6 m) wide and over 300 feet (>90 m) long, instrumented in anticipation of mining another drift of the same cross-sectional dimensions at an angle of 7.5 degrees to the initial drift. Instruments include horizontal and vertical closure and extensometer gages to monitor salt deformation as the wedge pillar is cut. Inclinometers will also be used to measure displacements. Stress and pressure cells will detect the stress transients during the mining of the second drift. To detect deformation and fracturing within the pillar, the wedge pillar will be instrumented with acoustic emissions sensors. The wedge pillar is designed to produce yielding and progressive fracturing and failure of the narrow portions of the pillar. Results derived from the measurements will include source properties and event locations for use in estimating factors of safety in pillar design and in validating numerical modeling assumptions and constitutive relations. Ultrasonic velocity measurements will be

made in orthogonal directions at numerous locations in the pillar. The results of these measurements will be used to determine the appropriate velocity to use in the AE triangulation studies and to help locate the fracturing portions of the pillar.

Rhoderick, J.E., and A.D. Buck. 1981a. *Borehole Plugging Program (Waste Disposal): Report 2. Petrographic Examination of Several Four-Year-Old Laboratory Developed Grout Mixtures.* Miscellaneous Paper C-78-1. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Specimens from five grout mixtures were stored in either simulated brine groundwater at 73°F or in laboratory air for approximately 4 years. The variables included type of cement, use of a natural pozzolan, and use of salt in two mixtures. Available specimens were inspected; a specimen stored wet and one stored dry from each grout mixture were examined by x-ray diffraction (XRD) for phase composition and by scanning electron microscopy (SEM) to study microstructure.

The results showed that: a) cracking of specimens was common; it was believed to be due mainly to temperature change and/or moisture change effects; b) the mixture variables were generally not recognizable; and c) the phase composition and microstructure of the five grout mixtures were considered normal.

Rhoderick, J.E., and A.D. Buck. 1981b. *Composition of Rock Core from Hole AEC-8, New Mexico.* Miscellaneous Paper SL-81-34. Vicksburg, MS: U.S. Army Engineer Waterways Experiment Station. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: AEC-8 is a bore hole about 5000-ft deep located within the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico.

About 28 ft of rock core from seven depth intervals in this hole was characterized by petrographic examination. This included logging, examination of the rock with a stereomicroscope, examination of thin sections with a polarizing microscope, and examination of each sample by x-ray diffraction.

The following rock types were identified: reddish sandstone (57.6-63.0 ft), reddish silty claystone (560.4-563.2; 614.0-617.1 ft), impure grayish anhydrite (684.0-686.8 ft), grayish gypsiferous dolomite (733.6-734.0 ft), brownish siltstone (972.4-975.2 ft), and colorless to reddish halite (1001.7-1007.2 ft).

Rhoderick, J.E., G.S. Wong, and A.D. Buck. 1981. *Examination of Samples of Bell Canyon Test 1-FF Grout.* SAND81-7110; Miscellaneous Paper SL-81-5; ONWI-246. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Portland cement grout identified as BCT-1-FF (Bell Canyon Test 1-FF) was used in borehole plugging experiments of the Bell Canyon Tests in Hole AEC-7 at the Waste Isolation Pilot Plant Site in New Mexico during September 1979 and February 1980. This grout was made with fresh water. A study of this grout was begun in August 1979 in the laboratory to evaluate the possible effects of temperature, pressure, and storage in fresh water or simulated groundwater (brine) on its phase composition and compressive strength at early ages.

Phase composition was determined by x-ray diffraction (XRD). Temperatures ranged up to about 150°F and included elevation at a few hours' age after mixing; pressure was as high as 1500 psi; specimens were stored in simulated groundwater (brine) or in fresh water.

Data from 1 to 90 days showed:

- a. higher temperatures accelerated early strength gain. These differences essentially vanished by 90 days age.
- b. hydration products as identified by XRD were normal; this indicated that a temperature range of 78 to 153°F was not significant.
- c. pressure did not affect composition.
- d. storage in simulated groundwater (brine) or fresh water had no detectable effect.
- e. since the BCT-1-FF grout mixture contained added sulfate, it formed more ettringite as judged by X-ray diffraction than comparable portland cement mixtures without added sulfate.

Richey, S.F. 1986. *Hydrologic-Test Data from Wells at Hydrologic-Test Pads H-7, H-8, H-9, and H-10 Near the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Open-File Report 86-413. Albuquerque, NM: US Geological Survey.

ABSTRACT: Hydrologic testing was conducted in 1980 and 1981 at wells at hydrologic-test pads H-7, H-8, H-9, and H-10 near the proposed Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. Tests were conducted in three zones above the horizon of the proposed underground storage facility. The zones are the Magenta Dolomite Member of the Rustler Formation, the Culebra Dolomite Member of the Rustler Formation, and the Rustler Formation-Salado Formation contact zones. Data presented are from bailing tests, density profiles, shut-in tests, slug tests, flow tests, pressure-pulse tests, and pumping tests.

Richey, S.F. 1987a. *Preliminary Hydrologic Data for Wells Tested in Nash Draw, Near the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Open-File Report 87-37. Albuquerque, NM: US Geological Survey.

ABSTRACT: Hydrologic testing was conducted at wells WIPP-25, WIPP-26, WIPP-27, WIPP-28, WIPP-29, and WIPP-30 in Nash Draw near the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. The three water-bearing zones tested were the Magenta Dolomite Member of the Rustler Formation, Culebra Dolomite Member of the Rustler Formation, and the Rustler Formation-Salado Formation contact zone. Inflatable packers were used in a variety of test configurations. Tests conducted include bailing, recovery after perforation, shut-in, slug, flow, and pressure pulse. Water-pressure response in the tested zone was monitored by a pressure-transducer system.

Richey, S.F. 1987b. *Water-Level Data from Wells in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico.* Open-File Report 87-120. Albuquerque, NM: US Geological Survey.

ABSTRACT: The US Geological Survey (USGS) monitored water levels in wells in the vicinity of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico during 1977 to 1985. Water-level data are presented, as are brief descriptions of measurement methods used.

Richey, S.F. 1989. *Geologic and Hydrologic Data for the Rustler Formation Near the Waste Isolation Pilot Plant, Southeastern New Mexico*. Open-File Report 89-32. Albuquerque, NM: US Geological Survey.

ABSTRACT: The US Geological Survey (USGS) is investigating the geohydrology in the vicinity of the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. Data presented in this report were compiled in support of a regional ground-water flow model. The data include water-level measurements obtained from the USGS's Ground-Water Site-Inventory and OMNIANA data bases and stratigraphic information interpreted from commercial geophysical logs.

Richey, S.F., J.G. Wells, and K.T. Stephens. 1985. *Geohydrology of the Delaware Basin and Vicinity, Texas and New Mexico*. Water-Resources Investigations Report 84-4077. Albuquerque, NM: US Geological Survey.

ABSTRACT: The Delaware Basin study area includes all or part of Crane, Culberson, Loving, Pecos, Reeves, Ward, and Winkler Counties, TX, and Eddy and Lea Counties, NM. Major aquifers in the Delaware Basin are the Capitan aquifer, Rustler Formation, Santa Rosa Sandstone (Dockum Group), and aquifers in the Cenozoic alluvium.

The Capitan Reef complex (Capitan aquifer) consists of the Capitan and Goat Seep Limestones and includes in ascending order, the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations of the Artesia Group. Water from the Capitan aquifer is used for domestic and irrigation purposes in Eddy County, NM, and for irrigation and industrial purposes in Texas. Available analyses indicate that dissolved-solids concentrations range from 303 to 31,700 mg/L, chloride concentrations range from 16 to 16,689 mg/L, and fluoride concentrations range from 0.5 to 3.0 mg/L.

The Rustler Formation contains water that generally is not suitable for domestic use because of its salinity. Chloride concentrations range from 15 to 210,000 mg/L, and dissolved-solids concentrations range from 286 to 325,800 mg/L. Fluoride concentrations range from 0.5 to 11.4 mg/L. Water from this aquifer is used for irrigation and stock watering, where it is of suitable quality.

The Santa Rosa Sandstone is the principal source of groundwater in the western third of Lea County and in the eastern part of Eddy County. In parts of Texas, the Santa Rosa Sandstone and the Cenozoic alluvium are hydraulically connected and are called the Allurosa aquifer. The Santa Rosa Sandstone-Allurosa aquifer is the source of municipal supply for the cities of Barstow, Pecos, Monahans, and Kermit, TX. Water quality is variable. For those analyses where the Santa Rosa Sandstone is a distinct entity, chloride concentrations range from 10 to 4,800 mg/L, dissolved-solids concentrations range from 205 to 2,990 mg/L, and fluoride concentrations range from 0.4 to 5.0 mg/L.

Water from the Cenozoic alluvium is used extensively for public water supplies, irrigation, industry, livestock watering, and rural-domestic supply throughout the Delaware Basin. The majority of the population in the study area in Texas utilizes this aquifer. The quality of water in the Cenozoic alluvium is variable. Chloride concentrations range from 5 to 7,400 mg/L, dissolved-solids concentrations range from 188 to 15,000 mg/L, and fluoride concentrations range from 0.3 to 10 milligrams per liter. The Cenozoic alluvium is hydraulically connected to Cretaceous units in parts of Reeves and Pecos Counties, TX; in these areas, the units are considered as one aquifer, the Pecos aquifer.

Robinson, J.Q. 1989. *A Clastic Evaporite Deposit in the Lower Castile Formation (Permian), Delaware Basin*. MS thesis. El Paso, TX: University of Texas at El Paso.

ABSTRACT: Soluble Permian age evaporites from the Delaware Basin in southeastern New Mexico and west Texas have been uplifted and exposed to various erosional processes resulting in dissolution of uncertain age, rates, and mechanisms. Halite units within the Castile Formation are absent from the western central basin margin; these units were previously assumed to have been removed by deep-seated subsurface dissolution and replaced by a dissolution and collapse breccia.

In drill cores, this breccia exhibits several distinct textures that occur in specific stratigraphic positions within the breccia deposit. A fine-grained clast-poor texture is confined to the base. Breccias exhibiting pseudo-bedded, matrix-supported tabular clast texture and disoriented, rounded polyclast texture are interbedded and comprise the bulk of the breccia. A fine-grained, thinly bedded texture characterizes the upper breccia.

These strata comprise a radially shaped feature that drapes a central basin slope including an upslope, canyon-like gap. The linear distance from the gap to breccia edge is approximately 5.8 mi (9.5 km). The cored anhydrite breccia has been identified as several clastic units that onlap halite downslope. With increased downslope lateral distance away from the gap, there is a decrease in grain size and in clast-to-matrix ratio. The finest grain textures are confined to the top and base of the breccia. These lateral and vertical relationships of the units plus radial thinning of the breccia suggest that it was deposited by subaqueous sediment gravity flows in a clastic evaporite fan setting.

Robinson, J.Q., and D.W. Powers. 1987. "A Clastic Deposit Within the Lower Castile Formation, Western Delaware Basin, New Mexico," *Geology of the Western Delaware Basin, West Texas and Southeastern New Mexico*. Eds. D.W. Powers and W.C. James. El Paso Geological Society Guidebook 18. El Paso, TX: El Paso Geological Society. 69-79.

ABSTRACT: In the vicinity of CP Hill, about 16 km south-southwest of Whites City, NM, a brecciated sequence in the lower Castile Formation has been examined in detail. Four distinct units associated with the breccia sequence have been defined. Unit A is clast poor, structureless to thinly bedded, and contains kerogen. It occurs only over nodular anhydrite. Unit B is pseudo-bedded, with anhydrite matrix supporting tabular anhydrite clasts. Unit C contains abundant rounded polyclasts and is grain-rich. Unit D is similar to A, but clasts are finer in Unit D. These beds are arranged in vertical sequence and show lateral thinning in an apparent fan shape. The textures, grading, and vertical and lateral relationships suggest this breccia unit was deposited as a subaqueous debris flow.

Rodriguez, A.L. 1988. "Salt Impact Studies at WIPP Effects of Surface Storage of Salt on Microbial Activity," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal. Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 579-582.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) currently under construction in southeastern New Mexico is a research and development facility to demonstrate the safe disposal of transuranic waste in a deep geological formation (bedded salt). The Ecological Monitoring Program at the WIPP is designed to detect and measure changes in the local ecosystem which may be the result of WIPP construction activities. The primary factor that may affect the system prior to waste emplacement is windblown salt from discrete stockpiles. Both vegetation and soil microbial processes should reflect changes in soil chemistry due to salt

importation. Control and experimental (potentially affected) plots have been established at the site, and several parameters are measured quarterly in each plot as part of the soil microbial sampling subprogram. This subprogram was designed to monitor a portion of the biological community, which can be affected by changes in the chemical properties at the soil surface. An indirect measure of microbial activity in leaf litter is made using an enzyme assay. Litter is also used to measure the rate of organic matter loss via microbial decomposition in each plot.

Roedder, E., and H.E. Belkin. 1977. *Preliminary Report on Study of Fluid Inclusions in Core Samples From ERDA No. 9 Borehole, Nuclear Waste Site, New Mexico.* Reston, VA: US Geological Survey. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Fluid inclusions have been studied in core samples from a preliminary selection of ten horizons above and below the proposed site of an underground nuclear waste repository in salt beds in the vicinity of Carlsbad, NM. The techniques used include mainly petrography, freezing stage, heating stage, and crushing stage. The purpose was to determine those inclusion parameters that might be pertinent to an understanding of the origin and geological history of these salt beds, and to anticipate what physical and chemical problems these inclusions might cause during long-term storage of hot radioactive wastes. Possible migration of fluid inclusions up the thermal gradient (toward the wastes) is a particularly important aspect.

Four general types of inclusions were found in these samples: type A — extremely abundant but minute primary liquid inclusions, with or without a tiny vacuum bubble, outlining primary growth features; type B — much larger liquid inclusions, trapped during several stages of recrystallization of the primary salt, some with a small vacuum bubble and/or unidentified daughter crystals; type C — scarce, large liquid inclusions with large and variable gas bubbles under pressure, presumably from fracturing and refilling of type B inclusions; and type D — empty (i.e., gas) inclusions, found principally along grain boundaries, that have leaked and have lost their liquid contents.

The total weight % of liquid as fluid inclusions in these 10 samples, as measured, ranged from 0.1 to 1.7%, mostly as type B inclusions; the amount of liquid in these same samples in situ was larger, almost certainly at least twice as large, since many of the largest inclusions, that are the major contributors to the total percentage and the intergranular fluids, have been drained during the boring and sample preparation. The temperature at which these inclusions were trapped was generally in the range 25-45°C. The brines in them are never simple saturated NaCl solutions, or even NaCl-KCl solutions; freezing temperatures indicate that they must contain considerable amounts of other ions such as Mg and Ca.

The inclusion walls show visible changes within minutes, possibly solution and redeposition, as well as deformation, when the host crystal is uniaxially stressed. Internal fracturing of the inclusion walls, usually without leakage, occurs upon freezing. Leakage from internal pressure upon heating (i.e., decrepitation) had not yet been studied.

The distribution of primary type A inclusions provides evidence that they have not moved visibly (i.e., less than a few micrometers at most) in that fraction of the 225 million years between original deposition and the present, and that these samples have been in the small but finite normal geothermal gradient. Due to the difference in ambient temperature, these results are not immediately applicable to the problem of the rate of movement of inclusions toward the wastes in the shorter times but much larger thermal gradients expected during waste storage.

This work represents a preliminary scoping of the problem to determine what can and should be done in further studies of additional samples selected to be of maximum pertinence.

Roedder, E., and H.E. Belkin. 1978. "Fluids Present During the Diagenetic History of the Salado Formation, Delaware Basin, Southeastern New Mexico as Recorded by Fluid Inclusions," *EOS Transactions, American Geophysical Union*, Vol. 59, no. 4, 226. (Abstract Only).

ABSTRACT: Inclusions were examined in cores from the site of a proposed underground nuclear waste repository in the Permian Salado salt beds. Petrography and freezing, and heating, and crushing stages were used. The aim was to help understand the origin and geological history of the basin and the diagenetic mineral assemblages and to anticipate what problems the inclusions might cause during long-term waste storage. The available data indicate the following diagenetic stages:

The original fine-grained, dark-gray salt contains vast numbers of $\sim 1\text{--}2\ \mu\text{m}$, mostly one-phase primary liquid inclusions ($\leq 10^{10}\text{cm}^{-3}$) in arrays outlining cubic hopper growth. Low first-melting temperatures show the trapped fluid to be a strong bittern, not simply saturated NaCl. Subsequent recrystallization and grain growth caused inclusion coalescence, yielding a few larger inclusions in coarse clear salt. Only $\sim 1\%$ of the salt remained unrecrystallized. The new inclusions also contain strong bitterns, variable in composition and possibly derived in part from those in the original hopper crystals. Some contain unidentified birefringent daughter crystals. Large inclusions ($\sim 1\ \text{mm}$) have small shrinkage (vapor) bubbles, containing no detectable noncondensable gas (10^{-14}g ; crushing stage data) and, homogenizing at $20\text{--}46^\circ\text{C}$. Later, fracturing in the presence of a pore fluid containing bubbles of gas (methane?) under pressure (crushing stage data) caused trapping of this mixture in some opened inclusions, yielding variable G/L ratios.

These inclusions make up <1 volume %; an additional possibly even greater volume % fluid is present in situ, filling intergranular pores. The evidence for extensive recrystallization is important, but available data do not permit more than qualitative evaluations of the deleterious effects of such fluids on atomic waste storage.

Roedder, E., and H.E. Belkin. 1979. "Application of Studies of Fluid Inclusions in Permian Salado Salt, New Mexico, to Problems of Siting the Waste Isolation Pilot Plant," *Scientific Basis for Nuclear Waste Management, Materials Research Society Annual Meeting, Boston, MA, November 28-December 1, 1978*. Ed. G.J. McCarthy. New York, NY: Plenum Press. Vol. 1, 313-321.

ABSTRACT: This paper presents a summary of the data obtained when inclusions in cores from the proposed Waste Isolation Pilot Plant (WIPP) Site were examined petrographically and with microscope freezing, heating, and crushing stages. Fluid now present in the samples studied ranges widely from <0.1 to $1.7\ \text{wt.}\%$; the total in situ fluid content of the rock is certainly greater. The inclusion fluid is not just saturated NaCl solution, but a variable and extremely saline bittern containing some noncondensable gases under pressure. The inclusions move in thermal gradients and react quickly to uniaxial stress, but decrepitation is estimated to be a more important mechanism of fluid release under thermal loading. Subsequent movement of the released fluids is not considered.

Roedder, E., and H.E. Belkin. 1980a. "Thermal Gradient Migration of Fluid Inclusions in Single Crystals of Salt From the Waste Isolation Pilot Plant Site (WIPP)," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium on the Scientific*

Basis for Nuclear Waste Management, Boston, MA, November 27-30, 1979. Ed. C.J.M. Northrup, Jr. New York, NY: Plenum Press. Vol. 2, 453-470.

ABSTRACT: Selected salt single crystals from core samples of bedded salt from the Waste Isolation Pilot Plant Site have been tested to determine the rate of migration of their liquid-filled (fluid) inclusions in thermal gradients. Gradients of $1.5^{\circ}\text{C}\cdot\text{cm}^{-1}$, maintained for period of 3-10 days, at ambient temperatures of 108-260°C, resulted in rates of movement of 1.2-5.4 $\text{cm}\cdot\text{yr}^{-1}$ for cubic inclusions 1 mm on an edge. Inclusions 0.1 mm on an edge moved only ~30% as fast. Increase in ambient temperature and/or gradient increased the rate, in approximately direct proportion. The migration rate for inclusions in different parts of a given sample, however, may vary by a factor of three, for unknown reasons, and some other interesting observed phenomena are still unexplained.

Roedder, E., and H.E. Belkin. 1980b. "Migration of Fluid Inclusions in Polycrystalline Salt Under Thermal Gradients in the Laboratory and in Salt Block II," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting, Columbus, OH, December 9-11, 1980.* ONWI-212. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 361-363.

ABSTRACT: Samples of salt from ERDA-9 with fluid inclusions near crystal boundaries were heated at about 150°C with a gradient of 1.5°C for as long as 1000 hours to determine fluid inclusion behavior at the grain boundary. Inclusions lost 50 to 90 volume % of fluid at the boundary by evaporation, were resealed to form vapor-rich inclusions, and began moving back down the thermal gradient. Leakage of inclusions along grain boundaries must be considered a valid source of fluid around canisters buried in salt.

Published data for the Salt Block II experiments are interpreted differently from others. Hydrous minerals on the surface of the block indicate about 179 g of brine, including 134 g of water, were delivered to the surface instead of 111 g of water. Inclusions which "stopped" migrating toward the heat source at 7 cm may have resulted from intersecting grain boundaries and the apparent lack of movement beyond 15 cm is because small inclusions do not change shape during migration. Calcium content, as indicated by mineral efflorescences, is sufficient to depress inclusion freezing temperatures and may be enhanced in inclusions by evaporation at the grain boundaries. The efflorescence of halite can also be due to evaporating fluid rather than primary scrapings for samples. Carnallite and bischofite in the efflorescence must have formed during the cooling period, as they will lose water at temperatures of 130 and 160°C, respectively. Size and shape of inclusions from earlier work are not comparable to the after-experiment inclusions and inferences from the Salt Block II experiment. Rates of migration at these temperatures for cubic inclusions 0.5 mm (along the edge) should be about 2.5 cm/year at 15 cm from the heater hole wall rather than the 1 cm/year generally assumed. Intergranular fluid in Waste Isolation Pilot Plant (WIPP) samples correspond to about 0.1 the fluid obtained during the Salt Block II experiment, indicating this is not an adequate source of the fluid. DWP

ANNOTATION: The source of Salt Block II data in the Roedder and Belkin paper is included in this bibliography as Lambert (1980b). The issue of fluid inclusion migration in salt due to thermal gradients became moot for the WIPP at about the time of publication of these various results because it was legislatively determined that WIPP would not be used for wastes generating significant heat. A small proportion of waste at WIPP is expected to be remote-handled transuranic waste.

Rogers, A.M., and A. Malkiel. 1979. "A Study of Earthquakes in the Permian Basin of Texas-New Mexico," *Bulletin of the Seismological Society of America*. Vol. 69, no. 3, 843-865.

ABSTRACT: A microearthquake seismograph network has been employed to study earthquakes occurring in the Permian Basin of Texas and New Mexico. The earthquakes are predominantly located on the Central Basin platform, although a few occur in the Delaware Basin. The majority of the earthquakes occur at the depths of sedimentary rocks, and the focal depths are also coincident with the depths at which hydrocarbon production and water-flood (secondary recovery) operations are conducted. Comparison of the historic earthquake activity with water-flood data shows that there was a possible increase in the number of large earthquakes ($M > 3.0$) in the mid-1960s when the number of water-flood projects and their injection pressures increased. The first felt event occurred in 1966. This tentative correlation suggests that the earthquakes are related to hydrocarbon production in this area.

Rose, W. 1977. *Development of a Conceptual Model to Explain Brine Flowage into Wells Drilled Through the Salado-Castile Formation Contact in Locations Such as the ERDA6 Site Near Carlsbad in Southeastern New Mexico*. Socorro, NM: New Mexico Tech. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: High pressure zones within the Castile are probably widespread but not present everywhere. The zones pose a potential hazard to the integrity of an overlying repository, especially if nearby wells have penetrated them. The ERDA-6 brine pocket is probably less than 800 ft in radius based on a porosity of 0.15, a permeability of 1 darcy, and a formation thickness of 40 ft. It is recommended that the Castile not be drilled at potential sites where other factors are favorable. "Sensing at distance" methods for detecting brine should be developed to make drilling unnecessary. ERDA-6 should be re-entered and further tested; the abandoned Gulf Covington well should be considered for reopening. Special plugging materials for these wells should be designed if they are reopened for further testing. Further searches for sites should concentrate on "prospective salt beds not overlying troublesome bottom water."
DWP

Sandia [National] Laboratories. 1977. "A Radioactive-Waste Isolation Pilot Plant," *Sandia Technology*. Eds. J.A. Mogford and W.L. Garner. SAND77-0701. Albuquerque, NM: Sandia National Laboratories. Vol. 3, no. 1, 2-5.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) program is to demonstrate that bedded salt is suitable for disposal of radioactive waste, principally transuranic waste produced by national defense programs of the last 30 years. Sandia National Laboratories program responsibilities include site selection, design and development, technical guidance for facility operation, environmental impact assessment, and technical support to the Energy Research and Development Administration.

The site should be selected to keep radioactive materials from interacting with the biosphere and produce the least possible conflict with other human endeavors. The site must possess the proper geology (e.g., thickness, depth, extent, absence of moving water). Mineral resources and geological stability are being evaluated. Hydrological studies are important because all credible release mechanisms involve transport by water. As some resources may be excluded by site selection, other techniques for resource recovery that will not jeopardize the security of the site are being investigated.

The WIPP design is influenced by the requirement to demonstrate that waste will be retrievable during pilot plant operations. All waste will be in solid form. Two facilities and storage levels at depths of 600 and 850 m are provided to handle "cold" and "hot" wastes separately.

Supporting studies concern rock mechanics and mine design, as well as studies to determine the interaction of waste with rock. The *Environmental Impact Statement (EIS)* has established that geologic processes will not destroy the site integrity for at least a few hundred thousand years. The consequences of inadvertent human penetration of the repository are being investigated. The *EIS* and a conceptual design report are essential steps for the WIPP before construction can start in 1979. The first waste is expected in 1983. DWP

Sandia National Laboratories and D'Appolonia Consulting Engineers. *Basic Data Report for Drillhole WIPP 14 (Waste Isolation Pilot Plant - WIPP)*. SAND82-1783. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-14 is an exploratory well drilled in eastern Eddy County, NM, in section 9, T22S, R31E. The borehole was drilled to a depth of 1000 ft measured from ground level. It penetrated, from top to bottom, 15.4 ft of Quaternary sands, 125.6 ft of the Triassic Santa Rosa Sandstone, and in the Permian strata, 497.7 ft of the Dewey Lake Red Beds, 312.9 ft of the Rustler Formation and 48.4 ft of the Upper Salado Formation. Seven hundred ft of the well were cored, at consecutive and nonconsecutive 10-ft intervals to a depth of 925.5 ft. Cuttings were collected where core was not taken. Density, gamma-ray neutron, and caliper logs were run the full depth of the hole.

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1982b. *Basic Data Report for Deepening of Borehole WIPP 13 (Waste Isolation Pilot Plant - WIPP)*. SAND82-1880. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-13 is a borehole drilled in eastern Eddy County, NM, in section 17, T22S, R31E, to investigate a subsurface seismic "disturbed zone." The first 1035 ft of the borehole were drilled in July and August 1978. The deepening of WIPP-13 was performed in 1979 between August and October. This report documents the deepening of WIPP-13 to 3861.8 ft. Only rocks of the Salado and Castile Formations were penetrated in the deepening. Cores were obtained for some portions of the hole, and cuttings were collected from some of the sections not cored. A suite of geophysical logs was run to provide information on lithology, structure, and geochemistry.

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1982c. *Basic Data Report for Drillhole WIPP 12 (Waste Isolation Pilot Plant - WIPP)*. SAND82-2336. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-12 is a borehole drilled in eastern Eddy County, NM, to investigate the stratigraphy, structure, and lithology in the WIPP area. WIPP-12 was drilled in section 17, T22S, R31E, between November 9 and December 7, 1978. The hole was drilled to a depth of 2785.8 ft. It encountered from top to bottom, 16.2 ft of sand, 3 ft of Mescalero caliche, and 9.6 ft of the Gatuña Formation, all of Quaternary age; 138.2 ft of the Triassic Santa Rosa sandstone, 483 ft of the Dewey Lake Red Beds, 326 ft of the Rustler Formation, 1771.5 ft of the Salado Formation, and 48.3 ft of the Castile Formation, all of Permian age. Cores or cuttings were obtained for the entire hole. A suite of geophysical logs, including neutron-gamma and density curves, was run to the full depth of WIPP-12. The borehole demonstrated that the elevation of the top of the Castile is about 160 ft above the same horizon in ERDA-9.

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1983a. *Basic Data Report for Drillhole AEC 8 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0269. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: AEC-8 was originally drilled in 1974 to a depth of 3028 ft by Oak Ridge National Laboratory as part of the initial investigations of a site for radioactive waste disposal. In 1976, Sandia National Laboratories deepened the borehole from the top of the Castile Formation into the Bell Canyon Formation to test the hydraulic properties of the Bell Canyon. The borehole encountered, in descending order, Holocene sands (20 ft), Mescalero caliche (6 ft), Santa Rosa Sandstone (143 ft), Dewey Lake Red Beds (491 ft), Rustler Formation (322 ft), Salado Formation (1990 ft), Castile Formation (1335 ft), and the upper Bell Canyon Formation (603 ft). The borehole stratigraphy is in normal order, and there is no significant deformation. An extensive suite of geophysical logs provides information on the lithology and stratigraphy. The potentiometric surfaces of Bell Canyon fluid-bearing zones are 550 ft (for the zone at 4821-4827 ft) and 565 ft below land surface (for the zone at 4844-4860 ft).

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1983b. *Basic Data Report for Drillhole ERDA 10 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0271. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole ERDA-10 was drilled to obtain information on possible dissolution of halite within the Castile Formation and on the hydrologic characteristics of the fluid-bearing zones in the Bell Canyon Formation. The borehole is located in section 34, T23S, R30E in southern Eddy County, NM. ERDA-10 was drilled to a depth of 4431.5 ft. Cores from the Castile were taken to obtain direct information, which was supplemented by geophysical logging. Based on preliminary analysis of the data, the ERDA-10 stratigraphic section is interpreted as a sequence of sandstones, siltstones, claystones, and evaporites normal for the area. No evidence of dissolution of significant amounts of halite was observed.

ANNOTATION: The outside cover of this report incorrectly lists Sandia National Laboratories and the US Geological Survey as authors.

Sandia National Laboratories and D'Appolonia Consulting Engineers. 1983c. *Basic Data Report for Drillhole AEC 7 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0268. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: AEC-7 is a borehole drilled in western Lea County, NM, in section 31, T21S, R32E. AEC-7 was drilled to 3918 ft in 1974 by Oak Ridge National Laboratory (ORNL); Sandia National Laboratories (SNL) deepened the hole to 4732 ft in 1979. The borehole provided stratigraphic and lithologic information in the initial and final drilling. The borehole was used extensively for tests of bore hole plugs and plugging operations.

AEC-7 penetrated, in descending order, Holocene sands and Mescalero caliche (8 ft), Santa Rosa Sandstone (109 ft), Dewey Lake Red Beds (542 ft), Rustler Formation (325 ft), Salado Formation (2014 ft), Castile Formation (1521 ft), and the upper Bell Canyon Formation (197 ft). Cores were obtained from much of the borehole. An extensive suite of geophysical logs provides information on stratigraphy, lithology, and structure. Beds were in normal stratigraphic sequence and without structural deformation, except in the lower Castile. Anhydrite II and Halite II appear to be repeated in the borehole. This section was penetrated during deepening by SNL; the structural complication is consistent with deformation found nearby in ERDA-6. The potential site on which AEC-7 is located was abandoned in 1976 after ERDA-6 was drilled.

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

Sandia [National] Laboratories and US Geological Survey. 1979a. *Basic Data Report for Drillhole WIPP 13 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0273. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-13 was drilled in the SW 1/4 section 17, T22S, R31E of eastern Eddy County during July and August 1978 to investigate the nature of a resistivity anomaly. The stratigraphic section was normal, consisting of 13 ft of Quaternary deposits (including artificial fill for drill pad), 53 ft of the Triassic Santa Rosa Sandstone, 451 ft of Dewey Lake Red Beds, 269 ft of the Rustler Formation, and 179 ft of the upper member of the Salado Formation. Consecutive cores were taken from 570 to 595, 656 to 729, and 827 to 878 ft.

Cuttings were collected at 10-ft intervals throughout the rest of the hole. Geophysical logs were run to aid in interpretation of the stratigraphy.

The Waste Isolation Pilot Plant (WIPP) is intended to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. Eventual conversion of the facility to a repository for TRU defense wastes is anticipated. The WIPP will also provide research facilities for interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1979b. *Basic Data Report for Drillhole WIPP 25 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0279. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-25 was drilled on the eastern edge of Nash Draw (SW 1/4, section 15, T22S, R30E) in Eddy County, NM, to determine subsurface stratigraphy and examine dissolution features above undisturbed salt in the Salado Formation. Determination of dissolution rates will refine previous estimates and provide short-term (geologically) rates for Waste Isolation Pilot Plant (WIPP) risk assessments. The borehole encountered, from top to bottom, Pleistocene sediments (17 ft with fill material for pad), Dewey Lake Red Beds (215 ft), Rustler Formation (333 ft), and 90 ft of the upper Salado Formation. A dissolution residue, 37 ft thick, is at the top of the Salado Formation overlying halite-rich beds. In addition to obtaining nearly continuous core from the surface to total depth (655 ft), geophysical logs were taken to measure acoustic velocities, density, radioactivity, and formation resistivity. An interpretive report on dissolution in Nash Draw will be based on combined borehole basic data, surface mapping, and laboratory analyses of Nash Draw rocks and fluids.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes and to then be converted to a repository. The WIPP will also provide research facilities for interaction between high-level waste and salt.

ANNOTATION: The interpretive report, mentioned in abstracts for drillholes WIPP 25-30 in the Nash Draw area, was not prepared as such. Lambert (1983a) does, however, include interpretation of the Nash Draw drilling as part of evaluating dissolution processes in the area.

Sandia [National] Laboratories and US Geological Survey. 1979c. *Basic Data Report for Drillhole WIPP 26 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0280. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-26 was drilled in Nash Draw (SE 1/4 NE 1/4, section 29, T22S, R30E) Eddy County, NM, to determine subsurface stratigraphy and examine dissolution features above undisturbed salt in the Salado Formation. Determination of dissolution rates will refine previous estimates and provide short-term (geologically) rates for Waste Isolation Pilot Plant (WIPP) risk assessments. The borehole encountered, from top to bottom, surficial deposits (10 ft with fill material for pad), Rustler Formation (299 ft), and the upper 194 ft of the Salado Formation. A dissolution residue, 11 ft thick, is at the top of the Salado Formation overlying halite-rich beds. In addition to obtaining nearly continuous core from the surface to total depth (503 ft), geophysical logs were taken to measure acoustic velocities, density, radioactivity, and formation resistivity. An interpretive report on dissolution in Nash Draw will be based on combined borehole basic data, surface mapping, and laboratory analyses of Nash Draw rocks and fluids.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes and to then be converted to a repository. The WIPP will also provide research facilities for interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1979d. *Basic Data Report for Drillhole WIPP 27 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0281. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-27 was drilled in Eddy County, NM (NW 1/4 section 21, T21S, R30E) to investigate evaporite dissolution features and to determine the stratigraphy of surface and near-surface formations. The borehole encountered, from top to bottom, 79 ft of Quaternary deposits, 73 ft of the Rustler Formation, and 171 ft of the upper portion of the Salado Formation. Consecutive cores were obtained for the entire depth of WIPP-27. Geophysical logs measure acoustic velocities, density, radioactivity, and formation resistivity. An interpretive report on dissolution in Nash Draw will be based on combined borehole data, surface mapping, and laboratory analyses of Nash Draw rocks and fluids.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1979e. *Basic Data Report for Drillhole WIPP 28 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0282. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-28 was drilled in Nash Draw (NE 1/4, section 18, T21S, R31E) in Eddy County, NM, to determine subsurface stratigraphy and examine dissolution features above undisturbed salt in the Salado Formation. Determination of dissolution rates will refine previous estimates and provide short-term (geologically) rates for Waste Isolation Pilot Plant (WIPP) risk assessments. The borehole encountered, from top to bottom, Mescalero caliche (12 ft with fill material for pad), Dewey Lake Red Beds (203 ft), Rustler Formation (316 ft), and the upper 270 ft of the Salado Formation. A dissolution residue, 58 ft thick, is at the top of the Salado Formation overlying halite-rich beds. In addition to obtaining nearly continuous core from the surface to total depth (801 ft), geophysical logs were taken to measure acoustic velocities, density, radioactivity, and formation resistivity. An interpretive report on dissolution in Nash Draw will be based on combined borehole basic data, surface mapping, and laboratory analyses of Nash Draw rocks and fluids.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes and then be converted to a repository. The WIPP will also provide research facilities for interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1980a. *Basic Data Report for Drillhole WIPP 29 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0283. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-29 was drilled in Nash Draw (SE 1/4, section 34, T22S, R29E) in Eddy County, NM, to determine subsurface stratigraphy and examine dissolution features above undisturbed salt in the Salado Formation. Determination of dissolution rates will refine previous estimates and provide short-term (geologically) rates for Waste Isolation Pilot Plant (WIPP) risk assessments. The borehole encountered, from top to bottom, unnamed Pleistocene deposits (12 ft with fill material for pad), Dewey Lake Red Beds (203 ft), Rustler Formation

(131 ft), and the upper 234 ft of the Salado Formation. A dissolution residue, 105 ft thick, is at the top of the Salado Formation overlying halite-rich beds. In addition to obtaining nearly continuous core from the surface to total depth (358 ft), geophysical logs were taken to measure acoustic velocities, density, radioactivity, and formation resistivity. An interpretive report on dissolution in Nash Draw will be based on combined borehole basic data, surface mapping, and laboratory analyses of Nash Draw rocks and fluids.

The WIPP is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes and then to be converted to a repository. The WIPP will also provide research facilities for interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1980b. *Basic Data Report for Drillhole WIPP 18 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0275. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-18 is an exploratory borehole whose objective is to determine the nature of the near-surface formations after seismic information indicated a possible fault. The borehole is located in section 20, T22S, R31E, in eastern Eddy County, NM, and was drilled between March 14 and 30, 1978. The hole was drilled to a depth of 1060 ft and encountered, from top to bottom, surficial Holocene deposits (5 ft, including artificial fill for drill pad), the Mescalero caliche (4 ft), the Santa Rosa Sandstone (129 ft), the Dewey Lake Red Beds (475 ft), the Rustler Formation (315 ft), and the upper portion of the Salado Formation (132 ft). Cuttings were collected at 10-ft intervals. A suite of geophysical logs was run to measure acoustic velocities, density, and radioactivity. On the basis of comparison with other geologic sections drilled in the area, the WIPP-18 section is a normal stratigraphic sequence, and it does not show structural disruption.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1980c. *Basic Data Report for Drillhole WIPP 19 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0276. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-19 is an exploratory borehole whose objective was to determine the nature of the near-surface formations after seismic information indicated a possible fault. The borehole is located in section 20, T22S, R31E, in eastern Eddy County, NM, and was drilled between April 6 and May 4, 1978. The hole was drilled to a depth of 1038.2 ft and encountered, from top to bottom, surficial Holocene deposits (7 ft, including artificial fill for drill pad), the Mescalero caliche (7 ft), the Santa Rosa Sandstone (82 ft), the Dewey Lake Red Beds (494 ft), the Rustler Formation (315 ft), and the upper portion of the Salado Formation (143 ft). Cuttings were collected at 10-ft intervals. A suite of geophysical logs was run to measure acoustic velocities, density, and radioactivity. On the basis of comparison with other geologic sections drilled in the area, the WIPP-19 section is a normal stratigraphic sequence, and it does not show structural disruption.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1980d. *Basic Data Report for Drillhole WIPP 21 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0277. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-21 is an exploratory borehole whose objective is to determine the nature of the near-surface formations after seismic information indicated a possible fault. The borehole is located in section 20, T22S, R31E, in eastern Eddy County, NM, and was drilled between May 24 and 26, 1978. The hole was drilled to a depth of 1046 ft and encountered, from top to bottom, surficial Holocene deposits (6 ft, including artificial fill for drill pad), the Mescalero caliche (6 ft), the Santa Rosa Sandstone (34 ft), the Dewey Lake Red Beds (487 ft), the Rustler Formation (308 ft), and the upper portion of the Salado Formation (178 ft). Cuttings were collected at 10-ft intervals. A suite of geophysical logs was run to measure acoustic velocities, density, and radioactivity. On the basis of comparison with other geologic sections drilled in the area, the WIPP-21 section is a normal stratigraphic sequence, and it does not show structural disruption.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1980e. *Basic Data Report for Drillhole WIPP 22 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0278. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-22 is an exploratory borehole whose objective is to determine the nature of the near-surface formations after seismic information indicated a possible fault. The borehole is located in section 20, T22S, R31E, in eastern Eddy County, NM, and was drilled between March 14 and 30, 1978. The hole was drilled to a depth of 1448 ft and encountered, from top to bottom, surficial Holocene deposits (6 ft, including artificial fill for drill pad), the Mescalero caliche (7 ft), the Santa Rosa Sandstone (68 ft), the Dewey Lake Red Beds (492 ft), the Rustler Formation (311 ft), and the upper portion of the Salado Formation (565 ft). Cuttings were collected at 10-ft intervals. A suite of geophysical logs was run to measure acoustic velocities, density, and radioactivity. On the basis of comparison with other geologic sections drilled in the area, the WIPP-22 section is a normal stratigraphic sequence, and it does not show structural disruption.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt.

Sandia [National] Laboratories and US Geological Survey. 1980f. *Basic Data Report for Drillhole WIPP 30 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0284. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-30 was drilled in east-central Eddy County, NM, in NW 1/4, section 33, T21S, R31E, to obtain drill core for the study of dissolution of near-surface rocks. The borehole encountered from top to bottom, the Dewey Lake Red Beds (449 ft including artificial fill for drill pad), Rustler Formation (299 ft), and the upper 160 ft of the Salado Formation. Continuous core was cut from the surface to total depth. Geophysical logs were taken the full length of the borehole to measure acoustic velocities, density, and distribution of potassium and other radioactive elements. Information from this bore hole will be included in

an interpretive report on dissolution in Nash Draw based on combined borehole data, surface mapping, and laboratory analyses of rocks and fluids.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes and then be converted to a repository. The WIPP will also provide research facilities for interactions between high-level waste and salt. Administration policy, as of February 1980, is to hold the WIPP Site in reserve until the first disposal site can be chosen from several potential sites, including the WIPP.

Sandia [National] Laboratories and US Geological Survey, 1980g. *Basic Data Report for Drillhole WIPP 32 (Waste Isolation Pilot Plant - WIPP)*. SAND80-1102. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-32 is an exploratory borehole drilled to examine the subsurface at a small topographic high in Nash Draw. The borehole is located in east-central Eddy County, NM, in NE 1/4 SE 1/4 section 33, T22S, R29E, and was drilled in August 1979. The hole was drilled to a depth of 390 ft, and encountered, from top to bottom, the Rustler Formation (166 ft) and the upper Salado Formation (224 ft). Core was taken from 4 to 353 ft. Geophysical logs were run the full length of the hole to measure formation properties.

The Waste Isolation Pilot Plant (WIPP) is to demonstrate (through limited operations) disposal technology for transuranic (TRU) defense wastes. The WIPP will also provide facilities to research interactions between high-level waste and salt.

Sandia National Laboratories and US Geological Survey, 1981a. *Basic Data Report for Drillhole WIPP 33 (Waste Isolation Pilot Plant - WIPP)*. SAND80-2011. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-33 is an exploratory borehole to investigate the nature of unusually thick fill material in the northwest portion of the WIPP Site; a breccia pipe was considered a possible, though unlikely, cause of the fill. The borehole is located in section 13, T22S, R30E, in east-central Eddy County, NM and was drilled during July 1979. The hole was drilled to a depth of 840 ft and encountered, from top to bottom, surficial Holocene deposits (44 ft including artificial fill for drill pad), the Dewey Lake Red Beds (357 ft), the Rustler Formation (276 ft), and the upper portion of the Salado Formation (163 ft). Selected intervals were cored and cuttings were taken for examination by geologists. Geophysical logs were taken the full length of the borehole to measure radioactivity, resistivity, and density. The stratigraphic profile was found to be normal, and no breccia was observed.

Sandia National Laboratories and US Geological Survey, 1981b. *Basic Data Report for Drillhole WIPP 34 (Waste Isolation Pilot Plant - WIPP)*. SAND81-2643. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole WIPP-34 was drilled to investigate a structural low in an area about 2-1/2 miles north of the center of the WIPP Site. The borehole is located in section 9, T22S, R31E, in east-central Eddy County, NM, and was drilled during August and September 1979. The hole was drilled to a depth of 1,820 ft and encountered from top to bottom, surficial Holocene deposits (10 ft, including artificial fill for drill pad), the Santa Rosa Sandstone (144 ft), the Dewey Lake Red Beds (503 ft), the Rustler Formation (316 ft), and the Salado Formation (847 ft). Cuttings and cores were taken at selected intervals. Geophysical logs were

run for the entire length of the hole. The structural low was verified by data from WIPP-34; however, it was not apparently caused by dissolution of halite.

Sandia National Laboratories and US Geological Survey, 1982. *Basic Data Report for Drillhole WIPP-11 (Waste Isolation Pilot Plant - WIPP)*, SAND79-0272. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Seismic reflection data from petroleum industry sources showed anomalous reflectors in the Castile Formation over a small area about 3 miles north of the center of the Waste Isolation Pilot Plant (WIPP) Site. Additional corroborative seismic reflection data were collected as part of WIPP investigations, and WIPP-11 was drilled to investigate the anomaly. WIPP-11 was drilled near the northwest corner of section 9, T22S, R31E. It penetrated, in descending order, sand dune deposits and the Gatuña Formation (29 ft), Santa Rosa Sandstone (132 ft), Dewey Lake Red Beds (502 ft), Rustler Formation (288 ft), Salado Formation (1379 ft), and most of the Castile Formation (1240 ft). Beds within the lower part of the Salado and the upper anhydrite of the Castile are thinner than normal; these beds are displaced upward structurally by the upper Castile halite, which is highly thickened (about 968 ft). The lowest halite is thin (51 ft), and the basal anhydrite was not completely penetrated. Subsequent seismic and borehole data has shown WIPP-11 to be in a structural complex now identified as the "disturbed zone."

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level waste, though there are no plans at this time to dispose of high-level waste or spent fuel at the WIPP.

Sandia National Laboratories and US Geological Survey, 1983a. *Basic Data Report for Drillhole ERDA-6 (Waste Isolation Pilot Plant - WIPP)*, SAND79-0267. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole ERDA-6 was drilled in eastern Eddy County, NM, to investigate a candidate site for a nuclear waste repository. The site was subsequently rejected on the basis of geological data. ERDA-6 was drilled in the NE 1/4 SE 1/4, section 35, T21S, R31E. The borehole encountered, from top to bottom, 17 ft of Quaternary deposits, 55 ft of the Triassic Santa Rosa Sandstone, 466 ft of the Dewey Lake Red Beds, 273 ft of the Rustler Formation, 1785.5 ft of the Salado Formation, and 374.5 ft of the upper Castile Formation, all of Permian age. Cores or drill cuttings were taken throughout the hole. A suite of wireline geophysical logs was run to a depth of 883 ft to facilitate the recognition and correlation of rock units, to ensure identification of major lithologies and to provide depth determinations independent of drill-pipe measurements.

The site at ERDA-6 was rejected because the structure of the lower Salado and the Castile is too severe to develop a repository along a single set of beds. The borehole also intersected a reservoir of pressurized brine and gas at about 2710 ft. The pore volume for the reservoir was estimated to be in the range from about 200,000 to about 2 million barrels. ERDA-6 was re-entered in 1981 by the Department of Energy (DOE) for the purpose of further testing the brine reservoir. Those tests are described in separate reports by the DOE and its contractors.

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

ANNOTATION: The principal facts of testing the brine reservoir at ERDA-6 are reported in D'Appolonia Consulting Engineers, Inc. (1982); Popielak et al. (1983) prepared a major interpretive report of the testing of ERDA-6.

Sandia National Laboratories and US Geological Survey. 1983b. *Basic Data Report for Drillhole ERDA 9 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0270. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Borehole ERDA-9 was drilled in eastern Eddy County, NM, to investigate and test salt beds for the disposal of nuclear wastes. The hole was placed near the southeast corner of section 20, T22S, R31E. It was drilled between April 28 and June 4, 1976, to a depth of 2,889 ft (measured from a kelly bushing altitude of 3,420.4 ft MSL). The borehole encountered, from top to bottom, Holocene deposits (including artificial fill of 22 ft), the Pleistocene Mescalero caliche (5 ft) and Gatuña Formation (27 ft), 9 ft of the Triassic Santa Rosa Sandstone, 487 ft of the Dewey Lake Red Beds, 290 ft of the Rustler Formation, 1976 ft of the Salado Formation, and 53 ft of the Castile Formation, all of Permian age. Cuttings were collected at 5-ft intervals from the land surface to a depth of 1,090 ft, and consecutive cores were taken to a depth of 2,876.6 ft. A suite of wireline geophysical logs was run the full length of the borehole to measure distribution of radioactive elements and hydrogen, and variations in rock density and elastic velocity.

On the basis of the borehole findings and related hydrological and geophysical programs, the site was judged suitable to pursue the extensive geological characterization program that followed. The core from ERDA-9 provided a suite of samples extensively tested for rock mechanics, physical properties, and mineralogy. Drill-stem tests in ERDA-9 indicated no significant fluids or permeability in the Salado beds of interest.

The Waste Isolation Pilot Plant (WIPP) is a demonstration facility for the disposal of transuranic (TRU) waste from defense programs. The WIPP will also provide a research facility to investigate the interactions between bedded salt and high-level wastes.

Sandia National Laboratories and University of New Mexico. 1981. *Basic Data Report for Drillhole WIPP 15 (Waste Isolation Pilot Plant - WIPP)*. SAND79-0274. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: WIPP-15 is a borehole drilled in March 1978, in section 18, T23S, R35E, of south-central Lea County. The purpose of WIPP-15 was to examine fill in San Simon Sink to extract climatic information and to attempt to date the collapse of the sink. The borehole was cored to total depth (810.5 ft) and encountered, from top to bottom, Quaternary calcareous clay, marl and sand, and claystones and siltstones of the Triassic Santa Rosa Formation (?). Neutron and gamma-ray geophysical logs were run to measure density and radioactivity.

The sink has about 547 ft of Quaternary fill indicating subsidence and deposition. Diatomaceous beds exposed on the sink margin yielded samples dated by ^{14}C at $20,570 \pm 540$ years before the present and greater than 32,000 years before the present; these beds are believed stratigraphically equivalent to diatomaceous beds at 153-266-ft depth in the core. Aquatic fauna and flora from the upper 98 ft of core indicate a pluvial period (probably Tahokan) followed by an arid or very arid time before the present climate was established.

Aquifer pump tests performed in the Quaternary sands and clays show transmissivities to be as high as 600 ft²/day. As the water quality was good, the bore hole was released to the lessee as a potential water well.

Sandia National Laboratories and Westinghouse Electric Corporation. 1989. *Waste Isolation Pilot Plant Compliance Strategy for 40 CFR Part 191*. March 17, 1989. DOE-WIPP 86-013. Carlsbad, NM: WIPP Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) will be operated in compliance with the radioactive waste-disposal Standard (40 CFR Part 191) of the Environmental Protection Agency (EPA). The Standard has been remanded by the Court of Appeals (First Circuit) to the EPA. The original version of the Standard is being used in the interim, and compliance strategy will be revised to respond to any changes in the Standard, resulting from the court's decision.

"The WIPP Project's strategy for compliance includes defining the procedures and authorities for evaluating and determining compliance, evaluating performance using existing data and the results of ongoing studies, reporting results of compliance evaluations, and consulting and cooperating with the State of New Mexico under existing agreements."

"The Standard establishes requirements for both the management and storage (Subpart A) and the disposal (Subpart B) of radioactive wastes....data from operational effluent monitoring will be modeled to assess annual radiation doses to members of the public from management and storage operations at the WIPP" (Subpart A). Dose calculations will be evaluated with sampling and monitoring. "Predictions of long-term performance will be used to evaluate compliance with the dose and release limits of Subpart B." "The DOE WIPP Project Office, its management and operating contractor (Westinghouse Electric Corporation), and its scientific advisor (Sandia National Laboratories) are responsible for developing and implementing the program to evaluate compliance with the requirement of the standards." "The DOE Headquarters will determine whether or not WIPP complies with the Standard."

The WIPP *Safety Analysis Report* includes calculations similar to those required to determine compliance with Subpart A. "Compliance with Subpart A will be monitored and documented annually following the first receipt of waste at the WIPP and throughout its operational life."

If the evaluation shows that "...compliance with Subpart B cannot be achieved, ...transuranic (TRU) waste emplaced during the demonstration period will be retrieved. This decision is presently projected to occur within 5 years after the first receipt of waste." Satisfactory compliance with Subpart B and the "...decision to dispose of TRU waste at the WIPP would convert the WIPP from a demonstration facility to a disposal facility." DWP

Sandia National Laboratories, Experimental Programs Division. 1982. *Simulated-Waste Experiments Planned for the Waste Isolation Pilot Plant (WIPP)*. SAND82-0547. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The US Department of Energy (DOE) manages a research and development program to provide a technical basis for systems designs and safety and environmental assessments for future repositories of radioactive wastes resulting from US defense activities. The Waste Isolation Pilot Plant (WIPP) in southeast New Mexico is being developed within that program as a research and development facility to demonstrate the safe disposal of such wastes in bedded salt. The Simulated-Waste Experiments (SWEs) refer to the in situ tests (without radioactivity) in the WIPP research and development program which address the technical issues of isolating radioactive wastes in bedded salt. The SWEs include tests that concern the program areas of repository development and interactions of the waste package with the host rock. Data obtained from these tests will be used in evaluating performance assessment models and in developing a technical basis for future repository designs and operations.

Sandia National Laboratories. Waste Management Technology Department. 1987. *The Scientific Program at the Waste Isolation Pilot Plant*. SAND85-1699. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a research and development (R&D) facility in salt in NM; it will become a repository for transuranic (TRU) wastes if site evaluation, facility design, and operations prove satisfactory through the pilot plant phase. The R&D program is developed to demonstrate safe disposal of TRU waste and to develop the technology base for emplacing and isolating defense high-level waste in other repositories. The technology is to be developed in five areas: site evaluation and characterization; waste handling and operations; repository design and construction; waste package design and long-term performance; and repository decommissioning, sealing, and long-term performance.

The site has been validated for construction, but other activities in these areas continue to be investigated to increase confidence that radioactive wastes can be isolated safely in rock salt. The WIPP has proceeded through several phases, including construction of underground experimental areas to provide an understanding of waste isolation phenomena in the areas of thermal/structural interactions, waste package performance, and plugging and sealing of openings to the repository. Modeling is an important part of establishing technology and determining whether WIPP will meet long-term performance standards. Many of the models depend on specific information developed in the laboratory and field to validate the models for further predictions. Many of the issues from the scientific program for WIPP are expected to be resolved by the early 1990s. DWP

Sanford, A.R., and T.R. Toppozada. [Undated]. *A Report on the Seismicity of the Proposed Radioactive Waste Disposal Site in Southeastern New Mexico*. DOE/OR/21400--T342. Oak Ridge, TN: Oak Ridge National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The seismicity within 300 km of the proposed nuclear waste disposal site in southeastern New Mexico was determined. The primary data used to establish seismic risk were: reports of felt shocks prior to 1961; instrumental epicenters and magnitudes from 1961 through 1972; and lengths, displacements, and ages of fault scarps cutting Quaternary geomorphic surfaces. The principal results of this study were that: earthquakes exceeding local magnitude 3.5 have not occurred within 40 km of the site in the past 12 years and are not likely to have occurred in the past 50 years; major earthquakes, magnitude 7.8, are possible within 115 km of the site on the average of once every 50,000 years but these events will produce accelerations of only about 0.07g at the site; and the earthquakes located on the Central Basin Platform 80 to 100 km southeast of the site could be related to water injection for secondary recovery of oil, but the evidence is not conclusive.

Sanford, A.R., and T.R. Toppozada. 1974. *Seismicity of Proposed Radioactive Waste Disposal Site in Southeastern New Mexico*. Circular 143. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

ABSTRACT: Seismicity was determined for the area within a 300-km radius from the proposed nuclear waste disposal site in southeastern New Mexico. The primary data used to establish seismic risk were: reports of felt shocks prior to 1961; instrumental epicenters and magnitudes from 1961 through 1972; and lengths, displacements, and ages of fault scarps cutting Quaternary geomorphic surfaces. The principal results of this study were: earthquakes exceeding local magnitude 3.5 have not occurred within 40 km of the site in the past 12 years; probably not in the past 50 years; on the average of once every 50,000 years major earthquakes

(magnitude 7.8) are possible within 115 km of the site, but these events will produce accelerations of only about 0.07 g at the site; and some evidence indicates that earthquakes located on the Central Basin Platform, 80 to 100 km southeast of the site, could be related to water injection for secondary recovery of oil.

Sanford, A.R., S. Sandford, F. Caravella, L. Merritt, J. Sheldon, and R.[M.] Ward. 1978. *A Report on Seismic Studies of the Los Medaños Area in Southeastern New Mexico*. Socorro, NM: New Mexico Institute of Mining and Technology. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: New instrumental data has been acquired on earthquakes in the Los Medaños area since 1974 using a continuously recording seismograph (station CLN) near the site. The equipment records on film, producing high-resolution seismograms with excellent time control. Film is changed every 3 weeks. From April 1973 through most of October, 1974, the station operated 83% of the time, and 291 local and regional seismic events were recorded. Epicenters have been obtained for 75 events. Epicenters for many shocks are located on the Central Basin Platform (CBP) at one location near the southeastern corner of New Mexico and another about 50 km further southeast. Other epicenters include the region around Valentine, TX, and the Tularosa Basin. Longer studies indicate a surprising result—that earthquake activity appears as intense in geologically stable areas as in active areas such as the Rio Grande Rift. Either the stable areas are becoming active or, more likely, the magnitudes of events in these stable areas are limited. There is no geologic evidence consistent with CBP seismic activity, and extrapolating the data probably is invalid. Fluid injection for oil recovery may induce the activity. Two seismic events about 40 km northwest of CLN are the most important. Three additional events within 60 km of CLN have been recorded during 1975-1977 but cannot be located as they were recorded at only one station. DWP

Sanford, A.[R.], S. [Sandford], T.[C.] Wallace, L.[J.] Barrows, J. Sheldon, R.[M.] Ward, S. Johansen, and L. Merritt. 1980. *Seismicity in the Area of the Waste Isolation Pilot Plant (WIPP)*. SAND80-7096. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Since April 1974, New Mexico Institute of Mining and Technology has operated a short-period vertical-component seismograph 7 km from the center of the Waste Isolation Pilot Plant (WIPP) Site. Peak magnifications ranged from 405 to 1400 K. In the time period from April 1974 to February 1979, approximately 500 earthquakes were recorded by the instrument to distances as great as 660 km. With the aid of readings from stations operated by other organizations, epicenters and magnitudes for 159 earthquakes within about 300 km of the WIPP Site were obtained.

The greatest concentration of seismic activity is centered on the Central Basin Platform. This zone of activity, approximately 120 km in a north-south direction and 100 km in an east-west direction, approaches to within 60 km of the site. Other significant clusters of earthquakes occur near Snyder, Big Springs, and Valentine, TX.

Comparable levels of earthquake activity are observed within 100, 200, and 300 km of the site. Most reported Quaternary faulting lies to the west of 104.3 degrees W longitude. Comparable levels of activity were observed to the east and west of this longitude, indicating the observed distribution of earthquake activity is probably not representative of the long-term (500,000 years) seismicity of the region.

Several lines of evidence suggest that most earthquakes from the Delaware Basin eastward are induced by the production of hydrocarbons, but absolutely convincing proof is lacking. If due to natural tectonic forces, an extrapolation of the observed earthquake-frequency relation

indicates an earthquake of magnitude 5 1/2 is possible somewhere within 300 km of the site each 100 years.

Sanford, A.R., T.R. Toppozada, R.M. Ward, and T.C. Wallace. 1976. "The Seismicity of New Mexico: 1962 through 1972," *Abstracts with Programs, Geological Society of America, Albuquerque, NM, May 20-21, 1976*. Vol. 8, no. 5, 625-626. (Abstract Only).

ABSTRACT: Epicenters and magnitudes have been determined for 183 earthquakes that occurred within or bordering New Mexico from January 1, 1962 through 1972. The crustal model used for earthquake locations consisted of a 42-km-thick layer with a velocity of 6.15 km/sec overlying a semi-infinite layer with a velocity of 8.10 km/sec. Because of the small number of seismograph stations, P_g arrivals beyond the crossover distance were used in the location procedure, a computer adaptation of the arc method. Locations obtained are believed to be better than ± 15 km in nearly all cases.

The majority of seismic activity appears to follow two broad belts. One belt extends southwestward from the northeast corner of New Mexico across the Rio Grande Valley to the vicinity of Grants and then southward to the Silver City area. This diffuse zone of epicenters may be associated with Late Cenozoic volcanics. The other belt of seismicity follows the Rio Grande Valley, which has been an active rift structure since Miocene time. Shocks with $M_L \geq 3.4$ have also occurred in the High Plains and the Colorado Plateau.

Recurrence rates have been calculated for regions of 697,000, 311,000, 125,000, and 49,000 km² centered on stations located at Socorro and Albuquerque. The maximum magnitude earthquakes/100 years/100,000 km² for the four areas are 5.1, 4.7, 4.7, and 5.1, respectively. These levels of seismic activity are less than 1/100 of that observed in southern California.

Sattler, A.R., and C.L. Christensen. 1980. *Measurements of Very Large Deformations in "Potash Salt" in Conjunction With an Ongoing Mining Operation*. SAND79-2254. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Room and pillar deformation was measured in conjunction with a relatively new type of mining operation in a southeastern New Mexico potash mine. The extraction ratio was approximately 90% in a first mining operation. Due to severe deformations encountered, instrumentation had to be developed/modified for these measurements. This paper concentrates on experiment design, design of special instrumentation, field installation of equipment, and presentation of the data. Measurements made include extensometers in the pillar, in the floor and ceiling in the room between pillars, "absolute" level measurements, floor/ceiling closure, and stress (strain) measurements. Associated laboratory rock mechanics measurements of samples from the mine are being done separately.

Two separate room pillar complexes were instrumented. In the first complex, floor/ceiling deformations of approximately 1 in./day and pillar deformations around 1/2 in./day were measured. In the second complex, instrumentation was installed while the pillar was a part of a long wall and the subsequent sequential mining (long wall-pillar with only one adjoining room on one side —pillar in the middle of room pillar complex) was observed. Data return from this operation was good.

Sattler, A.R., and T.O. Hunter. 1979. *Pre-WIPP In-Situ Experiments in Salt. Part I - Executive Summary. Part II - Program Description*. SAND79-0625. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The pre-Waste Isolation Pilot Plant (WIPP) Program of experiments has been planned for a specially excavated area in a potash mine in southeastern New Mexico. This program is intended to acquire information to resolve generic issues about isolation of high-level waste in salt and to obtain data to help design the disposal system for the WIPP. In general, these experiments will help to evaluate thermochemical and mechanical responses of salt to heating; numerical modeling capability; and ability to plan and execute in situ experiments for the WIPP. Experiments supporting facility design and operations will evaluate: techniques and equipment for drilling large-diameter holes for waste canisters; transportation and emplacement techniques; canister retrieval; techniques for scanning salt to identify and locate gas and/or brine inclusions; borehole plugging; and air filtration and ventilation requirements.

WIPP program uncertainties have delayed the pre-WIPP activities.

DWP

Sattler, A.R., H.C. Walker, and T.O. Hunter. 1979. "In Situ Experiments to Support Development of the Waste Isolation Pilot Plant (WIPP)," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium, Boston, MA, November 27-30, 1979*. Ed. C.J.M. Northrup, Jr. SAND79-0905C. New York, NY: Plenum Press. Vol. 2, 491-498.

ABSTRACT: The main Waste Isolation Pilot Plant (WIPP) in situ activities will be associated with the early shaft complex to be planned and developed about FY80-81. There will be complexes for large-scale rock mechanics design verification, drifts with the heat load of anticipated waste, and experiments to address: transuranic waste emplacement and retrieval (without radioactivity), non-radioactive high-level waste interactions, thermal structural experiments, stable nuclide migration, brine migration, permeability, borehole plugging, operation and design, and instrument development and monitoring. The activities in progress range from laboratory and bench-scale to field experiments.

DWP

Saulnier, G.J., Jr. 1987. *Analysis of Pumping Tests of the Culebra Dolomite Conducted at the H-11 Hydropad at the Waste Isolation Pilot Plant (WIPP) Site*. SAND87-7124. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Culebra Dolomite Member of the Permian Rustler Formation was hydrologically evaluated in a series of pumping tests conducted at the H-11 hydropad at the Waste Isolation Pilot Plant (WIPP) Site in 1984 and 1985. The H-11 hydropad was constructed in 1983 and consists of three wells, H-11b1, H-11b2, and H-11b3, each completed open-hole to the Culebra Dolomite. At H-11, the Culebra Dolomite is a 25-ft thick argillaceous dolomite with 0.1- to 0.5-ft thick layers with a high density of vugs. The vugs range in size from 0.1 to 0.5 in. in diameter; most are 0.1 to 0.2 in. in diameter. The thin vuggy layers alternate with thicker, more competent layers, which have few vugs, but which do contain high-angle fractures. Some of the vugs and fractures are gypsum-filled.

The three pumping tests performed in 1984 consisted of 12- to 21-hour pumping periods at each of the three wells, while using the other two wells at the hydropad as observation wells. The 1985 pumping test was conducted at H-11b3 with H-11b1 and H-11b2 as observation wells. The 1985 test was a 32-day multirate test with four pumping and recovery periods. The 1984 tests were conducted by lowering a submersible pump and pressure transducers in the boreholes. The 1985 test added a downhole packer with feed-through assembly designed to isolate the test interval and reduce or minimize the effect of well-bore storage. The data from all tests were recorded and stored on floppy disks.

The pumping tests at the H-11 hydropad were analyzed with the INTERPRET reservoir-analysis software developed by Scientific Software-Intercomp. The analysis of the test data from both test periods indicates that at H-11, the Culebra Dolomite behaves as a multilayered, double-porosity reservoir with slab-type geometry. The INTERPRET analysis of the H-11 pumping tests provided estimates of the double-porosity parameters ω and λ . ω is defined as the ratio of the storage capacity of the secondary-porosity system of the producing formation, usually considered to be fractures, to the storage capacity of the combined primary- and secondary-porosity systems.

The range of values calculated for the double-porosity parameter ω in the observation wells was 0.30 to 0.43 for the 1984 tests and 0.07 for the 1985 test. The lower value for 1985 is probably due to the fact that the Culebra in all wells for this testing period was packer-isolated. The ω values for the type curves used to analyze the 1985 H-11 test suggest that the primary-porosity part of this double-porosity reservoir provides 93% of the storage capacity of the formation. The double-porosity parameters λ (also called the interporosity flow parameter) describes the ability of fluid to flow from the primary-porosity system to the secondary-porosity system (e.g., from matrix to fractures). The definition includes the ratio of the permeability of the primary-porosity system to the permeability of the secondary-porosity system. The average λ value for the H-11 tests was 3.0×10^{-6} , with an effective range of 3.73×10^{-7} to 1.25×10^{-6} . Analysis of the λ values determined for the H-11 test data indicates a permeability contrast between the primary- and secondary-porosity systems of about 1.0×10^{-6} with a characteristic slab-block dimension of 1 to 2 ft.

Using INTERPRET, the average transmissivity of the Culebra was calculated to be 23.2 ft²/day for the 1984 tests, 26.2 ft²/day for the 1985 test, and 24.0 ft²/day using the results of all the tests. The storativity of the Culebra, as determined from the pumping tests, is between 2.9×10^{-3} and 4.5×10^{-4} . The skin factors calculated from the pumping-well data range from -3.3 to -4.6, indicating that these wells behave as stimulated wells. The 1985 test at H-11b3 had both the highest transmissivity and the most negative skin factor, possibly implying that H-11b3 had undergone development during and after its 1984 test.

The results of the 1984 series of tests were also analyzed to determine the degree of anisotropy at the H-11 hydropad. The storage coefficient was estimated to be 6.3×10^{-4} . The average maximum transmissivity vector was 31.1 ft²/day oriented 5.8 degrees north of east and the average minimum transmissivity vector was 19.3 ft²/day oriented 5.8 degrees west of north. The ratio of the maximum to minimum transmissivity vectors was calculated to be 1.6, indicating a low degree of anisotropy at H-11, although the degree of anisotropy may be dependent on fracture orientation and locations of the wells.

Saulnier, G.J., Jr. 1988. *Field Operations Plan for Permeability Testing in the WIPP-Site Underground Facility*. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The far-field permeability and formation pressure of the Salado Formation is to be tested underground at the Waste Isolation Pilot Plant (WIPP) Facility to help estimate brine seepage into the repository. Data will also be acquired on the extent that underground openings have disturbed pressure and saturation. Twelve to 15 underground locations, each with arrays of up to 5 boreholes, will be tested. A double-packer test tool will be used to shut in the test and guard intervals, and pressure build-up in each brine-filled hole will be monitored. Pressure-pulse (pulse-withdrawal rather than pulse-injection) tests will also be conducted. Both bedded halite and interbeds above and below the disposal horizon will be tested. Testing may be completed late in 1990. DWP

Saulnier, G.J., Jr., and J.D. Avis. 1988. *Interpretation of Hydraulic Tests Conducted in the Waste-Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site.* SAND88-7001. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A series of sub-horizontal boreholes from 8- to 41-ft deep was drilled from four depth levels in the waste-handling shaft at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. The waste-handling shaft is one of three shafts built at the WIPP Site to provide surface access to the underground waste repository under construction 2150 ft below the ground surface. The boreholes were drilled at the 782- and 805-ft-depth levels in a mudstone and a claystone of the unnamed lower member of the Rustler Formation; at the 850-ft-depth level in bedded halite in the upper Salado Formation; and at the 1350-ft-depth level in halite, anhydrite, and polyhalite of the Salado Formation. Examination of the cores recovered from one borehole at each level indicated no direct evidence of construction-induced fracturing. Pulse-injection tests were conducted in packer-isolated intervals in six of the boreholes to estimate the formation's hydraulic conductivity and apparent formation pressure and to determine whether there was evidence of construction-enhanced permeability up to one shaft diameter from the shaft wall.

The pulse-injection tests were performed using a multipacker test tool configured to isolate three test zones in each borehole tested. The test tool was equipped with pressure transducers and thermocouples to sense the fluid pressure and temperature in each test zone and the pressure in the packer-inflation system. Ports in each test interval also allowed fluid injection to impose near-instantaneous pressure pulses on the isolated intervals. During the test sequences, the pulses were shut in and the fluid-pressure responses were monitored with an automated data-acquisition system.

The pulse-injection tests were analyzed using graph-theoretic-field-modeling (GTfM) techniques. The GTfM numerical model can incorporate the effects of the pretest pressure histories of the test intervals into model simulations of the fluid-pressure response to the pulse injections. The simulations were compared to the observed test data. The analyses were performed in an iterative manner for ranges of hydraulic conductivity and apparent formation pressure to obtain a best-fit match of the model simulations and the observed data. The pulse-injection tests have been affected to an unknown degree by compliance of the multipacker test tool. The compliance effects add a level of uncertainty to the final results.

Acceptable simulations were achieved for most of the tests. The results of the analyses of the tests at the 1350-ft-depth level were the most uncertain because equipment limitations and safety considerations prevented the application of pressure pulses significantly greater than the apparent formation pressures. At the 782-ft-depth level, apparent pressure communication either through the formation or the test tool or both was observed between the test zones.

Water and gas were produced in boreholes at the 850-ft-depth level. In particular, one borehole had an observed inflow, apparently issuing primarily from the shaft liner-to-formation contact. The water inflow filled the boreholes both before and after testing. An attempted pulse-injection test in the test zone closest to the shaft wall at the 850-ft-depth level could not be performed because the attempted applied pulse could not be maintained and properly shut in. The test zone included the shaft liner-to-formation contact and the pressure appears to have been dissipated by a discrete fracture in the formation or by the contact itself.

All zones tested except the near-shaft-wall zone at the 850-ft level had low hydraulic conductivities. The analyses indicate a range of hydraulic conductivity between 6.0×10^{-15} and 1.0×10^{-13} m/sec. Considering the limited time available for pretest pressure buildup and for the conduct of the tests, and the uncertainty surrounding the packer-compliance effects of the test tool, the range of about one order of magnitude in interpreted hydraulic conductivity indicates that all zones and geologic units tested have similar and low hydraulic conductivities. The formation pressures determined by the analyses have a moderate degree of uncertainty

because they were derived from relatively short-term tests in rocks with low hydraulic conductivity. The time limitations for testing did not allow an adequate pretest period for the buildup of pressure to near ambient conditions before initiating the pulse-injection sequences. The apparent formation pressures nonetheless indicate a pattern in which the tested formations are depressurized within 10 ft of the shaft. The apparent formation pressures at each depth level tested generally increase moving from the shaft into the formations and increase with depth from land surface. At the 805-ft-depth level in the upper Salado Formation near the Rustler-Salado contact, the tested formation has undergone significant depressurization in zones greater than one shaft diameter from the shaft and the formation appears to be depressurized relative to the formations above and below this level.

Saulnier, G.J., Jr., G.A. Freeze, and W.A. Stensrud. 1987. *WIPP Hydrology Program Waste Isolation Pilot Plant Southeastern New Mexico Hydrologic Data Report #4*. SAND86-7166. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #4* is organized in five parts. Part A presents hydrologic data obtained during a series of pumping tests on the Culebra Dolomite Member of the Rustler Formation at the H-11 hydropad in October 1984. The tests alternately tested each of the three wells at the H-11 hydropad while using the other two wells as observation wells. The pumping periods varied from 2 to 13 hours. Average pumping rates were from 2.25 to 4.14 gpm in these wells. Part B describes well development and a 100-hour pumping test of the Culebra Dolomite Member conducted at well DOE-2. The well was treated with 20% hydrochloric acid to enhance performance. A pumping rate of approximately 35 gpm was used. Water level was measured frequently at WIPP-13, H-6b, WIPP-12, and WIPP-18. Drawdown was 29.7 psi in DOE-2, with 92% recovery 7.5 days after pumping ceased. Water levels in WIPP-13 responded within 3 hours of starting to pump. Part C describes well development and hydrologic testing at WIPP-12, WIPP-13, WIPP-18, WIPP-19, WIPP-21, and WIPP-22. Only WIPP-13 appeared to have sufficient Culebra permeability to sustain a pumping test. The Culebra permeability at WIPP-12 was so low that an acid treatment failed to enhance flow. The Culebra also has low permeability at WIPP-18, WIPP-19, WIPP-21, and WIPP-22. Slug-injection tests in these wells recovered in 24 to 48 hours. A 50-hour pumping test was conducted at WIPP-13 at approximately 34 gpm while eight wells were monitored for water-level changes. Part D presents data from bore-hole-deviation surveys at the WIPP Site multiple-well hydropads. In 1986, the H-2, H-3, and H-11 hydropads, and well H-7b2, were surveyed for downhole deviation using a rate-averaging gyroscope. Part E presents water-level data collected from wells in the observation-well network from April through October 1986. Eight wells are completed in the Magenta, 45 are completed at the Culebra, one well monitors the Rustler-Salado contact, and two wells monitor Bell Canyon water levels. DWP

Saulnier, G.J., Jr., T.L. Cauffman, V.A. Kelley, J.F. Pickens, and W.A. Stensrud. 1989. "Practical Aspects of Design and Field Implementation of a Convergent-Flow Tracer Test," *Ground Water*. SAND89-7079A. Vol. 27, no. 5, 728. (Abstract Only, Presented at Tracers in Hydrogeology: Principles, Problems, and Applications, National Water Well Association Conference, Houston, TX, October 31-November 1, 1979).

ABSTRACT: INTERA Technologies conducted a four-well convergent-flow tracer test in a fractured region of the Culebra [Dolomite Member of the Rustler Formation] at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico as part of the site-characterization program directed by Sandia National Laboratories. The Culebra Dolomite is considered to be a potential offsite pathway in the event of a natural or man-made breach of the WIPP repository.

The tracer test consisted of pumping one well at a rate of 23 L/min to establish an approximate steady-state convergent flow field and injecting traced fluid at three wells located 21 to 43 m from the pumping well. The conservative organic tracers, metatrifluorobenzoate, pentafluorobenzoate, and orthotrifluorobenzoate, were introduced individually into the tracer-addition wells. A volume of untraced fluid was injected following the traced fluid to displace all tracer solution from the well and into the formation. A tracer-injection system utilizing downhole packers was designed to facilitate traced fluid injection and to minimize the injection-zone volume. The tracers were injected with a uniform concentration and vertical distribution. Tracer analysis of the water samples was complicated by the formation-water salinity and required specialized analytical procedures. Tracer-concentration data were corrected for flow time through the injection and discharge plumbing.

Times-to-peak concentration at the pumping well for the tracers introduced at two wells located 21 m from the pumping well were 8 and 144 hours indicating significant formation heterogeneity. The tracer breakthrough curves, simulated using the double-porosity flow-and-transport model SWIFT II, yielded estimates of 0.001 for fracture porosity and 3 m for effective matrix-block size.

S-CUBED. 1988. *WIPP Horizon Flow Tests (Using High Resolution Gas Flow Test Tool) Test Region Measurements*. La Jolla, CA: S-CUBED. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This document outlines procedures for performing single-hole, gas flow tests of low permeability formations through small diameter (1 7/8 to 2 inch) boreholes. The High Resolution Gas Flow Test (HRGFT) tool consists of four packers that can isolate lower and upper guard units as well as the central test region. Test regions can be varied by some or all of the packers. Pressures in portions of the borehole tool, test region temperature, and packer pressure are monitored and logged. The document also includes test procedures for the HRGF, discusses operational features of the data system, and provides transducer calibration data.

DWP

Scully, L.W. 1977. "Conceptual Design of the Waste Isolation Pilot Plant for ERDA TRU Waste," *Transactions of the American Nuclear Society, 1977 Annual Meeting, San Francisco, CA, November 27-December 2, 1977*. Vol. 27, 435-436. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) will demonstrate that it is feasible to dispose of radioactive waste in bedded salt. Low- and intermediate-level transuranic (TRU) wastes from US defense programs will be disposed at the WIPP, and high-level wastes will be used in experiments. The WIPP will be a full-scale facility which will not be used to full capability until the safety of operations and disposal is assured. While there is no requirement for Nuclear Regulatory Commission (NRC) licensing, the design has been produced as though an NRC license were required. The facility will have one level at about 2100 ft for contact handled TRU waste and another level at about 2600 ft for remotely handled waste and high-level waste experiments. The design will allow handling 1,200,000 ft³ of contact handled waste and 250,000 ft³ of remotely handled waste per year for a nominal operating life of about 25 years.

DWP

Seedorff, W.A., Jr. 1978. *Resource Study for the Waste Isolation Pilot Plant Site, Eddy County, New Mexico*. San Carlos, CA: Agricultural and Industrial Minerals, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Site area, approximately 18,960 acres, was studied to define and evaluate the potash resources and reserves, determine the impact on the industry and market supply if the WIPP area is withdrawn from mining, and value leaseholder and State of New Mexico interests. Conclusions were based on available data from government and company core-hole information. Selected samples were metallurgically tested. The lower limit of mining thickness was established as 4.5 ft.

Lessee values for four tracts of about 4797 acres totals \$1,780,800. Lessor values for the State of New Mexico for these tracts is \$27,200.

Drilling is too widely spaced for accurate resource determinations. The WIPP Site is estimated to contain about 153 million tons of recoverable resources in generally low grade deposits that may be economic in 20 to 40 years. About 29.7 million tons are recoverable as ore and could be processed economically by Duval and International Minerals. These are classified as reserves. Estimated products from the recoverable resources are 30.9 million tons of langbeinite and 6.0 million tons of muriate of potash. Estimated products from the reserves are 4.2 million tons of langbeinite and 1.8 million tons of muriate of potash. The products from both resources and reserves are small compared to US resources, and withdrawal will not affect market supply in the foreseeable future. Other deposits in the Carlsbad district will be mined earlier because of more favorable grade, thickness, location, and capital requirements. Because the outer zone (IV) includes about 69% of the resources, releasing this zone for mining would further minimize the impact. "Withdrawal of the WIPP acreage will have no measurable impact on the economy of the Carlsbad area for many years in the future." The expenditures for the WIPP Project are expected to have a far greater impact on the economy of the area. DWP

Seltz, M.G., D. Bowers, and D.R. Fortney. 1981. *A Groundwater Stream Experiment for the Waste Isolation Pilot Plant.* ANL-81-28. Argonne, IL: Argonne National Laboratory. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This project was conducted to evaluate the practicality of using laboratory groundwater stream experiments to model a hydraulic breach of a nuclear waste repository located deep in a bedded salt environment. A test plan is included in this report that gives details of the apparatus, rocks, solutions, and analyses to be used in a groundwater stream experiment.

Preliminary experiments revealed the essential impermeability of halite; only a small concentration of water (about 75 ppm) moved in halite by diffusion, with a coefficient of 2.0×10^{-7} cm²/sec. From work completed in this program, groundwater stream experiments appear to be a practical method of establishing the chemical interactions that would occur in a breached repository in bedded salt.

Senseny, P.E. 1986. *Triaxial Compression Creep Tests on Salt From the Waste Isolation Pilot Plant.* SAND85-7261. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Twenty-six triaxial compression creep tests were performed on argillaceous and clean salt from the Waste Isolation Pilot Plant (WIPP). The average water- and ethylenediaminetetraacetic acid-insoluble content of the argillaceous salt was 1.5 and 0.75%, respectively. This small quantity of impurities corresponded to consistent but small increases in the deformation measured during the tests.

Results of these tests are similar to those obtained previously with two exceptions. The first is that the stress dependence of the steady-state strain rate at 25°C is greater than reported

previously. The second is that the temperature dependence of the transient strain limit appears to be greater than reported previously.

Senseny, P.E. 1990. *Creep of Salt From the ERDA-9 Borehole and the WIPP Workings*. SAND89-7098. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Six triaxial compression creep tests were performed to measure the creep deformation of salt from the ERDA-9 borehole and salt from the underground workings at the Waste Isolation Pilot Plant (WIPP). Even though the test matrix is quite limited, important results were obtained that added to existing data from previous test matrices. The WIPP salt was annealed to reduce the hardening that occurred as the openings deformed after mining. Five tests were performed at a temperature of 25°C, a confining pressure of 15 MPa, and stress differences of either 10.0 or 15.0 MPa. The sixth test was performed at a temperature of 22°C, a confining pressure of 20.7 MPa, and a stress difference of 11.7 MPa. Test duration ranged from approximately 160 to 335 days.

Deformation of these six specimens is compared with that obtained previously under identical test conditions for specimens from other horizons of the ERDA-9 borehole and from unannealed specimens from the WIPP workings. Results suggest that the magnitude of the transient deformation depends on the horizon from which the specimen was taken and whether the specimen hardened in situ as the mined openings deformed.

Serata, S. 1979. *Empirical Design Basis of Underground Salt Openings in the WIPP Project*. Document No. DR-51-R-1. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Rock mechanics methods developed by Serata for use in salt at depths exceeding 2000 ft are summarized as a basis for Title I design work for the Waste Isolation Pilot Plant (WIPP). The methods are based on surveys of world-wide literature as well as interactive modeling and empirical results from potash mining and other underground activities. Among the findings, the following points are important for deeper excavations: creep closure in salt is highly site-specific, with no general simple rules; discontinuity planes above and below the opening profoundly affect long-term behavior; creep laws are not useful without information about weakness planes; single and multiple room excavations behave very differently; creep failure occurs regardless of extraction ratios; conventional rock creep concepts are generally not applicable because of pronounced brittle-ductile characteristics of rock salt below 2000 ft; pillar behavior cannot be determined only by pillar dimensions; roof strata behavior is governed by geological complexities and the geometry of structures rather than by room width or roof slab dimensions by themselves; stress conditions change with time; and stability is profoundly affected by interaction of stress envelope and weakness planes.

Basic design for the WIPP is to construct multiple rooms simultaneously with narrow yield pillars. This will maximize stress relief with minimum disturbance to weak strata and form a large protective stress envelope. Multiple rooms will experience greater initial closure than single rooms, but they are expected to establish long term creep stability, possibly greater than for single rooms.

The design would be refined further under Title I work.

DWP

Serata, S., and J.F. McNamara. 1981. *Second Benchmark Problem for WIPP Structural Computations, REM Program Results*. Berkeley, CA: Serata Geomechanics, Inc. (Copy on

file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The second benchmark problem is designed to calculate the long-term behavior of waste storage facilities in salt having complex stratigraphy. Two drift configurations were considered, involving different size rooms located at different depths. The isothermal case held a constant temperature of 300 K, while a second case simulated heat producing waste beneath the room floor. A proprietary finite-element code (REM) was used to evaluate the problem.

Horizontal movement dominated along the slide lines in the cases. Room closure and mid-pillar displacement curves show that no long-term creep stability occurs in either case, as indicated by large room closure rates at 10 years. Thin layers, such as the anhydrite in the floor, need to be more precisely approximated. The benchmark problem has provided a suitable and adequate means of comparing diverse codes in use. DWP

Sargent, Hauskins & Beckwith. [Undated]. *Phase III. Volume I. Subsurface Exploration and Laboratory Testing. Railroad and Access Roads.* Albuquerque, NM: Sargent, Hauskins & Beckwith. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Phase III of the subsurface exploration and laboratory testing program included exploratory drilling, test pit excavations, sampling subsurface soils and rocks, in situ rock testing, and laboratory testing of samples. Volume I reports field work and laboratory tests. Reported data include: logs of test borings B-301 through B-309; logs of test pits TP-101 through TP-149; field density tests; laboratory tests to provide sieve and hydrometer analyses, Atterberg limits, moisture content, unit weight, moisture-density relationships, relative density, California Bearing Ratio data, and chemical data; and visual soil classification data. Data are not analyzed. DWP

ANNOTATION: Vol. 2 of the data is the reference included in this bibliography as Dames and Moore, 1979b.

Sargent, Hauskins & Beckwith. 1979a. *Volume I. Subsurface Exploration & Laboratory Testing. Plant Site: Waste Isolation Pilot Plant.* Phoenix, AZ: Sargent, Hauskins & Beckwith. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The data for test borings and laboratory tests for Phase I and II of subsurface exploration and laboratory testing are reported. Lithologic logs and field permeability tests are included. Among the data developed for soil samples were grain size analysis, liquid limits, plastic limits, plasticity index, specific gravity, moisture-density relations, penetration tests, and soil classifications and descriptions. The data are not analyzed. DWP

Sargent, Hauskins & Beckwith. 1979b. *Volume II. Subsurface Exploration & Laboratory Testing. Plant Site: Waste Isolation Pilot Plant.* Phoenix, AZ: Sargent, Hauskins & Beckwith. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report, as volume 2, includes visual soil classification data of the subsurface exploration and laboratory testing program. Data are not analyzed. DWP

Sergent, Hauskins & Beckwith. 1979c. *Seismic Refraction Survey Report, Waste Isolation Pilot Plant.* Phoenix, AZ: Sergent, Hauskins & Beckwith. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Reconnaissance seismic refraction data from the Waste Isolation Pilot Plant (WIPP) surface facility site area have been acquired and interpreted as generalized profiles of compressional wave velocities and depths to velocity interfaces in near-surface rocks. Four east-west and six north-south traverses completed in late 1978 total about 24,600 linear ft. Small explosive charges in shallow holes provided the seismic energy source. Back-to-back spread lengths of 300 and 600 ft employed 12 and 24 geophones, respectively, over 20- to 25-ft intervals. Profiles were reversed to obtain continuous velocity profiles and information about velocity anisotropy and interface attitudes. Recorded data varied from fair to excellent quality, and the results are considered reliable. Depths shown on velocity cross sections are estimated to include usual errors of about $\pm 15\%$.

"In general, the seismic results throughout the profiled area suggest some degree of layering affect of the material, with slight monotone variation, toward the southwest, in the attitude of the more competent, lower interfaces. Five to six velocity zones are present to a maximum depth of about 90 ft along the investigated profiles. The deepest depth penetrated by the seismic waves along the lines of these surveys was about 150 ft." DWP

Serne, R.J., D. Rai, M.J. Mason, and M.A. Molecke. 1977. *Batch K_d Measurements of Nuclides to Estimate Migration Potential at the Proposed Waste Isolation Pilot Plant in New Mexico.* PNL-2448. Richland, WA: Battelle Pacific Northwest Laboratories.

ABSTRACT: Laboratory measurements to determine the sorption distribution coefficients, K_d , of radionuclides present in, and potentially leached from radioactive wastes, in contact with representative geologic media have been conducted. The nuclides studied include Cs, Sr, Tc, Ru, Sb, Ce, Eu, Pu, Np, Cm, Am, U, and Pa. The crushed rock materials used were from the vicinity of the Waste Isolation Pilot Plant (WIPP), a project to isolate radioactive wastes in a bedded salt facility, near Carlsbad, New Mexico. Solutions used consist of salt brine and groundwater, specific to the WIPP Site, plus distilled water, for laboratory intercomparisons. The batch K_d data reported herein, plus data from sorption and migration measurements being conducted or planned elsewhere, will be used to evaluate the potential for radionuclide migration from the bedded salt WIPP Facility. The data can be used for transport modeling and for safety-assessment determinations.

Seward, P.D. 1982. *Abridged Borehole Histories for the Waste Isolation Pilot Plant (WIPP) Studies.* SAND82-0080. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Abridged hole histories for 72 boreholes drilled for the Waste Isolation Pilot Plant (WIPP) Project summarize borehole locations, depths, hole conditions, geophysical logs, and observations. The report is a working document and is not interpretive. A map of borehole locations is included.

Shaffer, S-E. 1977. *Preliminary Alternate Site Studies*. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Certain criteria were established to evaluate the area of southeastern New Mexico within the Delaware Basin in regard to alternate site studies for the Waste Isolation Pilot Plant (WIPP) Program. Based on current information and criteria, the Los Medanos site is the best area for the WIPP. However, the criteria now established are arbitrary and reflect present knowledge and engineering capabilities; greater knowledge and technical advances could result in relaxation of some of these criteria, thus opening up new areas for possible sites.

Shaffer, S-E. 1982. *Bibliography of Geology of Southeastern New Mexico*. SAND82-0770. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This volume is composed of 1464 geological citations cross-indexed by subject and author. A reference map is included.

Shelfelbine, H.C. 1982. *Brine Migration: A Summary Report*. SAND82-0152. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: As defined in this report, brine migration is the movement toward a heat source of the water trapped in rock salt. This phenomenon is of interest because the disposal of heat-producing radioactive wastes can trigger brine migration. Contact between the brine and the waste packages could lead to such undesirable interactions as corrosion of the canister or even migration of the radionuclides. This report summarizes a Sandia National Laboratories program to characterize brine migration. Based on this program and on the work of others, we conclude that brine migration is not a significant problem. The quantities of water (less than 20 L/waste canister in 1000 years) are too small for concern.

Shelfelbine, H.C., and G.E. Raines. 1980. "Fluid Migration Studies in Salt," *Proceedings of the 1980 National Waste Terminal Storage Program Information Meeting*, Columbus, OH, December 9-11, 1980. ONWI-212. Columbus, OH: Battelle Memorial Institute. 358-360.

ABSTRACT: Current fluid migration studies in salt have two objectives: 1) determine fluid character and 2) define mechanisms that cause fluid to migrate toward heat sources. The Sandia National Laboratories program is concentrating on the characteristics and processes for the WIPP site. The program has resulted in: a) additional fluid characteristics, showing about 0.5% fluid by weight and high potassium and magnesium content in fluids in salt, 3) an experiment (Salt Block II) testing water release from a heated hole in a large salt block, 4) and 5) continuing and proposed studies, including applying vapor phase transport models of Salt Block II. These studies "have not yet provided complete answers to the original objectives. However, it is evident that the amounts of moisture released are very small even under the extreme conditions of the experiments." DWP

Siegel, M.D. 1990. "A Model for the Chemical Evolution of Groundwater in the Culebra Dolomite: Implications for Radionuclide Transport from the Waste Isolation Pilot Plant (WIPP)," *Abstracts with Programs, Geological Society of America, Dallas, TX, October 29-November 1, 1990*. Vol. 22, no. 7, A101. (Abstract Only).

ABSTRACT: The Culebra Dolomite Member of the Rustler Formation is a potential subsurface pathway for long-term transport of radionuclides from the Waste Isolation Pilot Plant to the accessible environment as defined by Environmental Protection Agency (EPA) 40 CFR 191. A model for the post-Pleistocene hydrochemical evolution of the Culebra has been used to identify chemical reactions that may control the composition of groundwaters produced by the mixing of repository fluids and Culebra waters and thereby the degree of radionuclide retardation in the Culebra. The model suggests that as Na, Cl, Mg, K, and SO_4 are added to the Culebra by saline repository brines, equilibrium will be maintained with gypsum and calcite, and dolomite supersaturation will increase. Calculations of solute mass transfer along modern flow directions and factor analysis of solute correlations suggest that ion exchange has affected the concentrations of Ca, Mg, Si, Li, and B in the Culebra. Corrensite, a mixed chlorite/smectite, is the dominant clay mineral in the Culebra fractures (20% by weight). It has a cation exchange capacity of approximately 45 meq/100 g and is the most likely ion-exchange medium. The hydrochemical model has been used to design radionuclide sorption and solubility experiments. The model and the experimental studies suggest that radionuclides will be retarded by sorption by clays within the Culebra and that the potential for coprecipitation of actinides in gypsum and calcite exists.

Siegel, M.D., J.O. Leckie, S.W. Park, S.L. Phillips, and T. Sowards. 1990. "Studies of Radionuclide Sorption by Clays in the Culebra Dolomite at the WIPP Site, Southeastern New Mexico," *Waste Management 90, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 25-March 1, 1990*. Ed. R.G. Post. SAND89-2387C. Tucson, AZ: University of Arizona. Vol. 2, 893-900.

ABSTRACT: The ability of radionuclide-rock interactions to retard the migration of plutonium and uranium within clay-lined fractures in the Culebra Dolomite Member of the Rustler Formation is being estimated in support of the performance assessment of the Waste Isolation Pilot Plant (WIPP). This paper describes progress in three coordinated studies: characterization of the properties of the groundwater and minerals in the Culebra that will control radionuclide retardation; development of a thermodynamic model for the adsorption of uranium onto corrensite, the mixed chlorite-smectite clay mineral found in Culebra fractures; and development of a data base of equilibrium constants and interaction parameters for calculations of the aqueous speciation of uranium and plutonium in Na-Cl-Ca- SO_4 - CO_3 solutions, which contain organic ligands, such as EDTA, and range in ionic strength from approximately 0.8-6.0 molal.

Stemmers, W.T., J.W. Hawley, C. Rautman, and G. Austin. 1978. *Evaluation of the Mineral Potential (Excluding Hydrocarbons, Potash, and Water) of the Waste Isolation Pilot Plant Site, Eddy County, New Mexico*. Open File Report 87. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The mineral potential of a proposed Waste Isolation Pilot Plant (WIPP) Site, located 40 km east of Carlsbad, Eddy County, NM, has been evaluated on the basis of information obtained from onsite field studies, the examination of records provided by Sandia National Laboratories (SNL), and pertinent literature. The site is located near the northern edge of the Delaware Basin; the upper part of the stratigraphic section is comprised of marine and continental red beds underlain by marine Ochoan evaporites.

Available data indicate that the only WIPP Site-related commodities that may have any economic potential are: caliche, salt, gypsum, lithium-bearing brines, sulfur, and uranium. A more detailed study, however, indicates that for one or more of several reasons including: commodity abundance; commodity accessibility; low demand for the commodity; and adequate

supplies of the commodity elsewhere, these six commodities are uneconomic at present and for the foreseeable future.

Sipes, Williamson & Associates, Inc. 1979. *Evaluation of Directional Drilling for Oil and Gas Reserves Underlying the Waste Isolation Pilot Plant Site Area, Eddy County, New Mexico.* Midland, TX: Sipes, Williamson & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Three cases were evaluated for directional drilling to obtain hydrocarbon reserves beneath the Waste Isolation Pilot Plant Site, and the incremental cost over straight-hole vertical drilling was determined. The incremental cost for drilling 55 wells from outside zone IV (case A) is \$87,226,000. Directional drilling of 44 wells from outside zone IV and 11 wells from inside zone IV (case B) is estimated to cost \$57,339,000. Drilling of all wells under zone IV as straight holes and all other wells as directional drilling from zone IV (case C) has an incremental cost of \$21,790,000. Several assumptions were made: the primary target is Pennsylvanian rocks at an average depth of 14,750 ft; well spacing is 320 acres; drilling restrictions for potash areas do not apply; minimum depth for beginning directional drilling is 4,800 ft; costs are estimated as of October 1979; maximum bottom-hole target radius of 500 ft would be allowed; the path of the directional hole below the kick-off point is not restricted; and geologic structures were not factored into cost estimates. Theoretically, all of the wells can be drilled by directional methods. DWP

Sipes, Williamson & Associates, Inc. 1980a. *Estimation of Potential Hydrocarbon Reserves and Associated Costs and Income for Oil and Gas Reserves Underlying the Waste Isolation Pilot Plant Site Area, Eddy County, New Mexico.* Midland, TX: Sipes, Williamson & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The potential hydrocarbon reserves, and associated costs and income have been evaluated for the Waste Isolation Pilot Plant (WIPP) Site area. The potential hydrocarbon reserves are estimated as 83,974,500 MCF (thousand ft³) of gas and 390,843 barrels of condensate. The undiscounted gross wellhead value of the reserves is estimated as \$287,502,346. Undiscounted costs for three distinct drilling cases range from about \$117,146,000 to \$182,306,000 with operating costs of \$10,146,324. The undiscounted loss of revenue to the State of New Mexico, if no drilling is allowed, is \$19,107,546 per annum. These estimates in preparation of the environmental impact statement should not be construed as a fair market value for these reserves. The evaluation is effective December 1, 1979. DWP

Sipes, Williamson & Associates, Inc. 1980b. *Appraisal Report for Tract 204M-2 (Superior Oil Company), Waste Isolation Pilot Plant Site, Eddy County, New Mexico.* Midland, TX: Sipes, Williamson & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Tract 204M-2 contains about 1,120 acres in Sections 28 and 29, T22S, R31E, under the southern half of the central four square miles of the Waste Isolation Pilot Plant (WIPP) Site. The fair market value of the tract was appraised at \$777,642, as of December 1, 1979, based on hydrocarbon reserves estimated at 1,863 barrels of condensate and 1,448,000 MCF (thousand cubic ft) of gas. One possible drilling location was designated for the southern half of Section 28. DWP

Sipes, Williamson & Associates, Inc. 1980c. *Appraisal Report for Tracts 204M-1, 204M-2 and 204M-3 (Superior Oil Company), Waste Isolation Pilot Plant Site, Eddy County, New Mexico.* Midland, TX: Sipes, Williamson & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Three tracts of land under lease to Superior Oil Company have been evaluated to determine the fair market value for hydrocarbons effective February 1, 1980. Tract 204M-1 (in Sections 9 and 10, T22S, R31E) contains about 1,120 acres and is appraised as having a value of \$517,440. Tract 204M-2 (in Sections 28 and 29, T22S, R31E) contains about 1,120 acres and is appraised at \$841,578. Tract 204M-3 (in Section 4, T23S, R31E) contains about 239.45 acres and is appraised at \$147,501. The hydrocarbon potential for Tract 204M-2 is considered favorable, and a possible drilling location has been assigned for the southern half of Section 28. The remaining acreage in these tracts was assigned a value based on acreage "since no proposed drilling locations could be forecasted from the engineering and geological data available."

DWP

Sipes, Williamson & Associates, Inc. 1981. *Oil and Gas Reserves Appraisal Report for Tracts 201M-3, 201M-4 and 201M-6 (Gulf Oil Corporation) in the Area of the Waste Isolation Pilot Plant Site, Eddy County, New Mexico.* Midland, TX: Sipes, Williamson & Associates, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Three tracts of land under lease to Gulf Oil Corporation have been evaluated to determine the fair market value for hydrocarbons effective June 1, 1981. Tracts 201M-3, 201M-4, and 201M-6 contain about about 640 acres each (total 1,920 acres) in sections 21, 27, and 33 of T22S, R31E. The fair market value of Tract 201M-3 is appraised at \$2,027,664. The fair market value of Tract 201M-4 is appraised at \$1,099,176.

The fair market value of Tract 201M-6 is appraised at \$1,846,184. Well locations in the northern half of Tract 201M-3 were assigned probable reserves. Well locations in Tract 301M-6 were assigned possible reserves. Other tracts were undesignated for reserves.

DWP

Sipes, Williamson & Aycok, Inc. 1976a. *Hydrocarbon Evaluation, Proposed Southeastern New Mexico Radioactive Material Storage Site, Eddy County, New Mexico.* SAND77-7033. Albuquerque, NM: Sandia National Laboratories. Vols. 1-2.

ABSTRACT: The proposed radioactive waste storage site, located in the northern portion of the Delaware Basin, was evaluated to determine the remaining economically recoverable oil and gas reserves. No hydrocarbons are produced within the current boundaries of the "site area," but oil and gas are being produced from 60 wells in a 368 square-mile radius of the site. The Delaware, Bone Springs, Wolfcamp, Strawn, Atoka, and Morrow zones produce about 22,682 MCF (thousand ft³) of gas and 429 barrels of oil per day. This area is considered to be potentially rich in hydrocarbon reserves. Fuller development and exploration is lacking due primarily to low gas prices, lack of sales outlets and/or pipelines, and moratoriums on drilling in the potash areas. Proved producing and proved nonproducing reserves exist in two wells in the Los Medanos field area immediately adjacent to the southwest corner of the "site area." Proved undeveloped, probable and possible reserves exist at six potential drilling locations in the Los Medanos field. Probable and possible reserves were assigned to 15 other potential drilling locations in the northwest and south-central portions of the "site area." Total economically recoverable reserves projected for these wells are 62,253,244 MCF of gas and 409,628 barrels of oil. The future net undiscounted revenue to the oil operators was determined to be \$48,410,821. The future net revenue is \$21,216,899, discounted at 10% per

annum. Fair market value for these projected reserves is \$12,730,139, assuming a fair market factor of 0.60. DWP

ANNOTATION: Foster (1974) evaluated hydrocarbon resources, for the area around WIPP, based mainly on geological and statistical methods.

Sipes, Williamson & Aycock, Inc. 1976b. *Directional Drilling Feasibility, Los Medaños Radioactive Waste Material Storage Site, Eddy County, New Mexico*. Midland, TX: Sipes, Williamson & Aycock. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The possibility of directionally drilling for hydrocarbon exploration below the proposed site has been investigated. The technique is feasible, with estimated additional costs of \$360,000 to \$586,000 per well, representing about 26 to 42% increases over straight drilling. These costs would make drilling a well for possible reserves of 1,670,000 MCF of gas uneconomical on a discounted cash flow basis. Locations assigned 2,087,000 MCF of probable reserves would be barely economical to uneconomical. Drilling deviated holes would probably be restricted to close-in locations in the Los Medaños field at the southwest edge of the site. DWP

Sipes, Williamson & Aycock, Inc. 1978. *Appraisal Report, Waste Isolation Pilot Plant Site, Eddy County, New Mexico Including Tract III: Containing 320 Acres of Land, More or Less, Situated in Section 36, Township 22 South, Range 30 East, Eddy County, New Mexico*. Midland, TX: Sipes, Williamson & Aycock, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Tract III is about 320 acres, mainly in the northern part of Section 36, T22S, R31E, in the southwest corner of the Waste Isolation Pilot Plant Site (WIPP) area. Tract III was appraised to determine the fair market value of oil and gas reserves underlying the tract. Proved undeveloped reserves were assigned to the Atoka "formation" and probable reserves to the Morrow "formation." Future net revenue, discounted at 10% per annum, was projected at \$5,566,814. The hydrocarbon fair market value for a single well on this tract is estimated to be \$3,507,653 (as of June 17, 1977). Department of Energy (DOE) guidelines extend control to a depth of 6,000 ft. Directional drilling of the proposed well site is feasible, requiring a horizontal displacement of about 3,000 ft. The incremental cost of directional drilling is projected to be \$415,945 for a drilling date of January 1, 1978. DWP

Sipes, Williamson & Aycock, Inc. 1979a. *Appraisal Report, Waste Isolation Pilot Plant Site, Eddy County, New Mexico Including: Tracts Nos. 227M-1 and 227M-2 (Nola Ptasynski: Containing 358.81 Acres of Land, More or Less, Situated in Sections 3 and 4, Township 23 South, Range 31 East, Eddy County New Mexico)*. Midland, TX: Sipes, Williamson & Aycock, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Two tracts of land under lease to Nola Ptasynski et al. have been evaluated to determine the fair market value for hydrocarbons effective January 1, 1979. Tract 227M-1 contains about 79.55 acres in Section 4, T23S, R31E, and was appraised with a value of \$25,089. Tract 227M-2 contains about 279.26 acres in Section 3, T23S, R31E, and was appraised with a value of \$156,405. Different economics apply to these tracts, because Tract 227M-2 would qualify for higher rates on gas produced as "new gas." In addition, these tracts

are now taken into the potash enclave, and drilling will be subject to approval by the Minerals Division of the US Geological Survey. Drilling could be deferred for an extended period of time, and values were decreased by 25% to reflect additional risk. DWP

Sipes, Williamson & Aycock, Inc. 1979b. *Appraisal Report, Waste Isolation Pilot Plant Site, Eddy County, New Mexico Including: Tract No. 219M-1 (Continental Oil Company: Containing 80 Acres of Land, More or Less, Situated in Section 25, Township 22 South, Range 30 East, Eddy County, New Mexico)*. Midland, TX: Sipes, Williamson & Aycock, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Tract 219M-1, under lease by Continental Oil Company, has been evaluated for fair market value effective July 24, 1978. The tract contains about 80 acres in section 25, T22S, R30E, and it has been appraised at a value of \$75,980.63. One drilling location was assigned to the tract. DWP

Sipes, Williamson & Aycock, Inc. 1979c. *Appraisal Report, Waste Isolation Pilot Plant Site, Eddy County, New Mexico Including: Tract No. 221M (Union Oil Company: Containing 640 Acres of Land, More or Less, Situated in Section 26, Township 22 South, Range 31 East, Eddy County, New Mexico)*. Midland, TX: Sipes, Williamson & Aycock, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Tract 221M, under lease to Union Oil Company, has been evaluated for fair market value effective January 1, 1979. The tract contains about 640 acres in Section 26, T22S, R31E, and it has been appraised at \$358,444. The tract is located outside the 1977 expansion of the potash enclave, and no reduction of the acreage value is warranted because of potash minerals. The tract is devalued by 25% because it is poorly located relative to deeper hydrocarbon structures. DWP

Sjaardema, G.D., and R.D. Krieg. 1987. *A Constitutive Model for the Consolidation of WIPP Crushed Salt and Its Use in Analyses of Backfilled Shaft and Drift Configurations*. SAND87-1977. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A constitutive model for the consolidation of wet crushed salt material is presented in this report. The material parameters for this model are derived from hydrostatic consolidation tests performed on wet salt taken from the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. The constitutive model is then used for analyses of the interaction between intact and crushed salt in realistic field configurations such as backfilled and open shafts and drifts. The calculations are used to show that the wet crushed salt does not significantly retard the rate of closure of shafts and drifts until the crushed salt is consolidated to approximately 95% of intact salt density. An approximate method for modeling the creep rate of intact salt is developed that more closely matches the closure data from empty drifts at the WIPP Site to provide a more realistic estimate of the crushed salt response.

Skokan, C.K., M.C. Pfeifer, G.V. Keller, and H.T. Andersen. 1989. *Studies of Electrical and Electromagnetic Methods for Characterizing Salt Properties at the WIPP Site, New Mexico*. SAND87-7174. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: At the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico, technical and engineering issues related to the long-term storage of hazardous wastes in bedded salt are being studied. For nuclear waste repositories with both long operational periods (50 year) and long performance assessment periods (10,000 year), the Disturbed Rock Zone (the zone of rock in which the mechanical and hydrologic properties have changed in response to excavation; abbreviated as DRZ) is important to both operational (e.g., slab or fracture failure of the excavation) and long-term performance (e.g., seal system performance and fluid transport). Because of the large contrast in electrical conductivity between crystalline salt and salt saturated with water, it is to be expected that electrical geophysical methods may play an important role in delineating portions of the DRZ. The Colorado School of Mines, under contract to Sandia National Laboratories (SNL), has carried out experimental surveys using the direct current electrical method and two electromagnetic methods underground in the mine workings. The results suggest that the various electrical methods are effective in locating low resistivity zones in the salt, which probably represent moisture-rich zones. Furthermore, it appears that such measurements might well be further optimized in terms of survey effort and design of systems to provide a high response to small-scale conductive features in the salt.

Snyder, R.P. 1985. *Dissolution of Halite and Gypsum, and Hydration of Anhydrite to Gypsum, Rustler Formation, in the Vicinity of the Waste Isolation Pilot Plant, Southeastern New Mexico.* USGS-OFR-85-229. Denver, CO: US Geological Survey.

ABSTRACT: Data from selected drill holes spaced at intervals of 1.5 to 15 km (5,000 to 50,000 ft) in southeastern New Mexico demonstrate a progressive removal of halite by dissolution, hydration of anhydrite to gypsum, and removal of gypsum by dissolution in the Permian Rustler Formation. Thickness of the Rustler decreases as halite is removed, but increases after complete removal due to the hydration of anhydrite to gypsum.

Snyder, R.P., and L.M. Gard, Jr. 1982. *Evaluation of Breccia Pipes in Southeastern New Mexico and Their Relation to the Waste Isolation Pilot Plant (WIPP) Site, With Section on Drill-Stem Tests.* Open-File Report 82-968. Denver, CO: US Geological Survey.

ABSTRACT: Four surficial domes, near the northwestern end of Nash Draw and 10 to 15 mi from the Waste Isolation Pilot Plant (WIPP) Site, are considered breccia pipes or chimneys through the evaporites. The origin of these features has been evaluated using a variety of geophysical data, surface and underground mapping in a mine, and drilling from the surface and underground.

Geophysical studies reveal several characteristics associated with breccia pipes. Known and highly suspect features have low resistivity. Gravity surveys do not provide consistently low gravity over known breccia pipes. Seismic reflection across several features revealed generally uninterpretable data through their centers.

Two locations (Hills A and C) were cored from the surface. Hill A was cored to a depth of 1981 ft, approximately to the level of the upper Yates Formation (Permian), ending in a dipping block (?) of probable Fletcher Anhydrite Member of the Salado Formation. Identifiable rocks of the Dewey Lake Formation were found as much as 1200 ft below the base of the unit in the area. Fragments of the Magenta and Culebra Dolomite Members of the Rustler Formation were found 900-1200 ft below their normal positions. Most Salado halite, and all Rustler halite, is missing in core from Hill A. Hill C was cored to a depth of 1300 ft, just below the depth at which Mississippi Chemical Corporation mined into the breccia pipe. Rocks from the Dewey Lake-Rustler contact are displaced about 620 ft below their normal position. Halite is still preserved from the lower Rustler at the bottom of the hole. Because of this, Hill A and C may have formed at quite different times.

The general sequence of events forming breccia pipes is: the cavity is dissolved in the Capitan Limestone or related rocks, overlying rocks collapse in a pipe that reaches the surface, sediment and water collect in the surface depression and infiltrate part of the breccia, the Gatuña Formation and overlying Mescalero caliche were deposited over the surface, and halite in the Rustler and upper Salado was dissolved to lower the area around the breccia column and to cause dips away from the pipe.

Seven intervals in WIPP-31, drilled in Hill A, were tested with standard drill-stem procedures to determine the pressure of liquid or gas and estimate quantity, quality, and source. Five of these tests were successfully completed. Two tests (808-1064 ft and 808-1235 ft) contained some fluid, but only diluted drilling mud was recovered. Respective permeabilities were calculated as 0.57 and 0.90 millidarcies. The interval from 1215-1396 ft is calculated to have a permeability of 0.11 millidarcy. Two lower intervals (1495-1687 ft and 1480-1984 ft) did not yield enough fluid to calculate permeability.

Several features, having some characteristics similar to these breccia pipes and located in the vicinity of the WIPP, have been examined and drilled, but they are not breccia pipes. The Capitan Limestone and related units are associated with demonstrable pipes, and these units do not exist at the WIPP Site. The breccia pipes are caused by deep dissolution, probably of the Capitan Limestone, and collapse of the overlying evaporite rocks sometime before 400,000 to 500,000 years. "No examples of breccia pipes that could lead to breaching of a repository at the WIPP Site have been found to date and are not likely because the Capitan Limestone is not present beneath the site." DWP

Spiegler, P. 1981. *An Approach to Calculating Upper Bounds on Maximum Individual Doses From the Use of Contaminated Well Water Following a WIPP Repository Breach.* EEG-9. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The radiological consequences have been evaluated for a possible breach event of the Waste Isolation Pilot Plant (WIPP) in which groundwater dissolves salt and water in the repository and transports waste through an aquifer to a well assumed to exist downgradient from the repository at a distance of 3 mi. It is assumed that waste is leached at the same rate salt is dissolved and that the water is naturally diluted along the path to the hypothetical well to about 5000 mg/L total dissolved solids. Water treated for drinking is assumed to have removed 90% of solutes, including radioactive elements.

Concentrations of isotopes at the well are based on the nuclear waste inventory presently proposed for WIPP, basic assumptions concerning the transport of waste, and treatment to reduce the salinity of the water. The concentrations of U-233, Pu-239, and Pu-240, all radionuclides originally emplaced as waste in the repository, would exceed current Environmental Protection Agency (EPA) drinking water limits. The concentrations of U-234, U-235, and U-236, all decay products of plutonium isotopes originally emplaced as waste, would be well below current EPA drinking water limits. The 50-year dose commitments from one year of drinking treated water contaminated with U-233 or Pu-239 and Pu-240 were found to be comparable to a one-year dose from natural background. The 50-year dose commitments from one year of drinking milk would be no more than about 1/5 the dose obtained from ingestion of treated water. These doses are considered upper bounds because of several very conservative assumptions. DWP

Spiegler, P. 1982a. *Analysis of the Potential Formation of a Breccia Chimney Beneath the WIPP Repository.* EEG-13. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: This report evaluates the potential to form a breccia pipe beneath the Waste Isolation Pilot Plant (WIPP) repository and the release radioactivity to the surface. Brine density flow does not appear to be capable of raising water to produce a solution cavern at the top of the Castile. Rock mechanics considerations indicate that it is not reasonable to form a breccia pipe by collapse of a cavern in the lower Castile. Even if rock mechanics is ignored, the overlying strata act as a barrier and would prevent the release of radioactivity to the biosphere. If a breccia pipe forms gradually, the Pu-239 in the waste (one of the most important long-lived components) would decay during formation. If Bell Lake and San Simon Sinks are the surface manifestation of a regional deep dissolution wedge, such a wedge is too far removed to represent pipe-forming activity near the WIPP Site.

It is highly unlikely that a breccia pipe will form under the WIPP repository. If it did, Pu-239 in brine reaching the surface would be less concentrated than the maximum permissible concentration in water specified in the *Code of Federal Regulations Title 10, Part 20*. DWP

Spiegler, P. 1982b. *Hydrologic Analyses of Two Brine Encounters in the Vicinity of the Waste Isolation Pilot Plant (WIPP) Site*. EEG-17. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Two drill holes, ERDA-6 and WIPP-12, encountered pressurized brine reservoirs in the vicinity of the Waste Isolation Pilot Plant (WIPP) Site. These brine reservoirs affect the consequences of repository failure scenarios through drilling and are further evaluated.

The data from ERDA-6 and WIPP-12 indicate naturally fractured reservoirs of the two-porosity type. The best estimate of the brine volume in ERDA-6 is about 60,000 to 120,000 barrels. The best estimate of the volume in WIPP-12 is about 5 to 10 million barrels. The excess pressure above current hydrostatic pressure suggests that the reservoirs were formed millions of years ago at greater depth and hydrostatic pressure. After the reservoirs sealed, erosion stripped part of the overburden. The fractures at the bottom of the anhydrite beds suggest that their formation may be related to the tilting of the entire Delaware Basin. If a drill hole connects such a brine reservoir to the repository, pressures are estimated to be insufficient to cause brine flow to the surface. If the brine in the repository zone is isolated and then intercepted by a second borehole after being pressurized, surface brine flow is calculated to be 3,150 barrels without gas and 12,000 barrels with gas. DWP

Spiegler, P. 1984. *Proposed Preoperational Environmental Monitoring Program for WIPP*. EEG-26. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The State of New Mexico is recommending an environmental surveillance program for the Waste Isolation Pilot Plant (WIPP) as a framework for discussions prior to establishing a cooperative monitoring program with the Department of Energy (DOE). Monitoring and sampling stations will be located within zones I-III with perimeter stations around zone III. Regional stations may be located up to 50 mi from the WIPP. The comprehensive monitoring covers air, water, soil, biota, and external radiation levels. Plutonium and americium are the main radionuclides, but other radionuclides such as H³, Sr⁹⁰, Cs¹³⁷, and the uranium series will be monitored to establish trends and origins of radiation levels in the area.

The State will independently evaluate the accuracy and precision of the results obtained by the DOE's program specified by the following objectives: split samples by a procedure approved by the State and the DOE; sample schedule and location expanded or altered in accordance with any reasonable request of the State; the State's samples analyzed by laboratories neither affiliated with nor under contract to the DOE; and State quality control program independent

of the DOE. In lieu of split samples, the State's representative may elect to monitor the sampling and analytic processes of DOE. If necessary, the State of New Mexico will conduct monitoring and surveillance in addition to the combined program. DWP

Spiegler, P., and D. Updegraff. 1983. *Origin of the Brines Near WIPP from the Drill Holes ERDA-6 and WIPP-12 Based on Stable Isotope Concentrations of Hydrogen and Oxygen.* EEG-18. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: Pressurized brine reservoirs encountered in drill holes ERDA-6 and WIPP-12 flowed to the surface. Stable isotopes of hydrogen and oxygen were analyzed to understand the origin of these brines. The average δD value is -4.6 for ERDA-6 and -1.1 for WIPP-12. The average $\delta^{18}O$ is 9.51 for ERDA-6 and 10.63 for WIPP-12. Several mechanisms to produce isotopic changes in brine were examined: altered trapped sea water; dehydrated gypsum; meteoric water mixed with trapped sea water; and evaporated meteoric water. Fluid sources from the Bell Canyon Formation, Salado Formation, Capitan Limestone, and Castile anhydrite were examined. The first three sources are not considered plausible, but dehydrating Castile anhydrite cannot be ruled out. "[T]he brines encountered at ERDA-6 and WIPP-12 are probably derived from ancient ocean waters that have been isotopically enriched in oxygen-18 by exchange interaction with rock." DWP

Staller, G.E., W.C. Wilson, and A.R. Smith. 1985. *A Rock-Salt Mine Saw.* SAND85-0056. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A saw has been developed for cutting rock salt at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. This saw uses commercially available hardware in conjunction with Sandia-designed equipment. It has been used to cut rock salt in situ as well as samples removed from the mine.

Starrett, J.M. 1989. *A Feasibility Study for Using Seismic Tomography to Monitor the Integrity of Salt Pillars.* MS thesis. Golden, CO: Colorado School of Mines.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM has been constructed to study the engineering and technical problems associated with storing nuclear waste in a bedded halite formation. One such problem involves the deterioration of the salt in the underground facility, including the development of a disturbed rock zone (DRZ) around the mining excavations. The feasibility of using seismic tomography to define and monitor deteriorated zones was investigated.

A data acquisition system consisting of a hammer and epoxied-bolt source, accelerometers, and an engineering seismograph produced and recorded clean and consistent signals in the WIPP underground environment with a strong component in the 1 kHz to 2 kHz range. Given an average velocity of approximately 15,000 ft/sec in the salt, a possible resolution of less than 5 ft was obtained. First arrival times were picked with a sampling interval of 50 microseconds, giving an accuracy of less than 1 ft. The system was convenient for field operations and data handling procedures.

Computer programs written to implement the ART and SIRI tomographic inversion algorithms, as well as a damped least squares routine, were tested in a series of model inversions. Inversion results were compared with the original models using an RMS error calculation. The comparisons were considered favorable because the RMS error values were in many cases

several hundred ft/sec, while the model velocities were generally in the 10,000-15,000 ft/sec range.

Using the ART program, the field data were inverted, and a clearly defined DRZ was not evident in the result. Based on subtle velocity trends and apparent response to pronounced deterioration in limited areas, however, it was concluded that the basis of a viable technique had been demonstrated. To enable the method to more clearly delineate subtle deterioration zones, refinements have been suggested. These include closer spacings, higher frequency signals, and higher frequency response characteristics of receiving and recording equipment.

Stein, C.L. 1985a. *Mineralogy in the Waste Isolation Pilot Plant (WIPP) Facility Stratigraphic Horizon.* SAND85-0321. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Forty-six samples were selected for this study from two cores, one extending 50 ft up through the roof of the Waste Isolation Pilot Plant (WIPP) Facility and the other penetrating 50 ft below the facility floor. These samples, selected from approximately every other foot of core length, represent the major lithologies present in the immediate vicinity of the WIPP Facility horizon: "clean" halite, polyhalitic halite, argillaceous halite, and mixed polyhalitic-argillaceous halite. Samples were analyzed for non-NaCl mineralogy by determining weight percents of water- and ethylenediaminetetraacetic acid-insoluble residues, which were then identified by x-ray diffraction. In general, WIPP halite contains, at most, 5 wt% non-NaCl residue. The major mineral constituents are quartz, magnesite, anhydrite, gypsum, polyhalite, and clays. Results of this study confirm that in previous descriptions of WIPP core, trace mineral quantities have been visually overestimated by approximately an order of magnitude.

Stein, C.L. 1985b. *Preliminary Report on Fluid Inclusions From Halites in the Castile and Lower Salado Formations of the Delaware Basin, Southeastern New Mexico.* SAND83-0451. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A suite of samples composed primarily of halite from the upper Castile and lower Salado Formations of the Permian Basin was selected from Waste Isolation Pilot Plant (WIPP) core for a reconnaissance study of fluid inclusions. Volume percent of these trapped fluids averaged 0.7 to 1%. Freezing-point depressions varied widely and appeared to be unrelated to fluid-inclusion type, to sedimentary facies, or to stratigraphic depth. However, because very low freezing points were usually associated with anhydrite, a relation may exist between freezing-point data and lithology. Dissolved sulfate values were constant through the Castile, then decreased markedly with lesser depth in the lower Salado. This trend correlates very well with observed mineralogy and is consistent with an interpretation of the occurrence of secondary polyhalite as a result of gypsum or anhydrite alteration with simultaneous consumption of dissolved sulfate from the coexisting fluids. Together with the abundance and distribution of fluid inclusions in primary or "hopper" crystal structures, this evidence suggests that inclusions seen in these halites did not migrate any significant geographical distance since their formation.

Stein, C.L., and J.L. Krumhansl. 1984. "Compositions of Brines in Halite from the Lower Salado Formation, Southeastern New Mexico," *Abstracts with Programs, Geological Society of America, 99th Annual Meeting, Reno, NV, November 5-8, 1984.* SAND84-1252A. Vol. 16, no. 6, 667. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a Department of Energy (DOE) sponsored repository for the long-term storage of transuranic (TRU) defense-related nuclear waste, located in the Delaware Basin near Carlsbad, NM. During excavation, a number of large fluid inclusions were recovered from an area of highly recrystallized halite in a thick salt bed at the repository horizon. Two distinct populations of inclusions were found with the following molar ratios: 182 and 417 for Mg/Ca; 4 and 8.3 for Mg/K; 0.4 and 1.4 for Mg/Na; 0.22 and 0.35 for Mg/Cl; 250 and 163 for Cl/Br; 14 and 6 for SO_4/Br . Overall, the inclusion compositions appear to reflect the changes in sea water chemistry during deposition of the Salado Formation.

In addition, 22 samples of brine "seeps" were collected from walls of recently excavated drifts at the same stratigraphic horizon as the fluid inclusion samples. A partial analysis of these fluids shows that they differ substantially in composition from those found in the inclusions, owing to a magnesium depletion ($\text{Mg/K} = 1.8$). Since seeps are associated with thin clay or anhydrite seams, these fluids may have originated by dewatering of clays and/or gypsum. Their composition may also have been modified by the selective uptake of Mg during clay diagenesis, and incongruent dissolution of bittern salts (principally polyhalite).

In conclusion, the wide variety of fluids found in WIPP workings and their small volumes argue strongly against the possibility that an interconnected hydrologic system exists that could effectively transport radionuclides away from the repository.

Stein, C.L., and J.L. Krumhansl. 1986a. *Chemistry of Brines in Salt from the Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico: A Preliminary Investigation*. SAND85-0897. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant is a US Department of Energy sponsored facility for the eventual disposal of defense-related transuranic nuclear waste, located in the Delaware Basin near Carlsbad, NM. The analyses of macro- and microscopic (intracrystalline) brines observed within the WIPP facility and in the surrounding halite, with interpretations regarding the origin and history of these fluids and their potential effect(s) on long-term waste storage are presented.

During excavation, several large ($\sim 10\ \mu\text{m}$ to several mm) fluid inclusions were recovered from an area of highly recrystallized halite in a thick salt bed at the repository horizon (2150 ft below ground level). Two populations of inclusions were distinguished on the basis of major element content, using analyses for Mg, Ca, K, Na, Cl, Br, and SO_4 . We propose that the inclusion compositions arise from the alteration of calcium sulfate to polyhalite and calcium carbonate to magnesite, respectively. Overall, the inclusion compositions suggest a significant departure from a simple sea-water evaporation model.

In addition, 52 samples of brine "weeps" were collected from walls of recently excavated drifts at the same stratigraphic horizon from which the fluid inclusion samples are assumed to have been taken. Analyses of these fluids show that they differ substantially in composition from the inclusion fluids (mainly by depletion of magnesium relative to potassium) and cannot be explained by mixing of the fluid inclusion populations. Because weeps are associated with argillaceous or anhydritic halite, these fluids may have originated by dewatering of clays and/or gypsum. Their compositions may have also been modified by selective uptake of Mg during clay diageneses and by the formation of authigenic magnesite and magnesium silicates.

Finally, holes in the facility floor that filled with brine were sampled but with no stratigraphic control; therefore it is not possible to interpret the compositions of these brines with any accuracy, except insofar as they resemble the weep compositions but with greater variations in both K/Mg and Na/Cl ratios. However, the Ca and SO_4 values for the floor holes are relatively close to the gypsum saturation curve, suggesting that brines filling floor holes have

been modified by the presence of gypsum or anhydrite, possibly even originating in one or more of the laterally continuous anhydrite units referred to in the WIPP literature as marker beds.

In conclusion, the wide compositional variety of fluids found in the WIPP workings suggests that an interconnected hydrologic system which could effectively transport radionuclides away from the repository does not exist; brine migration studies and experiments must consider the mobility of intergranular fluids as well as those in inclusions; and near- and far-field radionuclide migration testing programs need to consider a wide range of brine compositions rather than a few reference brines.

Stein, C.L., and J.L. Krumhansl. 1986b. "Geochemical Overview of the Waste Isolation Pilot Plant Near Carlsbad, New Mexico," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education*, Tucson, AZ, March 2-6, 1986. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 141-144.

ABSTRACT: The Waste Isolation Pilot Plant is a US Department of Energy sponsored repository for the long-term storage of transuranic defense-related nuclear waste, located in the Delaware Basin near Carlsbad, NM. During excavation, numerous large fluid inclusions were collected from highly recrystallized halite at the repository horizon. The inclusion fluid compositions define two distinct populations, based on analyses for Ca, Mg, K, Na, Cl, Br, and SO₄. Chemical and mineralogical evidence supports our conclusions that the fluid inclusion compositions arise from early diagenetic changes involving alteration of calcium sulfate (gypsum or anhydrite) to polyhalite, and calcium carbonate (calcite or aragonite) to magnesite.

Other brines occurring in the repository (as "weeps" oozing from the walls or collecting in drill holes in the floor) were also analyzed. These fluids were found to differ significantly from the fluid inclusions mainly by depletion of magnesium relative to potassium. The stratigraphic association of these fluids with argillaceous and anhydritic halite suggests an origin in evaporating sea water that was subsequently modified by dewatering of clays and/or gypsum, and selective uptake of magnesium relative to potassium during clay diagenesis. This interpretation is compatible with our observations of a suite of authigenic minerals that includes quartz, magnesite, and magnesium silicates.

Stein, C.L., and J.L. Krumhansl. 1988. "A Model for the Evolution of Brines in Salt from the Lower Salado Formation, Southeastern New Mexico," *Geochimica et Cosmochimica Acta*, SAND85-1999J, Vol. 52, 1037-1046.

ABSTRACT: Fluid inclusions were collected from a bedded salt horizon in the Lower Permian Salado Formation in the Delaware Basin, southeastern New Mexico. The sampling horizon, at depth of approximately 645 m, consists primarily of recrystallized halite, with thin layers of anhydrite. Other trace minerals, dispersed throughout the salt, include quartz, polyhalite, gypsum, K-feldspar, magnesite, and clays. Large fluid inclusions (up to several mm on an edge) are common in the halite; in addition, bands of microscopic (<10 μ m) fluid inclusions are present as primary ("chevron") structures in fragments of unrecrystallized salt. We sampled 109 large inclusions by individual extraction of the fluids, which were analyzed for Ca, Mg, K, Na, Cl, Br, and SO₄. The chemistry of the inclusion fluids and the associated mineralogy suggest that these brines represent Permian seawater that has undergone evaporation and subsequent modification by diagenetic reactions, dominated by the alteration of calcium sulfate to polyhalite, and magnesite formation. The range of fluid inclusion compositions suggests a significant departure from a simple sea water evaporation model.

Other brines from the same horizon in the Salado Formation were sampled and analyzed for the same elements as the fluid inclusions, and differed significantly from them primarily by the depletion of Mg relative to K. The association of these brines with argillaceous and/or anhydritic halite containing a suite of authigenic minerals (quartz, magnesite, and Mg-rich clays) suggests that these are intergranular brines with compositions determined over a much longer time scale than that required by the fluid inclusions. The principal reactions affecting intergranular brine chemistry are dehydration of gypsum, dewatering of detrital clays, and uptake of Mg during clay diagenesis. Overall, the observed variation in brine compositions implies that, if large-scale hydrologic circulation is occurring in the Salado halite, the time scale is limited by the rate required for low-temperature silicate diagenesis.

Stein, C.L., and D.F. McTigue. 1988. "Thermal Migration of Fluid Inclusions in Halite: A Field Experiment and Model Results," *EOS Transactions, American Geophysical Union*. Vol. 69, no. 44, 1446. (Abstract Only).

ABSTRACT: Liquid-filled inclusions in salt can migrate up an imposed thermal gradient by dissolution at the hot inclusion wall and reprecipitation at the cold wall. A large-scale field experiment was conducted over a period of about three years at the Waste Isolation Pilot Plant in which an array of electric heaters was emplaced in the Permian salt. The heat flux to the borehole walls was approximately 200 W/m²; the wall temperature reached about 140°C, and the temperature gradient at the wall was of the order of 40°C/m. Such gradients are about 1/100 those typically achieved in the laboratory, and on which most previous observations are based.

Post-test petrographic analysis of salt within 20-25 cm of the borehole shows abundant evidence of inclusion migration toward the heat source. The largest undeformed inclusions within this interval are of the order of 50 µm on a side. Above this size, inclusions are deformed into elongate "tubes" with aspect ratios of about 10:1 and ~500-1000 µm long. Assuming that this length represents the minimum path of an inclusion, we infer average migration velocities of the order of ~10⁻¹¹ m/sec (~1 µm/day). Both the observed minimum size for motion and the inferred velocity are in good agreement with the theoretical and laboratory results.

The alteration of polyhalite (K₂MgCa₂(SO₄)₄•2H₂O) to anhydrite in the heated salt indicates a possible source of a portion of the inclusion fluids due to release of structural water.

ANNOTATION: The theoretical results Stein and McTigue used to compare with their experiment were published by Olander et al. (1982) in the *Journal of Applied Physics* (Vol. 53, 669-681) in 1982. This paper is not included in this bibliography.

Stein, C.L., K.L. Higgins, and R.L. Morrison. 1989. "Laser Raman Microanalysis of Fluid Inclusion Gases in Halite," *EOS Transactions, American Geophysical Union*. Vol. 70, no. 43, 1393. (Abstract Only).

ABSTRACT: Laser Raman microanalysis was used to characterize the composition of the vapor phase in fluid inclusions in halite. These analyses were performed in conjunction with ongoing studies of halite fluid compositions for the US Department of Energy's Waste Isolation Pilot Plant. Samples were selected from clear, colorless, coarsely crystalline halite from a subsurface depth of approximately 645 m in the Permian Salado Formation in the Delaware Basin, southeastern New Mexico. The fluid inclusions in the samples examined are large (up to a few mm on an edge), with gas bubbles approximately 5 to 20% by volume of the inclusion.

Results were obtained using the 514.5 mm argon ion laser line for excitation and the integrated peak areas at 2325 ± 9 , 1554 ± 8 , and 2916 ± 4 cm^{-1} for N_2 , O_2 , and CH_4 , respectively. No other gases were detected. Gas compositions consisted of either N_2 and O_2 or, more commonly, N_2 and CH_4 . Although these results are not quantitative, the molar ratios $\text{N}_2:\text{O}_2$ and $\text{N}_2:\text{CH}_4$ are constant, and the former is similar to atmospheric $\text{N}_2:\text{O}_2$. Variable peak widths and line shifts in the Raman spectra suggest that internal fluid pressures are slightly greater than atmospheric.

The presence of methane in these inclusions suggests microbial organic decomposition; fluids trapped in at least some of the inclusions examined may have originated early in the diagenetic sequence. The occurrence of O_2 suggests that atmospheric compositions may not have changed significantly since the Permian, although contamination by present-day air has not been ruled out.

Stensrud, W.A., M.A. Bame, K.D. Lantz, A.M. LaVenue, J.B. Palmer, and G.J. Saulnier, Jr.
1987. *WIPP Hydrology Program. Waste Isolation Pilot Plant, Southeastern New Mexico, Hydrologic Data Report #5.*

Parts: A. *WIPP-13 Multipad Test.*

B. *H-4c, P-17, ERDA-9, and Cabin Baby-1 Slug Tests.*

C. *Engle and Carper Well Pumping Tests.*

D. *WIPP-12, H-14, and H-15 Drill-Stem Tests.*

E. *Water-Level Data.*

SAND87-7125. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #5* is divided into five parts. The Culebra Dolomite in WIPP-13 was pumped for 36 days at an average of 30.1 gpm to test the hydraulic response in wells in the northern part of the Waste Isolation Pilot Plant (WIPP) Site (Part A). During the pumping test and 72-day recovery period, 24 wells and the exhaust shaft showed apparent responses to the pumping, beginning in one well as soon as 1 hour after pumping began. Activities that may have affected water-level monitoring and interpretation are listed in part E of the data report. Part B reports the development pumping and slug tests of the Culebra in four wells in the center and south side of the WIPP Site. Three of the wells were first pumped for maximum stress to clean the wells and develop good hydraulic connections with the formation. These tests showed that minimum pumping rates could not be maintained for pumping tests. Two wells and the exhaust shaft, monitored during pumping at ERDA 9, showed responses. Slug tests in each hole showed that pressures decreased to or near pretest levels within one day of the slug. Part C reports the data from short-term pumping tests of two livestock wells located seven and 15 miles south of the WIPP Site. The Engle well, drawing from the Culebra, was pumped at an average of 9.8 gpm for seven days. The fluid pressure decreased about 44 psi; within one hour of stopping pumping, fluid pressures were above pressures at the beginning of the pumping test. The Carper well, completed in undifferentiated Quaternary and Tertiary deposits, was pumped for three days at an average of 12.9 gpm. The total pressure decline was about 14 psi; within five hours after pumping ended, the well recovered to within about 5 psi of original pressure. Part D reports drill-stem tests (DST) at three wells in various formations. Six DSTs in WIPP-12 tested the Castile brine reservoir and the Salado Formation. Salado intervals were determined by sulfate units which provided good packer seats. DST and pulse or slug tests in H-14 were conducted in members of the Rustler Formation and in the Dewey Lake Formation. The Culebra in H-15 was tested by DST and slug tests. H-14 and H-15 were drilled with fluids containing known amounts of a conservative tracer. Water samples collected during cleaning of these wells were tested to determine the drilling fluid loss and recovery. Tracer concentrations indicate most of the lost fluid was recovered during these operations. Part E reports the water level data recorded for 46 wells completed in the Culebra and eight completed to the Magenta. The data are uncorrected for fluid density or barometric-pressure fluctuations. DWP

ANNOTATION: Hydrologic data reports #1-4 are included under Hydro Geo Chem, Inc., (1985); Intera Technologies, Inc., and Hydro Geo Chem, Inc., (1985); Intera Technologies, Inc., (1986); and Saulnier et al. (1987).

Stensrud, W.A., M.A. Bame, K.D. Lantz, T.L. Cauffman, J.B. Palmer, and G.J. Saulnier, Jr. 1988. *WIPP Hydrology Program, Waste Isolation Pilot Plant, Southeastern New Mexico, Hydrologic Data Report #6.*

Parts: A. Waste-Handling Shaft Pulse Testing.

B. H-1, H-12, and P-15 Slug Tests.

C. H-2 Pumping Test.

D. H-16, H-17, and H-18 Drill-Stem, Slug, and Pulse Tests.

E. Water-Level Data.

SAND87-7166. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #6* is organized into five parts reporting data obtained from May through October 1987. Part A reports the results of pulse-injections tests in six horizontal holes at four levels within the Rustler and upper Salado Formations in the Waste Handling Shaft. Part B reports the history of three wells (H-1, H-12, and P-15) and the results of slug tests on the Culebra. For H-1, fluid pressure decreased to about pretest levels within one day. For H-12 and P-15, pressures decreased within about two days. Part C reports a 20-day pumping and water quality sampling test of the Culebra conducted at H-2a. Fluid pressures were observed at other wells at H-2 hydropad during the pumping test and 40 days after pumping ended. The pumping rate was about 17 gph during most of the test. Electrolytic conductivity values stabilized at about 14,000 $\mu\text{S}/\text{cm}$ after initial readings of about 28,000 $\mu\text{S}/\text{cm}$. Part D describes drill-stem tests (DSTs), slug, and pulse tests of the Rustler Formation in H-16, H-17, and H-18. DSTs in H-16 were conducted as the hole reached different testing intervals during drilling. The Culebra Dolomite Member was tested in H-17 and H-18. Part E presents water level data collected during the report period from 59 observation wells, some of which are completed to more than one interval. Forty-eight wells are completed to the Culebra, eight wells to the Magenta, two to the Rustler-Salado contact, and single wells to the Forty-niner Member, The Dewey Lake Formation, and the Bell Canyon Formation. The data are uncorrected for fluid density or barometric pressure. DWP

Stensrud, W.A., M.A. Bame, K.D. Lantz, J.B. Palmer, and G.J. Saulnier, Jr. 1988. *WIPP Hydrology Program, Waste Isolation Pilot Plant, Southeastern New Mexico, Hydrologic Data Report #7.*

Parts: A. WIPP-30, WIPP-12, and P-18 Slug Tests.

B. H-11b4 Drill-Stem, Slug, and Pumping Tests.

C. H-18 Pumping Test.

D. Water-Level Data.

SAND88-7014. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #7* is organized into four parts, A, B, C, and D, and contains hydrologic testing and water-level data from the Waste Isolation Pilot Plant (WIPP) Site from December 1987 through April 1988. Part A describes the slug tests performed at WIPP-30, WIPP-12, and P-18 to evaluate the hydrologic parameters of the Culebra Dolomite at each site. Part B describes the drill-stem, slug, and pumping tests performed at H-11b4. Part C describes a 72-hour pumping test conducted at H-18 as part of a well cleaning process preparing for the taking of Culebra water samples. Part D presents water-level data collected from December 1987 through April 1988 in observation wells completed in the Dewey Lake Red Beds, the Forty-niner, Magenta Dolomite, Culebra Dolomite, the contact between the Rustler and Salado Formations, and the Bell Canyon Formation. Fluid pressure data were collected from H-16, which is completed in all five members of the Rustler Formation. DWP

Stensrud, W.A., M.A. Bame, K.D. Lantz, J.B. Palmer, and G.J. Saulnier, Jr. 1990. *WIPP Hydrology Program, Waste Isolation Pilot Plant, Southeastern New Mexico, Hydrologic Data Report #8.*

Parts: A. H-11 Multipad Pumping and Convergent-Flow Tracer Test.

B. P-14 Air-Lift Pumping Test.

C. AEC-7 and D-268 Slug Tests.

D. H-2b1, H-3b1, and H-3d Slug and Pulse Tests.

E. Hydraulic Effects of Air-Intake Shaft Construction.

F. Water-Level Data.

SAND89-7056. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: *Hydrologic Data Report #8* is organized into six parts, A, B, C, D, E, and F, and contains hydrologic testing and water-level data from the Waste Isolation Pilot Plant (WIPP) Site from May 1988 through August 1989. Part A describes a multipad pumping and four-well convergent-flow tracer test at the H-11 hydropad. H-11b1 was pumped at 6.08 gpm for 63 days and water level responses were observed at 10 observation wells up to 15,500 ft from H-11. Conservative benzoic-acid tracers were injected after 9 days of pumping at H-11b2, H-11b3, and H-11b4, 70 ft, 69 ft, and 141 ft from H-11b1, respectively. Tracer breakthrough was achieved for all injectates. Part B describes a 72-hour airlift pumping test of the Culebra Dolomite conducted at P-14 after the well was reperforated and acid treated. Part C describes slug-injection/withdrawal testing of the Culebra Dolomite at wells AEC-7 and D-268. Both wells were shot perforated across the Culebra intervals and developed before testing. The slug tests were performed using small diameter inflatable minipackers installed in tubing above the packer-isolated Culebra Dolomite test intervals. Part D describes slug-injection/withdrawal and pulse-injection/withdrawal testing of the Magenta Dolomite at wells H-2b1 and H-3b1, and of the Forty-niner Member at well H-3d. Part E contains data regarding hydraulic effects of drilling the Air Intake Shaft pilot hole and upreaming of the Air Intake Shaft. Fluid-pressure responses were observed by transducers installed with a multipacker completion tool in well H-16, 56 ft from the shaft, and water-level responses were observed in other nearby wells. Part F also contains a log of shaft-construction activities. Part F contains water-level and fluid-pressure data collected from May 1988 through August 1989 in observation wells completed in the Dewey Lake Red Beds; the Forty-niner, Magenta Dolomite, Culebra Dolomite, and unnamed lower members of the Rustler Formation; the contact between the Rustler and Salado Formations; and the Bell Canyon Formation at and near the WIPP Site.

Stevens, K., and W. Beyeler. 1985. *Determination of Diffusivities in the Rustler Formation From Exploratory-Shaft Construction at the Waste Isolation Pilot Plant in Southeastern New Mexico.* Water-Resources Investigations Report 85-4020. Albuquerque, NM: US Geological Survey.

ABSTRACT: The construction of an exploratory shaft 12 ft in diameter into the Salado Formation (repository horizon for transuranic (TRU) waste material) at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico affected water levels in water-bearing zones above the repository horizon. The responses in the water-bearing zones were recorded at hydrologic test pads H1, H2b, and H3. Interpretation of the construction history of the exploratory shaft produced an approximation of construction-generated hydraulic stresses at the shaft. The magnitude of these stresses was estimated using the hydrographs from hydrologic test pad H1. Whereas flow rates from the Magenta Dolomite and Culebra Dolomite Members of the Rustler Formation into the exploratory shaft were unknown, the ratio of transmissivity to storage (diffusivity) was determined by mathematically simulating the hydrologic stresses with a flood wave response digital model.

In the Magenta Dolomite Member, the time of occurrence of the initial slope break, amplitude, and slope of the hydrograph recorded at test pad H1 were matched to a set of type curves generated using a diffusivity of 0.03 ft²/sec. In the Culebra Dolomite Member of hydrologic test pad H1, the timing was matched with a diffusivity of 0.5 ft²/sec. The slope and amplitude of the response were also matched with a diffusivity of 0.5 ft²/sec. In the Culebra at hydrologic test pad H2b, the diffusivity value obtained from matching the time of the response was less than 1.0 ft²/sec, and the diffusivity value obtained from matching the amplitude and slope was more than 0.5 ft²/sec. In the Culebra at hydrologic test pad H3, the diffusivity value from the response time was 1.0 ft²/sec, and the diffusivity values from the amplitude and slope were 0.5 ft²/sec.

These results indicate that the Magenta Dolomite and Culebra Dolomite Members of the Rustler Formation can be modeled as homogeneous, isotropic, and confined water-bearing zones. One simple and consistent explanation, but by no means the only explanation, of the lack of a single diffusivity value in the Culebra water-bearing zone is that local effects in or near the observation wells at the hydrologic test pads dampen the amplitude of water-level changes.

Stewart, D.B., B.F. Jones, E. Roedder, and R.W. Potter. [1979]. "Summary of United States Geological Survey Investigations of Fluid-Rock-Waste Reactions in Evaporite Environments Under Repository Conditions," *IAEA/OECD Underground Disposal of Radioactive Wastes Symposium, Finland, July 2-6, 1979*. Vol. 1, 335. (Available from R.R. Bowker, New York, NY).

ABSTRACT: The interstitial and inclusion fluids contained in rock salt and anhydrite, though present in amounts less than 1 weight %, are chemically aggressive and may react with canisters or wastes. The three basic types of fluids are bitterns residual from saline mineral precipitation including later recrystallization reactions; brines containing residual solutes from the formation of evaporites that have been extensively modified by reactions with contiguous carbonates or clastics; and re-solution brines resulting from secondary dehydration of evaporite minerals or solution of saline minerals by undersaturated infiltrating waters. Fluid composition can indicate that meteoric flow systems have contacted evaporites, or that fluids from evaporites have migrated into other formations.

The movement of fluids trapped in fluid inclusions in salt from southeastern New Mexico is most sensitive to ambient temperature and inclusion size, although several other factors such as thermal gradient and vapor/liquid ratio are also important. There is no evidence of a threshold temperature for movement for inclusions. Empirical data are given for determining the amount of brine reaching the heat source if the temperature, approximate amount of total dissolved solids, and Ca:Mg ratio in the brine is known. SrCl₂ and CsCl can reach high concentrations in saturated NaCl solutions and greatly depress the liquids. The possibility that such fluids, if generated, could migrate from a high-level waste repository must be minimized because the fluid would contain its own radiogenic energy source in the first decades after repository closure, thus changing the thermal evolution of the repository for designed values.

Stinebaugh, R.E. 1979. *Compressibility of Granulated Rock Salt*. SAND79-1119. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Crushed rock salt will be used extensively at the Waste Isolation Pilot Plant (WIPP) as a material for backfilling underground openings. This document addresses one of the characteristics of crushed salt, which must be known to assess the consequences of its usage, namely compressibility.

Stone, C.M., R.D. Krieg, and L.J. Branstetter. 1981. *The Effects of Clay Seam Behavior on WIPP Repository Design*. SAND81-0768. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The geology at the southeastern New Mexico Waste Isolation Pilot Plant (WIPP) Site consists of bedded layers of rock salt, anhydrite, polyhalite, mixtures of those materials, and thin clay seams. In spite of their very small (0.005 m-0.05 m) thickness, clay seams are important to structural characterization of the WIPP stratigraphy since slip might possibly take place across them. This report describes the results of a study to determine the effects of clay seam frictional slip on the closure of a well-defined drift configuration. A Mohr-Coulomb dry friction model was used to model the active clay seams. The main thrust of the study was to determine the effects of friction coefficient variability on drift closure. Results show that the drift closure varies by a factor of 3.0 over the range of friction coefficients studied. The maximum slip observed along any clay seam was 0.12 m. For values of $\mu > .7$, virtually no slip occurs along any clay seam.

Stormont, J.C. 1984. *Plugging and Sealing Program for the Waste Isolation Pilot Plant (WIPP)*. SAND84-1057. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents the current intentions and directions of the Waste Isolation Pilot Plant (WIPP) plugging and sealing program. The plugging and sealing program is responsible for developing the design basis and criteria for sealing the penetrations (boreholes, shafts, and drifts) associated with the WIPP. Estimates of sealing requirements indicate that the technical requirements for sealing will not be great. Conceptual designs presented in this report call for the use of salt, cementitious materials, and clay in the form of seals (or bulkheads) and backfills. The state of knowledge and remaining technical concerns for sealing the WIPP Facility are reviewed, and a program of laboratory, field, and modeling efforts to resolve these issues is described.

Stormont, J.C., ed. 1986a. *Development and Implementation: Test Series A of the Small-Scale Seal Performance Tests*. SAND85-2602. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The first in a series of in situ experiments to evaluate candidate salt repository sealing materials and sealing configurations has been initiated in the Waste Isolation Pilot Plant (WIPP). Test series A of the Small-Scale Seal Performance Tests is providing structural/thermal and fluid-flow information for the evaluation of a newly developed expansive salt-water based concrete. This report provides information necessary for evaluating these data, including "as-built" test configurations, instrumentation development and specifications, development and properties of the concrete, and applicable rock properties. Also included are descriptions of some activities required to implement this test, such as drilling and seal instrumentation emplacement.

Stormont, J.C. 1986b. "In Situ Seal Tests at the Waste Isolation Pilot Plant (WIPP)," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education*, Tucson, AZ, March 2-6, 1986. Ed. R.G. Post. SAND85-1989C. Tucson, AZ: University of Arizona. Vol. 2, 167-176.

ABSTRACT: The first in a series of in situ tests on candidate seal performance has been conducted at the Waste Isolation Pilot Plant (WIPP). These tests represent a phase of testing intermediate between laboratory and full-scale seal evaluations and are significant because they will provide an in situ evaluation of the thermal, mechanical, and fluid flow performance of

seal systems. The scale of the tests allowed the cost-efficient conduct of numerous tests under a wide range of conditions.

The first test series is evaluating an expansive, salt-water based concrete emplaced in boreholes drilled in the floor of the WIPP Facility. Emplaced seals range in size from 3-ft (91-cm) diameter by 3-ft (91-cm) length to 6-in (15-cm) diameter by 1-ft (30-cm) length to examine size effects. In some emplacements, the seal material and the adjacent rock was instrumented to obtain data on the temperature, stress, strain, and displacement fields. Results after 180 days indicate substantial interface pressures from creep of the surrounding rock salt. After the seals had cured about 1 month, a series of gas and brine permeability measurements, including tracers, was made. These measurements reveal that the concrete seal system is an excellent barrier to both brine and gas. These measurements will be repeated in the future to discern time-dependent effects.

Stormont, J.C. 1986c. "Summary of the Plugging and Sealing Program for the Waste Isolation Pilot Plant (WIPP)," *Working Papers From the US/FRG Workshop on Sealing and Backfilling of a Salt Repository*, Albuquerque, NM, September 23-25, 1986. Comp. R.F. Cook. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-2-1 through II-2-27. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Plugging and Sealing Program will develop the design bases and criteria for shaft, drift, and borehole seals for the Waste Isolation Pilot Plant (WIPP) with the goal of minimizing releases of radionuclides from man-made penetrations into the WIPP. The basic goal is to limit the flow of fluid through the repository rather than achieve a perfect seal. The plugging and sealing program consists of four main parts: formation and repository characterization, materials development, in situ seal performance, and seal design evaluation. The principal seal materials being considered are cementitious materials, salt, and bentonite. Granular salt is the focus of laboratory testing, mechanistic studies, and development of constitutive relations for numerical modeling. In situ experiments are being conducted in phases, beginning with the small-scale seal performance tests and progressing to the large-scale seal performance tests. A data base is being developed pertaining to all aspects of sealing and fluid movements in the facility. Designs will be evaluated in 1988 and 1992. DWP

ANNOTATION: See Stormont (1988) for design evaluation.

Stormont, J.C. 1986d. "Overview of the Small Scale Seal Performance Tests (SSSPTs)," *Working Papers From the US/FRG Workshop on Sealing and Backfilling of a Salt Repository*, Albuquerque, NM, September 23-25, 1986. Comp. R.F. Cook. Columbus OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-16-1 through II-16-3. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Seal components are being tested in situ to validate design concepts. Intermediate-scale tests span the large size difference between laboratory and full-scale in situ tests. The tests evaluate the system, including the intact formation, the "disturbed" zone around the excavation, the seal/rock interface, and the seal material.

Five test series have been designed: salt-water based concrete seals in vertical boreholes; salt-water based concrete in horizontal boreholes; salt or salt and bentonite block and mortar structures in 36-in.-diameter horizontal holes; compacted backfill materials in 36-in.-diameter

vertical boreholes; and salt-water based concrete in vertical boreholes including both halite and anhydrite zones. DWP

Stormont, J.C. 1987. *Small-Scale Seal Performance Test Series "A" Thermal/Structural Data Through the 180th Day*. SAND87-0178. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: As part of an in situ test of the performance of concrete seals, measurements of temperature, strain, stress, and displacement are being made in seals and in adjacent rock. The seals vary in size from 15.2-cm diameter by 30.4-cm length to 91.4-cm diameter by 91.4-cm length, and are located in vertical boreholes in predominately halite host rock. This report contains data collected through the 180th day after seal emplacement and presents discussion and conclusions based on these data. A double hump in the temperature history resulting from concrete hydration was consistently observed and is thought to be a result of the two-phase hydration of the concrete. The concrete-strain and stress data indicate that creep of adjacent rock is the predominant mechanism for stress and strain changes in the seals. The trend of these data suggests that they may eventually stabilize or equilibrate. The seals exhibited little structural response to a 2-MPa axial load from fluid flow/permeability testing, indicating substantial concrete/rock interface strength.

Stormont, J.C. 1988. *Preliminary Seal Design Evaluation for the Waste Isolation Pilot Plant*. SAND87-3083. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents a preliminary evaluation of design concepts for the eventual sealing of the shafts, drifts, and boreholes at the Waste Isolation Pilot Plant (WIPP) Facility. The purpose of the seal systems is to limit the flow of water into, through, and out of the repository. The principal design strategy involves the consolidation of crushed or granular salt in response to the closure of the excavations in salt. Other candidate seal materials are bentonite, cementitious mixtures, and possibly asphalt. Results from in situ experiments and modeling studies, as well as laboratory materials testing and related industrial experience, are used to develop seal designs for shafts, waste storage panel entryways, non-waste containing drifts, and boreholes. Key elements of the ongoing experimental program are identified.

Stormont, J.C. 1990a. *Discontinuous Behavior Near Excavations in a Bedded Salt Formation*. SAND89-2403. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Discontinuous behavior is being observed and measured in the vicinity of excavations constructed in a bedded salt formation 650 m below ground surface for the Waste Isolation Pilot Plant (WIPP) Facility. The 2-m thick salt layer in the immediate roof acts as a beam, shearing along a thin overlying anhydrite/clay seam. Vertical separations between the immediate roof layer and the overlying strata are often observed at the anhydrite/clay seam above the center of excavations of larger span (11 m). The floor of the excavations is comprised of a 1-m thick salt layer underlain by a 1-m thick predominantly anhydrite layer (referred to as MB-139). Fractures in MB-139 develop beneath most excavations, with increased fracture frequency with drift span and age. In the excavations of larger span (11 m), MB-139 eventually debonds along the underlying clay layer. The salt layer overlying MB-139 develops both shear and tension failure. In a few locations below excavations of large span, continuous fracture systems are developing from rib to rib through MB-139 and the overlying salt. In the ribs, there is limited fracturing within the first meter of most larger excavations. Vertical fractures develop in pillars at most intersections. The discontinuous behavior is qualitatively consistent with analyses of the formation behaving as a layered medium (elastic beam analysis) and limited tensile and compressive failure of the rock salt.

The significance of the discontinuous behavior is that it can dominate the effective fluid transport properties of the formation near the excavation, and therefore requires consideration in the design of repository seals. Furthermore, the discontinuous behavior must be monitored and is a very important consideration in the maintenance program designed to assume a safe underground environment.

Stormont, J.C. 1990b. *Summary of 1988 WIPP Facility Horizon Gas Flow Measurements*. SAND89-2497. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Numerous gas-flow measurements have been made at the Waste Isolation Pilot Plant (WIPP) Facility horizon during 1988. All tests have been pressure-decay or constant-pressure tests from single boreholes drilled from the underground excavations. The test fluid has been nitrogen. The data have been interpreted as permeabilities and porosities by means of a transient numerical solution method. A closed form steady-state approximation provides a reasonable order of magnitude permeability estimate. The effective resolution of the measurement system is less than 10^{-20} m².

Results indicate that beyond 1 to 5 m from an excavation, the gas flow is very small, and the corresponding permeability is below the system resolution. Within the first meter of an excavation, the interpreted permeabilities can be five orders of magnitude greater than the undisturbed or far-field permeability. The interpreted permeabilities in the region between the undisturbed region and the first meter from an excavation are in the range of 10^{-16} to 10^{-20} m². Measurable gas flow occurs to a greater depth into the roof above WIPP excavations of different sizes and ages than into the ribs and floor. The gas-flows into the formation surrounding the smallest excavation tested are consistently lower than those at similar locations surrounding larger excavations of comparable age. Gas flow measured in the interbed layers near the WIPP excavations is highly variable. Generally, immediately above and below excavations, relatively large gas flow is measured in the interbed layers. These results are consistent with previous measurements and indicate a limited disturbed zone surrounding WIPP excavations.

Stormont, J.C., and J.G. Arguello. 1988. *Model Calculations of Flow Through Shaft Seals in the Rustler Formation*. SAND87-2859. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A simple model of one-dimensional darcy flow through shaft seals in the Rustler Formation overlying the Waste Isolation Pilot Plant (WIPP) Facility horizon was developed to provide a means of conducting parametric evaluations of seal design and performance. The model provides for a number of intervals in series between the top of the Rustler Formation and the top of the Salado Formation. Each interval has three parallel flow paths (seal material, adjacent rock, and seal/rock interface). Ranges of input values for seal, rock, and interface performance were estimated from available literature and inference. Calculations were performed to determine the sensitivity of the flow rate through the seal system to the type, location, assumed performance, and number of seal components. The seal system response was determined to be most sensitive to permeability of the host rock. Uncertainties regarding the concrete/rock interface and the degradation of the concrete may render the concrete ineffective as a long-term flow barrier. Bentonite, owing to its low permeability and probable long-term stability, may be an acceptable long-term seal material. The results of these calculations highlight data needs that include determination of host rock permeability and measurement and predictions of bentonite stability.

Stormont, J.C., and C.L. Howard. 1986. *Development and Implementation: Test Series B of the Small-Scale Seal Performance Tests*. SAND86-1329. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The second in a series of in situ experiments to evaluate candidate salt repository sealing materials and sealing configurations has been initiated in the Waste Isolation Pilot Plant (WIPP). Test Series B of the Small-Scale Seal Performance Tests is providing structural/thermal and fluid-flow information for the evaluation of horizontally emplaced expansive salt-water based concrete seals. This report provides information necessary for evaluating these data, including "as built" test configurations and descriptions of activities such as drilling and seal instrumentation emplacement, including the development of an adequate seal-emplacement technique.

Stormont, J.C., and C.L. Howard. 1987. *Development, Implementation and Early Results: Test Series C of the Small-Scale Seal Performance Tests*. SAND87-2203. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The third in a series of in situ experiments to evaluate candidate salt repository seal materials and sealing configurations has been initiated in the Waste Isolation Pilot Plant (WIPP). Test Series C of the Small-Scale Seal Performance Tests is providing structural and fluid-flow information for the evaluation of seals made from salt and salt/bentonite mixtures pressed into block form. This report provides information about the development and implementation of this test including a description of the machine used to press the blocks; results from a limited study to optimize the blocks; estimates of block properties; description of instrumentation used in Test Series C to measure pressure and displacement; seal emplacement methods; and "as-built" hole, seal, and instrumentation configurations. Deformation and pressure data through about 160 days after seal emplacement are given. Preliminary fluid flow results indicate the salt/bentonite block-type seals may be effective barriers to flow shortly after installation.

Stormont, J.C., R.V. Matalucci, and H.S. Morgan. 1983. "Field Evaluation of Stress Measurement Techniques in Rock Salt," *30th International Instrumentation Symposium, Denver, CO, May 7-10, 1984*. SAND83-2051A. Albuquerque, NM: Sandia National Laboratories. (Abstract Only; Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: As part of the nuclear Waste Isolation Pilot Plant (WIPP) Research and Development Program, three underground field experiments were performed, one in potash and two in rock salt in southeastern New Mexico, to investigate the feasibility of using borehole inclusion stress meters to measure in situ stress and/or stress changes in salt. These tests provided a direct comparison of various inclusion gauges and served to determine time-dependent gauge response, to demonstrate repeatability of gauge response, and to investigate the effects of preload on gauge response. Gauges used were the strain gauged stress meter (SGS), US Bureau of Mines (USBM) pressure cells (borehole pressure cell [BPC] and cylindrical pressure cell [CPC]), and developmental pressure cell gauges (USBMX and Sandia Pressure Cell [SPC]).

Borehole deformation resulted in the loading of these borehole inclusion devices; this load was detected by a strain gauged columnar plug for the SGS and by hydraulic fluid pressure for the remaining gauges. Usually, these measurements can be related to in situ stress changes via analytical expressions, which depend on material properties of both the gauge and the rock. In

salt, however, the use of these expressions is complicated by the time-dependent deformation (creep) of the surrounding rock salt.

The gauges were calibrated in the laboratory and then installed underground in horizontal boreholes. These boreholes were nominally 50-ft deep and in some cases required diameter tolerances of less than .01-in. USBM pressure cells and SGSs were inserted in the boreholes with a special tool, and USBMX and SPC gauges were grouted in place. Preloads on the gauges ranged from less than 100 psi to 2500 psi.

Gauge output has been monitored for up to 8 months and will continue. Of the 30 SGSs, 24 BPCs, 10 CPCs, 2 USBMXs, and 2 SPCs installed, reasonable consistency was observed within individual gauge types. However, correlations between gauge types require further study and analysis. Some gauges responded significantly to induced stress changes, others showed less sensitivity. Gauge readings initially changed rapidly with time and approached steady-state equilibrium values at longer times. The relationship between the steady-state readings and the in situ stress state is currently under investigation. Gauge preload did not, after time, appear to significantly influence gauge response. A few early gauge failures were attributed to pressure leaks caused by corrosion.

Stormont, J.C., R.V. Matalucci, and H.S. Morgan. 1984. "Field Tests of Stress Measurement Techniques in Rock Salt," *Instrumentation in the Aerospace Industry, Proceedings of the 30th International Instrumentation Symposium, Denver, CO, May 7-10, 1984*. SAND83-2507C. Research Triangle Park, NC: Instrument Society of America. 421-444. (Available from Engineering Societies Library, New York, NY).

ABSTRACT: Three underground field tests were performed in southeastern New Mexico as part of the US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) Research and Development Program. These tests, one in potash-rich halite and two in relatively pure halite (rock salt), investigated the feasibility of using borehole inclusion stress meters to measure in situ stress and stress changes in salt. The tests provided a comparison of inclusion stress meters and demonstrated various qualities of gauge response, including time-dependent characteristics, repeatability, and the effects of preload. Three gauge types comprising five gauges were used: the strain gauged stressmeter (SGS); two US Bureau of Mines (USBM) hydraulic pressure cells called the borehole pressure cell (BPC) and the cylindrical pressure cell (CPC); and two development pressure cells called the USBMX and the Sandia Pressure Cell (SPC). Gauge response has been reasonably consistent. However, further study is required of the correlations between gauge types and between gauge output and the in situ state of stress.

Stormont, J.C., E.W. Peterson, and P.L. Lagus. 1987. *Summary of and Observations About WIPP Facility Horizon Flow Measurements Through 1986*. SAND87-0176. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Numerous gas-flow measurements have been made at the Waste Isolation Pilot Plant (WIPP) Facility horizon from 1984 through 1986. Almost all tests have been constant-pressure or pressure-decay tests from single boreholes drilled in the underground excavations. Results indicate that beyond about 2 m from an excavation, both halite and interbeds (anhydrite and clay layers) allowed very low gas flows, and calculated permeabilities are below 1 microdarcy. In regions within 2 m of an excavation, very high flow rates were measured in the interbeds immediately above and below an excavation when the test hole was drilled from near the center of the excavation. Further, measured flow rates increase with the width of the excavation. The halite also permits substantially greater gas flow within about 1 m of the excavations. Limited tracer measurements reveal that flow paths, in both the halite and interbeds in the near field region, are significantly larger than those in the presumed

undisturbed condition. The gas-flow measurements are consistent with the development of a (perhaps partially saturated) dilatant zone (increased porosity) around the excavations. Considerable uncertainty is associated with permeabilities calculated from these flow measurements, due to unknowns of rock saturation, entry pressure effects, flow homogeneity, etc.

Observations based on these gas flow measurements will aid in understanding the behavior and response of rocks surrounding the WIPP Facility excavations. The implications of these measurements for seal design are useful, particularly in assessing the degree of seal bypass to expect in adjacent rock. Results suggest that seals be emplaced as soon as possible after excavation and in as narrow drifts as possible to minimize potential bypass. These data are also useful in separate studies of brine influx and gas generation/dissipation. Future measurements will focus on the development and extent of the disturbed zone and on obtaining data that will make conversion of flow data to intrinsic permeabilities more defensible.

Stowe, R.L. 1985. *Creep Test of WIPP Site Anhydrite Core*. Miscellaneous Paper SL-85-13. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers.

ABSTRACT: A creep reaction frame, a test specimen deformation jacket, a data-acquisition system, and a triaxial chamber were readied and verified for their suitability for conducting triaxial creep tests of hard rock. All the equipment was found to be adequate for doing triaxial creep tests. A limited number of creep tests were conducted on anhydrite rock core from the Waste Isolation Pilot Plant (WIPP) Site. Three of the four creep stages were observed during the testing. A logarithmic function was found to best fit the transient and steady-state creep stages.

Stroup, D.E., and P.E. Senseny. 1987. *Influence Of Bentonite Content On Consolidation And Permeability Of Crushed Salt From The WIPP*. Topical Report RSI-0309. Rapid City, SD: RE/SPEC, Inc.

ABSTRACT: Nine consolidation tests were conducted under hydrostatic stresses of either 1.72 or 3.45 MPa at a temperature of 25°C to evaluate the influence of moisture and bentonite content on permeability and consolidation of crushed salt. Three percentages by weight of bentonite (5, 15, and 30) and two moisture contents (as-received and 2% above as-received by weight) were used in sample preparation. Permeability was measured using argon and brine.

Results show that permeability is lowered and consolidation decreased by the addition of bentonite to the crushed salt. Argon permeability is also lower for denser samples. Brine permeability, however, does not appear to decrease with increasing density. Volumetric strains obtained at the higher hydrostatic stress of 3.45 MPa and the additional 2% moisture are larger than those obtained at the lower hydrostatic stress of 1.72 MPa and the as-received moisture content. Predictions of long-term consolidation from the short-term results using a least squares fit of volumetric strain versus $\log_{10}(t)$ would underpredict long-term volumetric strain, especially for brine-penetrated material.

Sumlin, H.A. 1981. *A Report on the Development of Equipment and Techniques for Drilling and Machining Bedded Salt*. SAND80-2603. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: For several years, Sandia National Laboratories (SNL) has been involved in the development of equipment and techniques used in the evaluation of bedded salt as a storage media for nuclear waste, beginning with the *WIPP Conceptual Design Report* for the Waste Isolation Pilot Plant (WIPP) and continuing with field and laboratory experiments. They

indicate the need for a more complete understanding of bedded salt as an engineering material. This report discusses various aspects of bedded salt in its comparison to other materials, machining methods in the laboratory, and equipment development to support experiments in mines.

ANNOTATION: Design documents are described in Dennis et al. (1977) and Scully (1977). The WIPP Conceptual Design Report was published as SAND77-0274 in June 1977; it is not included in this bibliography because its subject matter is engineering design.

Sutherland, H.J., and S.P. Cave. 1979. *Gas Permeability of SENM Rock Salt*. SAND78-2287. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Laboratory measurements of the argon gas permeability for rock salt specimens from the Waste Isolation Pilot Plant (WIPP) Site in southeast New Mexico are obtained by using a transient, pressure step technique. Hydrostatic and differential pressure states are investigated as a function of confining pressure and time. These data, when combined with the results of other experimenters, lead to the conclusions that the in situ permeability of the undisturbed formation is less than 0.05 microdarcy; the introduction of non lithostatic stress states into the formation, as with mining, may produce connected porosity that will increase the permeability of the formation; and, hydrostatic pressure states applied for finite-time periods tend to "heal" the formation to its original undisturbed state.

Sutherland, H.J., and S.P. Cave. 1980. "Argon Gas Permeability of New Mexico Rock Salt Under Hydrostatic Compression," *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*. Vol. 17, no. 5, 281-288.

ABSTRACT: Laboratory measurements of the argon gas permeability for rock salt specimens from the Waste Isolation Pilot Plant (WIPP) Site in southeast New Mexico are obtained by using a transient, pressure step technique. Permeabilities of seven specimens are investigated as a function of hydrostatic compression and time. These data, when evaluated with the results of other authors, lead to the conclusions that if this formation is in a state of hydrostatic compression in its undisturbed state, then its in situ permeability is less than $5 \times 10^{-20} \text{ m}^2$. And, if any connected porosity is introduced into formation, as with mining, the formation can "heal" itself if it returns to a hydrostatic pressure state.

Sutherland, H.J., and D.E. Munson. 1983. *Subsidence Prediction for High Extraction Mining Using Complementary Influence Functions*. SAND82-2949. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Surface subsidence caused by high-extraction underground mining is described through complementary influence functions. The concept of complementary functions was introduced recently by Sutherland and Munson. This concept differs from other proposed concepts in that the surface displacement is the result of the combined contributions of mined and unmined zones. This approach eliminates computational difficulties experienced with the conventional influence functions in determining the deflections above the rib side and in the application of influence functions to complex room and pillar configurations. The analysis framework is reported here in two forms. The first is for the complete complementary influence function formulation and the second is the degenerate case of the complementary influence functions applied to a longwall geometry. The former is solved analytically; the latter graphically. Both are illustrated with analyses of actual case histories.

Sweet, J.N. 1979. *Pressure Effects on Thermal Conductivity and Expansion of Geologic Materials*. SAND78-1991. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Through analysis of existing data, an estimate is made of the effect of pressure or depth on the thermal conductivity and expansion of geologic materials that could be present in radioactive waste repositories. In the case of homogeneous dense materials, only small shifts are predicted to occur at depths ≤ 3 km, and these shifts will be insignificant as compared to those caused by temperature variations. As the porosity of the medium increases, the variation of conductivity and expansion with pressure becomes greater, with conductivity increasing and expansion decreasing as pressure increases. The pressure dependence of expansion can be found from data on the temperature variation of the isobaric compressibility. In a worst-case estimate, a decrease in expansion of $\sim 25\%$ is predicted for 5% porous sandstone at a depth of 3 km. The thermal conductivity of a medium with gaseous inclusions increases as the porosity decreases, with the magnitude of the increase being dependent on the details of the porosity collapse. Based on analysis of existing data on tuff and sandstone, a weighted geometric mean formula is recommended for use in calculating the conductivity of porous rock. The effect of pressure on the conductivity of rock with liquid inclusions will be small unless the liquid is boiled away in response to elevated temperature produced by the presence of a nearby heat source. In this case an appreciable decrease in the conductivity could occur. As a result of this study, it is recommended that measurement of rock porosity versus depth receive increased attention in exploration studies and that the effect of porosity on thermal conductivity and expansion should be examined in more detail.

Sweet, J.N., and J.E. McCreight. 1980a. *Thermal Conductivity of Rocksalt and Other Geologic Materials From the Site of the Proposed Waste Isolation Pilot Plant*. SAND79-1665. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The measurements first reported on the thermal conductivity of samples taken from a borehole at the site of the proposed nuclear Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM, have been extended to include additional samples and higher temperature measurements. Samples for measurements were taken from several depths of three wells, including the well AEC-8 from which samples were obtained. These samples ranged from relatively pure rock salt (NaCl) with small amounts of interstitial anhydrite to essentially nonsalt samples composed of gypsum or clay. The measurements in this test series were conducted at Sandia National Laboratories (SNL) using the longitudinal heat flow apparatus, at the Los Alamos Scientific Laboratory (LASL) using a transient line source technique, and at Dynatech Corp., Cambridge, MA, using a linear heat flow comparative technique.

In general, the data from the three laboratories agreed reasonably well for similar coarse grained translucent rock salt samples, with the LASL and SNL results typically being about 20% higher than those of Dynatech. The measured rock-salt conductivities in the temperature range 300-700 K are described relatively accurately by an expression of the form, $\lambda = \lambda_0 (300/T)^\gamma$, where λ_0 = conductivity at 300 K, $\gamma = 1.14$, and T is the temperature in K. The Sandia and LASL data are best described by $\lambda_0 = 6$ W/m-K, while for the Dynatech data, $\lambda_0 = 5$ W/m-K yields the best fit. It has been proposed that a two-parameter expression of the form given above for λ is generally applicable to a wide variety of nonmetallic solids, with the deviation of γ from one resulting from both thermal expansion effects and optic-acoustic phonon interactions, which are not included in the standard analysis of thermal conductivity caused by phonon transport. The data in the range $T > 500$ K frequently deviate by $\sim \pm 15\%$ from the predicted behavior. This is not believed to be the result of the onset of radiative thermal transport because the deviations are negative as well as positive. Infrared transmission measurements on rock-salt samples from the proposed WIPP Site show no transmission in the 3-10 μm wavelength range for samples > 5 cm thick. Use of the estimated infrared absorption

coefficient in the Rosseland radiative conductivity relation also leads to the conclusion that there is little radiative conduction for $T < 800$ K.

For nonsalt samples from the proposed WIPP Site, values of λ_0 fall in the range 0.5-3 W/m-K and frequently γ values are in the range $\gamma < 1$. All samples were dense with little or no porosity evident. On the basis of these experiments, it has been concluded that the thermal conductivity of materials found at the site can be predicted to an accuracy $\sim \pm 30\%$ from knowledge of the composition and grain size of these materials.

Sweet, J.N., and J.E. McCreight. 1980b. *Thermal Properties Measurements on Rocksalt Samples From the Site of the Proposed Waste Isolation Pilot Plant*. SAND80-0799. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Thermal conductivity, thermal expansion, and specific heat measurements have been made on a number of specimens cut from core samples obtained from drill holes at or near the site of the proposed Waste Isolation Pilot Plant (WIPP). The specific heat measurements were made by differential scanning calorimetry, and the results showed that the specific heats of both clean rock salt samples and of dirty samples with $\leq 7\%$ insoluble impurities were essentially identical to the published specific heat for pure NaCl. In the thermal expansion measurements, two distinct groups of samples were identified. The first group had average expansion coefficients in the temperature range 300-700 K close to that reported for pure NaCl. All the samples in this group were composed predominantly of halite, with only small amounts of other minerals or materials present. A second group of samples had expansion coefficients only ~ 0.3 - 0.5 that of NaCl. The samples in this group were composed largely of polyhalite, anhydrite, or siltstone.

The measurements first reported on the thermal conductivity of samples taken from a borehole at the site of the proposed nuclear WIPP near Carlsbad, NM, have been extended to include additional samples and higher temperature measurements. Samples for these measurements were taken from several depths of three wells, including the well AEC-8 from which samples were obtained. These samples ranged from relatively pure rock salt (NaCl) with small amounts of interstitial anhydrite to essentially nonsalt samples composed of gypsum or clay. The measurements in this latest series were conducted at Sandia National Laboratories (SNL) using the longitudinal heat flow apparatus, at the Los Alamos Scientific Laboratory (LASL) using a transient line source technique, and at Dynatech Corp., Cambridge, MA, using a linear heat flow comparative technique.

In general, the data from the three laboratories agreed reasonably well for similar coarse grained translucent rock salt samples, with the LASL and SNL results typically being about 20% higher than those of Dynatech. The measured rock salt conductivities in the temperature range 300-700 K are described relatively accurately by an expression of the form, $\lambda = \lambda_0(300/T)^\tau$, where λ_0 = conductivity at 300 K, $\tau = 1.14$, and T is the temperature in K. The Sandia and LASL data are best described by $\lambda_0 = 6$ W/m-K, while for the Dynatech data, $\lambda_0 = 5$ W/m-K yields the best fit. It has been proposed that a two parameter expression of the form given above for λ is generally applicable to a wide variety of nonmetallic solids, with the deviation of τ from one resulting from both thermal expansion effects and optic-acoustic phonon interactions, which are not included in the standard analysis of thermal conductivity caused by phonon transport. The data in the range $T \geq 500$ K frequently deviate by $\sim \pm 15\%$ from that predicted by the above functional form.

Swenson, F.A. 1974. "Rates of Salt Solution in the Permian Basin," *Journal of Research, US Geological Survey*. Vol. 2, no. 2, 253-257.

ABSTRACT: For safe, long-term storage of radioactive materials in salt beds, rates of solution of salt, which might imperil such storage, must be known. For solution to continue, fluid must move through the system. Major fluid discharge from the system is by surface streams. Using US Geological Survey records of stream flow and chemical quality of water, computations of sodium chloride discharges of numerous subbasins have been made. A map has been constructed showing tons of sodium chloride discharged per day and tons of sodium chloride discharged per square mile per year. Also shown are locations of major saline springs and their rate of discharge of sodium chloride in tons per day.

Swyler, K.J., R.W. Klaffky, and P.W. Levy. 1990. "Recent Studies on Radiation Damage Formation in Synthetic NaCl and Natural Rock Salt for Radioactive Waste Disposal Applications," *Scientific Basis for Nuclear Waste Management, Proceedings of the International Symposium on the Scientific Basis for Nuclear Waste Management, Boston, MA, November 27-30, 1979.* Ed. C.J.M. Northrup, Jr. New York, NY: Plenum Press. Vol. 2, 553-560.

ABSTRACT: Radiation damage formation in natural rock salt is described as a function of irradiation temperature and plastic deformation. F-center formation decreases with increasing temperature while significant colloidal sodium formation occurs over a restricted temperature range around 150°C. Plastic deformation increases colloid formation; it is estimated that colloid concentrations may be increased by a factor of 3 if the rock salt near radioactive waste disposal canisters is heavily deformed. Optical bandshape analysis indicates systematic differences between the colloids formed in synthetic and natural rock salts.

Szabo, B.J., W.C. Gottschall, J.N. Rosholt, and C.R. McKinney. 1980. *Uranium Series Disequilibrium Investigations Related to the WIPP Site, New Mexico. Part I: A Preliminary Study of Uranium-Thorium Systematics in Dissolution Residues at the Top of Evaporites of the Salado Formation. Implications to Process and Time. Part II: Uranium Trend Dating of Surficial Deposits and Gypsum Spring Deposits Near WIPP Site, New Mexico.* Open-File Report 80-879. Denver, CO: US Geological Survey.

ABSTRACT: (Part I) Eight samples representing dissolution residues at the top of the Salado Formation were selected from core of WIPP-25, in Nash Draw, between the depths of 179.9 to 183.1 m. Uranium systematics of these samples were studied to provide a uranium trend age estimate of the time of dissolution or provide insight into the dissolution mechanism. Uranium ranged from about 1-2 ppm for red clays to 0.2 ppm for gypsum to about 0.017 ppm for halite. Excluding sample A, a linear relationship on the uranium trend plots represents a minimum age of 700,000 years for the dissolution event. Sample A is thought to represent an earlier, recycled gypsum sample. The method appears to be applicable to determining the age of dissolution residues and events.

(Part II) The uranium trend method was used to examine the ages of the Mescalero caliche, the overlying Berino soil, and gypsum spring deposits in Nash Draw. Isochrons for the Mescalero caliche indicate it began forming about 600,000 years ago and continued over a relatively long time. The isochron for the overlying Berino soil indicates it began to form about 330,000 years ago. The gypsum spring deposit shows an age of about 380,000 years, while five specimens of mammal fossils from the gypsum deposit show ages ranging from about 25,000 to about 170,000 years. The older fossil age may represent a minimum (youngest) age for the spring deposit, but the reason for the range of ages is undetermined. DWP

Taggart, J.E., and J.R. Renault. 1977. *Mineralogical Analyses of Cuttings from Sandia WIPP Drill Hole #9*. Open-File Report 70. Socorro, NM: New Mexico Bureau of Mines and Mineral Resources.

ABSTRACT: Cuttings from Drillhole ERDA-9, located at the southeast corner of section 20, T22S, R31E, have been analyzed by x-ray diffraction (XRD) to determine mineralogy. Samples were run on a Phillips diffractometer using monochromatic CuK-alpha X-radiation at 40 kV and 20 mA, scanning at 2° 2 theta per min, strip chart speed 1 in./min, 0.5 x 10³ to 1 x 10³ counts per second full scale.

Minerals that are clearly present are noted as present; those that yield very small peaks are marked as a trace; and those that are difficult to distinguish from the background are labeled as a possible trace. Those marked as present or trace have excellent reliability, while those marked as possible trace should not be relied on too heavily. Large amounts of halite obscure the determination of feldspar, and polyhalite obscures dolomite.

Cuttings from a drill hole are affected by sample lag time and uphole contamination. Minor amounts of quartz in the bottom half of the hole may very well be uphole contamination. Significant bassanite was unexpectedly recorded. Though it may be natural, it is more likely a product of the solution of anhydrite during drilling. DWP

Teufel, L.W. 1981. *Mechanical Properties of Anhydrite and Polyhalite in Quasi-Static Triaxial Compression*. SAND81-0858. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Bedded salt of the Salado Formation at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico is being considered as a nuclear waste containment medium. The Salado Formation is composed of 85-90% rock salt and the remaining 10-15% of the formation consists primarily of polycrystalline anhydrite, smaller amounts of polycrystalline polyhalite, and minor amounts of clay. To provide a more complete evaluation of the thermomechanical behavior of rock in the Salado Formation adjacent to the proposed repository, a rock mechanics testing program has been initiated to determine the mechanical properties of the two most abundant "nonsalt" rocks, anhydrite and polyhalite. This report summarizes the mechanical properties of these two rock types in dry, room temperature, quasi-static triaxial compression experiments to 20 MPa confining pressure. In addition, Coulomb-Mohr and Mises-Drucker criteria have been fit successfully to both yield and failure stress data.

Thompson, D.J. 1988. *Environmental Thermoluminescent Dosimetry Measurements at the WIPP Site, 1976 - 1985*. SAND87-0843. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In 1975, the US Energy Research and Development Administration (ERDA) began evaluating a site in southeastern New Mexico for the possible construction and operation of a Waste Isolation Pilot Plant. The purpose of the facility was to test and demonstrate the operational and technical principles of a permanent repository in bedded salt for ERDA-generated transuranic radioactive waste. An extensive preoperational environmental study program to document the region's meteorology, geology, hydrology, flora and fauna, existing air and water quality, and background radiation was undertaken by Sandia National Laboratories. The purpose of this document is to report the final results of environmental thermoluminescent dosimeter measurements performed from January 1976 through December

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1985. These final results were obtained by reevaluating the quarterly raw data using a uniform analysis procedure.

Thorne, B.J. 1979. *Pressurize Drift Response*. CNSC-2053-01. Albuquerque, NM: Civil/Nuclear Systems Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Preliminary, unpublished calculations indicate gas generated by transuranic (TRU) waste in the Waste Isolation Pilot Plant (WIPP) could reach pressures two to four times the overburden stress (2200 psi) after about 100 years of storage. These pressures were used to test the effects of creep on a drift pressurized by gas. Calculations indicate that the gas pressure loads applied to hypothetical TRU repository drifts would not fracture competent rock salt. This conclusion is not sensitive to the rate of gas generation or peak gas pressure as long as the pressure builds up at a rate slow enough to allow creep in the salt to limit stress deviators, keeping the salt in a confined state.

Based on these results, it is hard to hypothesize a gas-generation rate that would lead to a rapid enough pressure buildup to cause brittle fracture of competent rock salt. About the only credible fracture mechanism would be the extension of existing cracks through the application of gas pressure to the crack surface. DWP

Thorne, B.J. 1980. *Drift Response to Elevated Temperature*. SAND80-7086; CSI-2053-02. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Numerical simulation of an early design for an unventilated Waste Isolation Pilot Plant (WIPP) experimental area, at a depth of 823 m (2700 ft), indicates that drift closure rate is strongly dependent on heat output density. The early design was an array of five parallel drifts 30 m (100 ft) long with 4.6 m (15 ft) width and height spaced on 23 m (75 ft) centers. A no heat case was calculated as a baseline against which to compare heat loading densities of 7.4 W/m² (30kW/acre) and 18.5 W/m² (75kW/acre). A primary creep model for southeast New Mexico rock salt was used for all material in the simulation.

Closure at 25 years for the 7.4 W/m² heat output density exceeded 45 against 25% for the no-heat baseline. In less than 14 years, closure exceeded 65% for the 18.5 W/m² heat output.

Tierney, M.S. 1990. *Constructing Probability Distributions of Uncertain Variables in Models of the Performance of the Waste Isolation Pilot Plant: The 1990 Performance Simulations*. SAND90-2510. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: A five-step procedure was used in the 1990 performance simulations to construct probability distributions of the uncertain variables appearing in the mathematical models used to simulate the Waste Isolation Pilot Plant's (WIPP's) performance. This procedure provides a consistent approach to the construction of probability distributions in cases where empirical data concerning a variable are sparse or absent and minimizes the amount of spurious information that is often introduced into a distribution by assumptions of nonspecialists. The procedure gives first priority to the professional judgment of subject matter experts and emphasizes the use of site-specific empirical data for the construction of the probability distributions when such data are available. In the absence of sufficient empirical data, the procedure employs the Maximum Entropy Formalism and the subject-matter experts' subjective estimates of the parameters of the distribution to construct a distribution that can be used in a performance simulation.

Tillerson, J.R., and P.R. Dawson. 1980. *Heated Mine Room and Pillar Secondary Creep Response*. SAND79-1199. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Heated salt mine room and pillar configurations have been simulated to provide information regarding parameters affecting room closure rates to designers of radioactive waste isolation facilities. A coupled secondary creep and heat transfer formulation with large strain capabilities was used to assess the effects of variations in creep law parameters, thermal properties, imposed boundary conditions, temporal integration, and meshing resolution on room closure rates. The greatest effect results from variations in parameters appearing in the creep constitutive equation. Several creep equations predict realistic creep rates compared to laboratory data but differ greatly in simulating pillar and room closure rates. The constitutive model needs to be improved by considering the activation energy and stress nonlinearity of salt over the range of temperatures and stresses as well as incorporating all regimes of creep behavior. DWP

Tillerson, J.R., and M.M. Madsen. 1978. *Thermoelastic Capabilities for the SANDIA-BMINES Program*. SAND77-0378. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The capability for simulating the thermoelastic behavior of geologic media has been added to the SANDIA-BMINES finite-element code. The equations governing the response of a continuum to a known temperature field are delineated in this report. In addition, the specifics of the implementation of the continuum equations into the existing finite-element program are described. Finally, the results of validation studies performed to assess the accuracy of the modified program are presented along with recommendations concerning future research and development efforts in this field.

Tillman, J.B., and A.E. Hunt. 1989. "Meeting the Challenge of Radioactive Waste Disposal at the WIPP," *Waste Management 89, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 26-March 2, 1989*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 1, 209-215.

ABSTRACT: The Department of Energy (DOE) is constructing the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico. This facility will initially store transuranic (TRU) waste generated from defense activities of the US in a fully retrievable mode during the pilot plant phase. In the next phase, full-scale operations, waste will be emplaced in a permanent disposal configuration. Since last year's Waste Management conference, the WIPP has made significant progress in its evolution toward becoming a functioning pilot plant. Facility construction is nearly complete, as are preoperational checkouts. Many 1988 challenges have been overcome, including: the implementation of a rigorous operational readiness review (ORR) program; the completion of several major institutional activities; and final testing of the TRUPACT-II containers. The status of these and other significant activities at the WIPP are described in this paper. Although additional requirements have been placed upon the WIPP, it is expected that these activities will be completed in time to support a late summer "opening date." The project remains in conformance with established technical and institutional baselines.

Tomasko, D. [1986]. "The Effects of Side-Wall Boundary Conditions on Convective Heat Transfer in a Porous Medium Heated From Below," *CUBE Symposium, Livermore, CA, October 15-17, 1986*. SAND86-1549A. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A coupled set of partial differential equations describing the stream function and temperature distribution in a porous medium heated from below are solved for various side-wall boundary conditions using a fourth-order-accurate Arakawa method. The results of the calculations performed with the porous medium model suggest that maximum convective heat transfer occurs when the walls are adiabatic. Similar isothermal profiles are obtained when a constant linear temperature gradient is imposed on the walls, although the overall heat transfer is nearly 40% less. Even less heat transfer occurs when the side walls are maintained at a constant hot or constant cold temperature. Application of the results of this study to aquifers heated from below indicates that heat transfer and natural convective transport are maximized when adiabatic conditions are assumed on the confining lateral boundaries. Use of more realistic boundary conditions can significantly reduce the overall transport.

Tomasko, D. 1987. *The Effects of a Bimodal Pore Distribution on Matrix Diffusion in a Fractured Porous Medium*. SAND87-0265. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Three models are developed for predicting the concentration of a conservative (nonreactive) solute during transport through a fractured porous medium consisting of two materials with different physical properties. The materials are assumed to be arranged in series along the fracture, so that the advecting fluid sequentially passes through two different matrix environments. In all cases, the matrices are assumed to be infinite in a direction perpendicular to the orientation of the fracture.

The first model predicts the time-dependent solute concentration using two one-dimensional transport equations for the fracture and two one-dimensional diffusion equations for the rock matrices. Longitudinal dispersion in the fracture is assumed to be negligible. The fracture equations are coupled by assuming a constant concentration at the boundary between the two materials, and the fractures are coupled to the matrices by appropriate flux terms.

In the second model, the number of equations required to predict the concentration of the solute in the fracture is reduced by a factor of 2 by developing simple, analytic expressions for a single, effective porosity and matrix-diffusion coefficient.

The third model is much more complex than the first two because of incorporation of longitudinal dispersion in the fracture transport equations. This model was developed and used to investigate the effects of axial dispersion on the predicted concentrations and to determine when the simpler models are appropriate.

Comparisons between the three models indicate that the predicted solute concentrations in a fracture for a constant source input are very similar except near the boundary between the two materials, where the maximum differences are ~20%. Even better results are obtained when the duration of the injection is short compared to the total time of the test.

The simplified model is then used to estimate the effect of fluid-filled vugs on matrix diffusion in the fractured Culebra Dolomite Member of the Rustler Formation at the proposed Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico. This objective is accomplished by assuming that the dolomite can be modeled as if it were composed of two materials arranged in series along a fracture. The first material is assumed to be a vug-free dolomite, whose properties are known from either the literature or laboratory analyses. The second material is assumed to be water; all the fluid-filled vugs along the fracture are gathered together into one large, dead-end pore volume. Thus, the advecting solute first passes through a region surrounded by a vug-free dolomite and then through a region of stagnant fluid.

The results of a calculation performed with material properties similar to those expected for the Culebra Dolomite indicate that significantly enhanced matrix diffusion and a subsequent increase in solute retardation occurs for as little as a 5% vugginess along the path of the fracture. These findings clearly demonstrate the need to properly characterize both matrix and

vug properties in consideration of solute transport through a vuggy, fractured porous medium. The results and methods presented in this report also suggest the use of an apparent matrix porosity and equivalent matrix-diffusion coefficient, if the values are representative of the system. Furthermore, the methods presented provide a means of reducing the uncertainty in properties essential for transport calculations through a composite material by combining macroscopic observations of vugginess with detailed laboratory analyses.

Tomasko, D., and A.L. Jensen. 1987. *A Linear-Flow Interpretation of the H-3 Multiwell Pumping Test Conducted at the Waste Isolation Pilot Plant (WIPP) Site.* SAND87-0630. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: An interpretation is presented of the H-3 multiwell pumping test conducted at the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico between October 15, 1985 and April 12, 1986. Unlike previous interpretations of this test that used a double-porosity radial flow model, this interpretation is based on a linear-flow process. A linear-flow conceptualization was implemented for three reasons. First, drawdowns in the pumped well (H-3b2) responded as if the Culebra Dolomite Member of the Rustler Formation were pumped from an elongated feature with a significantly higher permeability than the surrounding porous medium. Second, drawdowns in observation wells DOE-1 and H-11 exhibited nearly classic linear-flow behavior in specialty plots of drawdown versus the square root of time. Finally, DOE-1 and H-11 drawdowns had excellent type-curve matches with a linear-flow type curve.

Two techniques were developed to analyze the H-3 data with a linear-flow conceptualization. The first technique was used to find the orientation of the linear feature using data from a multiwell interference test by minimizing the squared differences between field observations and linear flow calculations. The second technique was used to calculate the transmissivity and width of the feature. To calculate consistent system parameters, this technique required developing a least-squares fitting procedure to minimize the effects of noise in the drawdown measurements.

Linear-flow analyses of the H-3 data yield the following parameter values for the linear feature: an average width of ~7,000 ft; an orientation of N29 degrees W; average transmissivities of ~2, 9, and 19 ft²/D at the pumped well, and between the pumped well DOE-1 and H-11, respectively; and an effective radius of the pumped well equal to ~350 ft. These findings are consistent with detailed two-dimensional numerical simulations with the SWIFT II computer code, recent geophysical interpretations of Controlled Source Audio Magneto Telluric surveys of the southern portion of the site, and double-porosity, radial-flow interpretations.

While the underlying assumptions of the linear-flow model differ from those of a double-porosity radial-flow model, the properties calculated for the Culebra are similar to those previously presented and indicate a basic insensitivity to the system flow model. In addition to yielding hydrologic values that are approximately the same, the two models are complementary and provide unique information for characterizing the aquifer double-porosity parameters from one model, and the orientation and width of a high-permeability elongated strip from the other. The two interpretations also provide a consistent picture of an extensively fractured porous medium in the vicinity of the H-3 hydropad.

Torres, T.M. 1986a. *Two-Dimensional Axisymmetric and Plane Strain Scoping Calculations for the Small-Scale Seal Performance Test, Test Series A.* SAND86-0488. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: This report presents two-dimensional axisymmetric and plane-strain scoping calculations for the Small-Scale Seal Performance Test (SSSPT), Test Series A. The SSSPT is part of the Plugging and Sealing Program for the Waste Isolation Pilot Plant (WIPP) and is a precursor to future large-scale in situ experiments. Test Series A is being conducted in a single isolated alcove (Room M) located in the underground salt formation; it contains several 3.66-m (12-ft) deep vertical bore holes of varying diameters with concrete plugs of different lengths. The bore holes in Room M are instrumented for monitoring the deformation, stress, and strain resulting from the creep of the salt and the effects of the plug. Data for comparison from the experiment are not yet available. However, as a precursor to three-dimensional calculations, the two-dimensional axisymmetric and plane-strain results presented herein are attempts to provide bounds on quantitative and qualitative structural behavioral trends for predicting the near-field response of the drift, plug, and salt.

Torres, T.M. 1986b. *Preliminary Evaluation of Drift Closure and Closure Rate Response With Respect to the Effects of Gas Occurrences Within the Waste Isolation Pilot Plant.* SAND86-1059. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: As part of the Waste Isolation Pilot Plant (WIPP) Research and Development Program, a gas-testing program has been developed to investigate the naturally occurring gases in the WIPP horizon rocks and to evaluate their effect on the safe operations and performance of the WIPP. This report presents a comparison of the structural response (closure and closure rates) of a drift drilled with pressure relief holes to the structural response of a drift drilled without pressure relief holes. The drifts under consideration are the E300 drift (mined with pressure relief holes) and the W170 drift (mined without pressure relief holes) located south of the Waste Handling Shaft. For the short-term (less than two years), differences between measured closures for the two drifts are negligible. The closure rate comparisons also indicate that the two drifts, thus far, are responding similarly.

Torres, T.M. 1988. *Design Evaluation: Structural Calculations for the Construction and Salt Handling Shaft and the Waste Handling Shaft at the Waste Isolation Pilot Plant (WIPP).* SAND87-2230. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: One fundamental strategy under consideration for sealing the Waste Isolation Pilot Plant (WIPP) shafts involves the consolidation of the salt backfill in specified portions of the shaft. The backfill is expected to consolidate, over time, into a rock-salt mass comparable to that of the surrounding intact salt. For purposes of preliminary design evaluation, the criterion for effective salt consolidation has been defined to occur when the fractional density of the crushed salt reaches 95% (i.e., porosity = 5%, the permeability of the crushed salt is approaching that of the intact host rock). Thus, the shaft is sealed with a backfill material (crushed salt and/or precompacted salt blocks) that eventually develops properties considered favorable for long-term sealing purposes.

This report describes the structural analyses performed to address two questions regarding WIPP shafts: How much deformation will occur in the shaft as a function of time and depth? If the salt backfill is emplaced in the shaft 30 years after excavation at some specific initial density, how long will it take for the backfill to consolidate to 95% relative density?

The two-dimensional axisymmetric shaft model was allowed to creep for a period of 30 years before instantaneous backfill emplacement. Results indicate that the backfill will consolidate to 95% density in less than 300 years at the repository horizon for an initial relative density of 0.60. Most of the backfill in the shaft reaches 95% density in less than 1000 years if the backfill is emplaced at an initial relative density of 0.85. Thus, the calculations show that salt

seal materials can reconsolidate in the WIPP shafts to densities nearly equal to those for the intact host rock salt in a relatively short time span.

Trucano, T.G. 1981. *Computer Modeling of Stress States Associated With Fluid Migration Experiments*. SAND81-2008. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Results of recent computer simulations of temperature and stress fields associated with fluid migration experiments are presented. The simulations are for a laboratory experiment and two in situ equivalents in each of which bedded salt is heated by a cylindrical thermal source. The heat transfer problem is solved using the COYOTE finite-element code. The mechanical response of the salt is computed using the finite-element code SANCHO. Differences in the stress state near the heater are of interest for the three problems. Tensile failure occurs in the salt when the heater is shut down. It is found that the extent of the fracture is much the same in all three of the simulations. Plots of failure contours, time histories of the bulk pressure, and stress profiles are included.

[TSC-D'Appolonia]. 1982a. *Exploratory Shaft, Exploratory Shaft Key, and Exploratory Shaft Station Instrumentation. Geotechnical Field Data Report No. 2*. Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: *Geotechnical Field Data Report No. 2* contains all the field data collected from instrumentation at the Waste Isolation Pilot Plant (WIPP) up to and including October 29, 1982 (including all data in the *Geotechnical Field Data Report No. 1*).

Rock mechanics data are reported from a variety of measuring devices installed at the exploratory shaft key area, exploratory shaft station, and within the exploratory shaft. Much of the installation locations and procedures are included in the report. Data are presented in tabular and graphic forms without further evaluation. DWP

[TSC-D'Appolonia]. 1982b. *Underground Excavation Field Instrumentation Data. Geotechnical Field Data Report No. 3*. Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: *Geotechnical Field Data Report No. 3* contains field data collected from drift level instrumentation at the Waste Isolation Pilot Plant (WIPP) from October 30, 1982 through November 30, 1982. This report supplements and updates *Geotechnical Data Report No. 2* and provides a cursory review of in situ conditions at the WIPP Site. Summary plots provided in the previous report are updated for drift-level instrumentation presently in existence, and new plots are provided for instrumentation installed since the previous report. Some drift-level instruments and most exploratory shaft instruments are currently connected to the automatic data logger. As this report is only to update drift-level conditions, the data as taken from the data logger for the exploratory shaft are not provided although they will be included in the next report. DWP

[TSC-D'Appolonia]. 1983a. *Geological Mapping and Water Inflow Testing in the SPDV Ventilation Shaft. Geotechnical Field Data Report No. 4*. Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report presents the results of geologic mapping and water inflow testing in the site preliminary design validation (SPDV) ventilation shaft. The geologic mapping was conducted as part of the in situ field tasks associated with the SPDV Program at the WIPP Site. The ventilation shaft, nominally 6 ft in diameter, was mapped from 97 to 2172 ft, the interval between the surface casing (at about 97 ft depth) and Marker Bed 139. Below the Culebra Dolomite Member, the shaft wall is wet from seepage. The upper Salado Formation is fluted by dissolution; an insoluble residue of clay and silt covers some areas of the shaft. Below 1180 ft, a crust up to 4 in. thick has formed on the shaft wall from dust exiting the facility. Rock samples were collected for description and testing, and shaft walls were photographed.

Water inflow rates into the shaft were estimated both by measuring water level rise in the shaft sump for one to two days and by collecting water in a trough and funnel at 840 ft depth for several minutes. Total water inflow is estimated to range from about 0.3 to 0.9 gpm with an average of about 0.6 gpm. The Rustler Formation produces about 0.3 to 0.4 gpm, mostly from the Culebra Dolomite Member. DWP

[TSC-D'Appolonia]. 1983b. *Geologic Mapping of Access Drifts "Double Box" Area. Geotechnical Field Data Report No. 5.* Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The double box area of the site preliminary design validation (SPDV) excavation includes portions of the 0 East and East 140 drifts and all of the North 140, South 90, and South 400 cross drifts. The geology of the access drifts in the double box area has been mapped to provide technical data for SPDV programs, to characterize and provide permanent documentation of the underground excavations, to provide a data base for selection of final locations of geomechanical instrumentation, and to serve as a guide to mining crews.

Seven lithologic units, designated units 0-6, were identified and described during mapping of the double box, and a reference stratigraphic section was established at "the west rib of the 0 East Drift directly opposite the point of its intersection with the South 400 Drift." The rock units identified in the double box area are laterally continuous. The beds are disrupted by small-scale depositional features. Small warps and flexures in the beds developed pene-contemporaneously with deposition or during compaction and diagenesis. No high-angle structural features were observed in the double box area. Some "small, irregular, damp patches or 'weeps' are found on the ribs and back of the drifts. Typically, they dry up within a few days to a few weeks. The weeps appear to be discrete, isolated manifestations of the presence of small quantities of brine in the halite or associated clay." DWP

[TSC-D'Appolonia]. 1983c. *Underground Excavation Field Instrumentation Data. Geotechnical Field Data Report No. 6.* Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: *Geotechnical Field Data Report No. 6* contains and summarizes instrumental data collected from the exploratory shaft and drift level at the Waste Isolation Pilot Plant (WIPP) from December 1 through December 31, 1982. In addition, the exploratory shaft instrumental data have been updated for every fifth day since the data logger was connected, approximately October 30, 1982. This report supplements and updates *Geotechnical Field Data Reports Nos. 2 and 3*, and it provides a cursory review of in situ conditions at the WIPP Site. Summary plots provided in the previous reports are updated for the active instruments, and new plots are presented for instruments installed during the reporting period. Most instruments in the

exploratory shaft and some in the drift level are connected to the automatic data logger, and these data are presented in tabular form as printed by the data logger system. DWP

[TSC-D'Appolonia]. 1983d. *Geologic Mapping of Exploratory Drift. Geotechnical Field Data Report No. 7*. Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: *Geotechnical Field Data Report No. 7* presents the underground mapping logs from the exploratory drift of the Waste Isolation Pilot Plant excavation for the site and preliminary design validation program. The exploratory drift is the southward extension of the East 140 drift beyond the double box area. Seven mapping units identified and described during mapping the double box area were mapped in the exploratory drift. The strata are laterally continuous and no structural features such as faults, joints, or sharp folds were discovered. "The small disruptions in stratification exhibited on the geologic logs . . . are typically syndepositional scour-and-fill structures and do not contradict the conclusion of lateral continuity. These structures result from the erosion of soft, bottom sediment by current or wave action with subsequent infilling by younger, usually similar, sediments." Some thin beds pinch out due to deposition of sediment over thin or patchy units. The argillaceous upper part of mapping unit 4 was generally moist when the drift was excavated; after several weeks, these areas are usually dry. "Several weeks following excavation, minor, localized weeps and areas of salt precipitate were observed on the exploratory drift ribs in association with Units 1, 2, and 3. . . ." These areas will be monitored. DWP

[TSC-D'Appolonia]. 1983e. *Underground Excavation Field Instrumentation Data For the Period April 16, 1982-January 25, 1983. Geotechnical Field Data Report No. 8*. Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: *Geotechnical Field Data Report No. 8* summarizes the instrumental data obtained from the exploratory shaft and drift level at the Waste Isolation Pilot Plant (WIPP) from April 16, 1982 through January 25, 1983. Representative plots for all instruments are presented, and the data for all instruments are summarized. This is the first report where all data for the period, including manually taken data, are on magnetic tape and are available upon request to the Department of Energy (DOE).

Data for some instruments installed during this reporting period are not included, although the data are provided on magnetic tape. Two strain gauges have been nonfunctional since the end of October, while a third strain gauge became nonfunctional in mid-December. One piezometer has not functioned since the end of November. Anchors on three extensometers were reset on January 18, 1983.

The measured displacements within the shaft increase with depth as predicted. Measurements were made at 1,073, 1,564 and 2,057 ft. Measurements have been ranging from .04 to .14 in. Closure rates within the shaft show a fairly steady value for the shaft. The closure rates vary with depth from about .001 to 0.10 in./year. The shaft piezometers have maintained steady pressures, $\pm 10\%$ of the individual reading, during the month. Two extreme piezometer values occur at the time of final manual reading and connection to data logger. It is not known why the peak occurs; the readings may be erroneous. Individual recorded pressures range from 85 to 150 psi for most piezometers, while two have less than 10 psi.

The rate of closure in the drifts is comparable to other deep salt mines. Instruments installed near the face as mining progressed measure early closure rates. Rates within 36 hours were usually less than 10 in./year despite initial measurements as high as 100 in./year. Closure rates

at or in excess of 50 days following excavation were generally in the range of approximately ± 1 to ± 4 in./year.

Over the past four months, displacements measured up to 50 ft into the roof and rib ranged from 0.5 to 2.0 in. Representative drift level extensometers indicate that most of the rock deformation occurs within the first 10 ft of the roof. In the East 140 Drift, most deformation occurs between 6 and 34 ft into the roof. DWP

[TSC-D'Appolonia]. 1983f. *Logging of Vertical Coreholes "Double Box" Area and Exploratory Drift. Geotechnical Field Data Report No. 9.* Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A series of vertical core holes was completed into the floor (invert) and roof (back) of the site preliminary design validation (SPDV) excavations from November 1982 through January 1983. The core holes described in this report include eighteen 50-ft (nominal) borings and five shallower borings. The eighteen 50-ft borings comprise nine pairs. One member of each pair was drilled vertically upward into the roof, and the other was drilled downward into the floor. Six of the 50-ft borings are located in the double box area. The remaining twelve 50-ft borings are located in the south exploratory drift. One shallower boring was cored to 11.3 ft to fill in a gap in an adjacent core.

The core samples and logs will be used to achieve one or more of the following objectives: confirm thickness, lateral extent, mineralogy, and stratigraphic continuity of host rock beyond the limits of excavation; confirm the continuity of structure beyond the excavations and the absence of any unusual features within the immediate zone of influence of the excavations; and provide core to be analyzed in conjunction with the characterization of interbedded materials.

Thirty units, including drift mapping units, were distinguished and correlated with certainty ranging from positive to likely. Five units are anhydrite, and the remaining beds are halite with varying clay and polyhalite content. The beds thin overall to the south, with one interval decreasing from 87.3 to 81.6 ft. All of the units are continuous. The only structure other than bedding is a large-scale, low-amplitude, sinusoidal flexure superimposed on the regional southeasterly dip. DWP

[TSC-D'Appolonia]. 1983g. *Underground Excavation Field Instrumentation Data, An Update for the Period January 26, 1983-February 21, 1983. Geotechnical Field Data Report No. 10.* Carlsbad, NM: Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: *Geotechnical Field Data Report No. 10* summarizes the instrumental data obtained from the exploratory shaft and drift level at the Waste Isolation Pilot Plant (WIPP) from January 26, 1983, through February 21, 1983. Representative plots for all instrument types are presented. All data for the period, including manually taken data, are on magnetic tape. Therefore, raw data sheets are not provided in this report. Data for some instruments installed during this reporting period are not shown because there are few data points, but the data are on magnetic tape. Other data summary plots for instruments installed earlier are not included as they follow the same general trends previously established. Anomalous data readings are noted on all applicable plots.

Displacements measured within the shaft increase with depth as predicted. Measurements have been ranging from .02 to .15 in. Closure rates show a fairly steady value for the shaft, and

they vary with depth from about .001 to 0.10 in./year. Shaft piezometers maintained steady pressures, $\pm 10\%$ of the individual reading, during the month. Two extreme piezometer values occur at the time of final manual reading and connection to data logger. At present, individual recorded pressures range from 85 to 145 psi for most piezometers, while two have less than 10 psi.

Multipoint borehole extensometer measurements up to 50 ft into the roof and rib show, over the past four months, displacements ranging from 0.5 to 2.0 in. Most of the rock deformation occurs within the first 10 ft of the roof with the exception that most of the deformation in the East 140 Drift occurs between 6 and 34 ft into the roof. In the floor of the south exploratory drift, one location shows a uniform displacement along the total length (50 ft) of the instrument. DWP

Tyler, L.D. 1985. "In Situ Tests and Instrumentation in the WIPP Facility," *Design and Instrumentation in Underground Laboratories for Radioactive Waste Disposal, Brussels, Belgium, May 15-17, 1984*. Eds. B. Come, P. Johnston, and A. Mueller. Boston, MA: A.A. Balkema. 330-340.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a Department of Energy (DOE) research and development facility for the purpose of developing the technology needed for the safe disposal of US defense-related radioactive waste. The in situ test program is defined for the thermal-structural interactions, plugging and sealing, and waste package interactions in a salt environment. An integrated series of large-scale underground tests addresses the issues of both systems design and long-term isolation performance of a repository.

Tyler, L.D. 1989. "Review of the Experimental Program Which Supports Transuranic Disposal at WIPP," *Waste Management 88, Tucson, AZ, February 28-March 3, 1988*. SAND88-2344. Albuquerque, NM: Sandia National Laboratories. (Abstract Only; Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The major objective of the Waste Isolation Pilot Plant (WIPP) experimental program is to develop the technology needed for the safe disposal of defense transuranic (TRU) waste. The experimental program focus is to provide models and data that will be used in conducting performance assessment to ensure compliance with the Environmental Protection Agency (EPA) disposal standards. The program is defined for the WIPP sealing system, disposal room system, and structural performance. Several large-scale underground tests have been operational since 1983 and are ongoing. The tests complement laboratory and modeling results and address the issues of both systems design and long-term isolation performance. Preliminary results from shaft and panel seal performance tests, room closure and brine inflow tests, and model predictions have had a significant impact on the WIPP assessment and design for long-term waste isolation.

Tyler, L.D., R.V. Matalucci, M.A. Molecke, D.E. Munson, E.J. Nowak, and J.C. Stormont. 1988. *Summary Report for the WIPP Technology Development Program for Isolation of Radioactive Waste*. SAND88-0844. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Since 1975, Sandia has conducted experiments and carried on modeling studies to gain an understanding of the phenomena pertinent to safe disposal of defense radioactive waste, both transuranic and high-level. The experiments have progressed in phases, from laboratory tests to small-scale field tests in salt and potash mines to full-size in situ tests in the Waste Isolation Pilot Plant (WIPP) Facility. Laboratory and small-scale in situ experiments

continue to the present to examine detailed behaviors and to assist in understanding and developing full-scale tests.

The technology experiments have been managed in three broad categories: Thermal/Structural Interactions (TSIs), Plugging and Sealing Performance and Design (P&S), and Waste Package Performance (WSPP). The history and major progress in each of these areas is summarized in this report. The TSI program has established the fact that the WIPP salt creep rate, and therefore closure of WIPP rooms, is about three times more rapid than our best models predicted prior to the tests. Studies to resolve this discrepancy are well advanced; in the interim, good agreement between predictions and observations is obtained by empirical adjustment of the elastic constants. The closure of backfilled waste room to about 5% void volume is predicted to take less than 100 years, the time during which active controls may be assumed to prevent human intrusion.

The waste package program has revealed that migration of interstitial brine to excavations in the WIPP salt occurs at a significantly greater rate than assumed by earlier investigations. A satisfactory model to explain the data utilizes darcy flow in very low permeability salt, which is driven by a pore pressure gradient caused when the excavation creates an atmospheric pressure boundary. This model, coupled with room closure predictions and backfill design using a salt/bentonite clay mixture, indicates that the rate of brine seepage will not result in a fluid or slurry state in the room, but rather in a compacted solid.

Examination of waste packages and their backfill is in its early stages. Contact handled (CH) transuranic (TRU) drums exhibit significant pitting corrosion after 18 months in a severe overtest environment of moist, heated salt and immersion in brine. Drums examined from a mildly heated, backfilled but unmoistened, environment show no significant corrosion to date. Defense high-level waste packages and the glass/metal materials interaction tests have been ongoing for several years; however, retrieval and analyses are not yet complete.

The Plugging and Sealing Program has developed a large laboratory and field test data base leading to a concept for sealing the WIPP. This concept relies on crushed salt or salt/clay mixtures for very long-term sealing and on cementitious plugs to provide quick-acting, short-term seals in critical locations. Permeability of WIPP Facility horizon salt and interbeds has been determined to be less than 10 nanodarcies. This data base is presently being greatly expanded.

The technology development to date supports the view that the WIPP can be safely constructed, operated, and finally sealed to prevent unacceptable releases to the biosphere and accessible environment. Studies will continue to improve our detailed understanding of relevant phenomena and to increase our confidence in the long-term predictive capability for performance assessment modeling.

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Uhland, D.W., and W.S. Randall. 1986. *1986 Annual Water Quality Data Report for the Waste Isolation Pilot Plant*. DOE-WIPP-86-006. Carlsbad, NM: Westinghouse Electric Corporation.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP), a Department of Energy (DOE) facility located in southeastern New Mexico, is designed to demonstrate the safe disposal of transuranic (TRU) radioactive waste. The Water Quality Sampling Program (WQSP) supports four major programs for the WIPP: Site Characterization Activities, Radiological Baseline, Ecological Monitoring, and Performance Assessment.

Results from 22 wells sampled from January 1985 through April 1986 under the WQSP are presented. Water-quality data from four water-bearing zones have been collected. These zones are the Culebra and Magenta Dolomite Members of the Rustler Formation, the Dewey Lake Red Beds and the Hays sandstone member of the Bell Canyon Formation. Results from the sampling include field chemistry data, as well as general water-quality parameters, trace metals, and priority pollutants. The salinity of the Culebra Member of the Rustler Formation varies significantly over the area. The chloride concentration ranges from thirty to over a hundred thousand parts per million. This report summarizes the first of several samplings that will define the pre-operational water-quality data base for the WIPP Project.

Uhland, D.[W.], J.G. Morse, and D. Colton. 1986. "The WIPP Water Quality Sampling Program," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, March 2-6, 1986*. Tucson, AZ: University of Arizona. Vol. 2, 211-216.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP), a Department of Energy (DOE) facility, will be used for the underground disposal of wastes. The Water Quality Sampling Program (WQSP) is designed to obtain representative and reproducible water samples to depict accurate water composition data for characterization and monitoring programs in the vicinity of the WIPP. The WQSP is designed to input data into four major programs for the WIPP Project: Geochemical Site Characterization, Radiological Baseline, Environmental Baseline, and Performance Assessment. The water-bearing units of interest are the Culebra and Magenta Dolomite Members of the Rustler Formation, units in the Dewey Lake Red Beds, and the Bell Canyon Formation.

At least two chemically distinct types of water occur in the Culebra, one being a sodium/potassium chloride water and the other being a calcium/magnesium sulfate water. Water from the Culebra wells to the south of the WIPP Site is distinctly fresher and tends to be of the calcium/magnesium sulfate type. Water in the Culebra in the north and around the WIPP Site is of the sodium/potassium chloride type and is much higher in total dissolved solids. The program, which is currently 1-year old, will continue throughout the life of the facility as part of the environmental monitoring program. Results presented here are preliminary in nature and will be updated as the program continues.

Uhland, D.W., W.S. Randall, and R.C. Carrasco. 1987. *1987 Annual Water Quality Data Report for the Waste Isolation Pilot Plant*. DOE-WIPP 87-006. Carlsbad, NM: Westinghouse Electric Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP), a Department of Energy (DOE) facility located in southeastern New Mexico, is a research and development facility designed to demonstrate the safe disposal of transuranic radioactive waste resulting from the nation's defense programs. The Water Quality Sampling Program (WQSP) supports four major programs for the WIPP: Site Characterization; the Performance Assessment; Radiological Baseline Program; and the Ecological Monitoring Program.

Results from 13 wells sampled from April through December 1986 under the WQSP are presented in this report. Water-quality data from three water-bearing zones have been collected. These zones are the Culebra and Magenta Dolomite Members of the Rustler Formation and the Dewey Lake Red Beds. Results presented from the sampling include field chemistry data, as well as general water-quality parameters, trace metals, and priority pollutants.

US Bureau of Mines. 1977. *Valuation of Potash Occurrences Within the Waste Isolation Pilot Plant Site in Southeastern New Mexico.* ALO-18. Salt Lake City, UT: US Bureau of Mines.

ABSTRACT: This study was performed for the Energy Research and Development Administration by Minerals Availability System personnel of the US Bureau of Mines. It was necessary to determine the commercial value, if any, of potash occurrences in the site selected for a Waste Isolation Pilot Plant for the purpose of preparing an environmental impact settlement. Analyses were made of all mineral deposits determined to be in the site. Mining and processing under the most favorable recovery systems were considered. Value determinations were based on estimated operating and capital costs of current mine-mill operations in the Carlsbad area.

Two groups of deposits, designated as mining units and occurring partially in the site, were determined to be commercial. The present value of the portions within the site, in terms of Federal and State taxes, royalties, and reasonable bonus bids, is about \$58.3 million. About 24.5 million tons of potash products would be produced from within the site over the life of the project. An additional 18.2 million tons of potash products could be recovered from currently subeconomic mineralization in the site at some future date if potash becomes more valuable compared to production costs.

US Department of Energy. [1979.] *Project Management Plan, Waste Isolation Pilot Plant Project.* WIPP-DOE-02. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The project management plan describes methods which will be used to manage the WIPP Project. "It provides the framework for managing the design, construction, and test and evaluation leading to pilot plant operation." The WIPP objectives have been modified as a result of the Deutch Task Force recommendations. The WIPP "will be designed to isolate Defense Program generated contact handled (CH) and remotely handled (RH) transuranic (TRU) waste. TRU waste will be retrievable. WIPP will also have the capability to conduct experimentation in an actual repository environment with high-level waste forms."

Important milestones under the revised design include starting the construction of shafts (August 1981), complete the construction and checkout (August 1985), receive the first shipment of TRU waste (March 1986), and begin full-scale operation (July 1990). Project responsibilities/participants under the direction of the WIPP Project Office include: a scientific advisor, an architect engineer, a technical support manager, construction contractor(s), and management/technical support services. Major design and construction

issues include: (1) mission, based now on the *Deutch Task Force report of October, 1978*, (2) design, based now on the mission, (3) licensing remains an unsettled issue that could significantly affect cost schedules, (4) site acquisition and control is complicated by ownership, resource, and legal and economic concerns, (5) construction risks parallel to design concerns, (6) geological anomalies may still be undiscovered, (7) waste acceptance criteria are still not identified, (8) transportation methods are not yet decided, (9) HLW waste experiments are not yet formulated, and (10) concerns about retrieving waste can not be settled pending resolution of other issues (e.g., waste acceptance criteria). DWP

US Department of Energy. [1979.] *Early Exploratory Shaft Development Proposal*. WIPP-DOE-17. Albuquerque, NM: US Department of Energy. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: An exploratory shaft is being planned, beginning in October 1980, for the WIPP using conventional methods to provide early data about the subsurface geology. Objectives for the early shaft include: evaluating geotechnical characteristics and verifying bed character in depth; providing hydrologic data for site confirmation and for further shaft design; validating design parameters or providing lead time for modification; initiating programs to demonstrate retrievability; providing experimental information for rock mechanics about the lower horizon; examining horizontal salt beds and identifying unknowns; reducing risk to DOE in continuing other work and providing information for further cost estimates; increasing assurance unknowns will not seriously affect baseline schedule; and fulfilling project schedule commitments of October 1978.

The total estimated early shaft costs are \$52.5 M, including engineering and in situ experiments. The shaft would be about 14 ft in diameter, 2700 ft deep, and would be lined from the surface into the salt.

In situ experiments under this program will provide verification of design predictions and a basis for the main experimental program. DWP

ANNOTATION: The early shaft described in this proposal was planned while the WIPP objectives included disposal of high-level waste. Two levels were thus included, with the lower (2700 ft) level located in thicker, very pure halite between the thick upper anhydrite of the Castile Formation and the Cowden anhydrite. The program for in situ experiments was described in Wowak (1979) and included in this bibliography.

US Department of Energy. 1980a. *Final Environmental Impact Statement, Waste Isolation Pilot Plant*. DOE/EIS-0026. Washington, DC: US Department of Energy. Vols. 1-2. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Final Environmental Impact Statement (FEIS)* for the Waste Isolation Pilot Plant (WIPP) is presented in two volumes that include public and agency comments and numerous appendices of technical information. The *FEIS* reviews the management background and alternatives to the WIPP. Two chapters analyze the waste forms and transportation issues. One chapter reviews the geological setting and details of the site area. One chapter analyzes the facilities and impacts of operation. Two chapters determine environmental impacts of the WIPP. Loss and commitment of resources are examined in one chapter. Three chapters review the relationship of WIPP to various plans, policies, permits, and requirements, and compare short- and long-term productivity for the WIPP Site area.

The alternatives are to (1) leave transuranic waste where it is at the Idaho National Engineering Laboratory (INEL); (2) to construct the WIPP for demonstration of transuranic (TRU) waste disposal and for research on disposal of defense related high-level waste; (3) disposal of TRU waste in the first available repository for high-level waste, with WIPP continuing to be investigated as a possible candidate for such a repository; and (4) delay WIPP until other sites can be evaluated and considered along with WIPP. Alternative two is the reference case for the *FEIS* as it is authorized by legislation. Alternative three is preferred by the Department of Energy (DOE).

The authorized facility, consisting of surface and subsurface facilities, would be constructed in two phases: the site and preliminary design validation (SPDV), involving surface facilities and limited underground access; and full construction of surface and subsurface facilities and operation for about 25 years. The alternative preferred by DOE involves a phase similar to SPDV while other sites and rock types are evaluated. No separate TRU facility is involved. Alternative four is essentially the same as alternative two, but is delayed.

The alternative of leaving waste at INEL is unacceptable because of the the possibility of human intrusion or volcanic activity. Alternatives two, three, and four are about the same in presenting small impacts. Consequences of transportation accidents could be severe, but they are similar for these alternatives. Hypothetical releases from the WIPP are unlikely from long-term naturally occurring processes, and the doses or dose commitments are predicted to be a small fraction of natural background doses. The scenarios involving hydrologic transport through the Rustler Formation are assumed to discharge at Malaga Bend on the Pecos River.

Unresolved technical issues involve interactions between waste and salt. Gas-generation rates and dispersal are unresolved; gas may permeate through the salt, or gas may accumulate, causing salt either to fracture or plastically flow. It is unlikely the repository would fail from gas generation and dispersal. DWP

ANNOTATION: The *Final Environmental Impact Statement (FEIS)* for the WIPP was prepared during a time of considerable change in the mission of the WIPP and uncertainty over directions in the waste management programs for the nation. The changes and uncertainty are partially reflected in the alternatives, but they have a further history.

The investigations in 1974 by Oak Ridge National Laboratory of the original site in southeastern New Mexico were delayed while retrievable surface storage facilities were considered. In 1975, when Sandia National Laboratories assumed responsibility for the scientific investigations for the site, and in the following years, the mission included disposal facilities for both TRU and high-level wastes. Two levels in the Salado Formation were considered for these different wastes. By 1980, Congress had limited the WIPP project to defense related radioactive waste and prohibited funding for any purpose related to licensing the WIPP by the Nuclear Regulatory Commission. In 1980, as noted in the *FEIS*, President Carter requested that Congress should rescind funds for the WIPP and cancel the project, but the Congress did not act on this proposal. The alternatives for the WIPP considered in the *FEIS* note that the authorized alternative differs from the alternative preferred by the DOE.

The WIPP is now considered a full-scale pilot plant to demonstrate that transuranic waste from defense activities can safely be managed, stored, and disposed of in bedded salt. The facility is required to meet the standards of the Environmental Protection Agency (EPA) prescribed in Subparts A and B of 40 *CFR Part 191*.

There are important differences in the assessments made for the WIPP in the *FEIS* of 1980 compared to the *Final Supplement, Environmental Impact Statement (SEIS)* of 1990 and performance assessment as it is currently being practiced. In 1980, scenarios analyzed in support of the *FEIS* examined the radiological consequences of transport through the Rustler Formation to a discharge point at Malaga Bend, the nearest point of the Pecos River along

probable flow directions. More recent analysis is based on a regulatory time limit of 10,000 years and scenarios which include closer release points in the subsurface 5 km or less from the waste panels or through stock wells penetrating the Culebra Dolomite Member of the Rustler Formation 5 km from the waste panels. The methodologies have changed by which such scenarios are evaluated and accepted or rejected, based on the EPA standard.

It should be noted that the issue of gas generated by waste decomposition was unresolved for the *FEIS* and is still unresolved. It is not certain how much gas will be generated nor what the effects will be.

US Department of Energy. 1980b. *Executive Summary Environmental Impact Statement, Waste Isolation Pilot Plant (WIPP)*. DOE/EIS-0026. Albuquerque, NM: US Department of Energy.

ABSTRACT: The executive summary of the *Final Environmental Impact Statement* presents, in a separate volume, the main findings of the statement in 61 pages. It has also been published in Spanish to make it more widely available. DWP

US Department of Energy. 1981. *Waste Isolation Pilot Plant. Volume I: Groundbreaking Through Shaft Sinking Site and Preliminary Design Validation*. WIPP-DOE 105. [Albuquerque, NM: US Department of Energy.] (Copy on file at the US Department of Energy Public Reading Room, National Atomic Museum, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) will be developed in two phases: Site and Preliminary Design Validation (SPDV) and full construction. During the SPDV Program, two shafts and an underground experimental area will be constructed. The SPDV Program is designed to confirm the geological adequacy of the WIPP Site. The report includes photography of early stages of drilling the first shaft for SPDV. DWP

US Department of Energy. 1982. *Site Validation Program*. WIPP-DOE-116, Revision 1. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) Site Validation Program follows the Site Selection and Site Characterization studies to increase the level of confidence in the site and to confirm that the site is suitable for the WIPP facility. For the validation program, the site will be evaluated against site qualification criteria which are being developed. Methods for data acquisition and confirmation will be developed. Direct access through shafts to the underground areas is planned as part of the Site and Preliminary Design Validation (SPDV) phase of the validation program. The site validation plan and reports will be issued for review comments before implementing the plan, and before final publication of the report. A Validation Declaration is scheduled for the end of March 1983, depending on the SPDV construction schedule. DWP

US Department of Energy. 1983a. *Summary of the Results of the Evaluation of the WIPP Site and Preliminary Design Validation Program*. WIPP-DOE-161. Albuquerque, NM: US Department of Energy.

ABSTRACT: Experiments and studies have been conducted during the Site and Preliminary Design Validation (SPDV) phase to determine the site suitability and validate the preliminary design for the Waste Isolation Pilot Plant (WIPP) Site. The site geology has been found to be as expected through both surface-based exploration and underground excavation during SPDV. In situ studies on the underground indicate that data are consistent with the design validation plan. The Department of Energy (DOE) concludes that adequate data have been obtained to make a decision about full construction of the WIPP Project. These data and information are presented to obtain review by the public and the state of New Mexico. DWP

ANNOTATION: The bulk of this report consists of a reprint of Weart (1983c) and the executive summary of the *Preliminary Design Validation Report*.

US Department of Energy. 1983b. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-163. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Quarterly Geotechnical Field Data Report (GFDR)* presents all information obtained from the geotechnical studies at the Waste Isolation Pilot Plant (WIPP) Site from March through July 1983, as well as all previous data collected from the geomechanical instruments. Part I presents geomechanical data, Part II is geologic mapping of two drifts and some test rooms, and Part III reports logging of vertical core holes.

Geomechanical instruments provide data to evaluate strain in the exploratory shaft key, water pressure behind the exploratory shaft liner, roof-to-floor and rib-to-rib closure in underground drifts, and displacements at depth into the drift ribs, floor, and roof.

Portions of the 0 East Drift, North 1420 Drift, and test rooms 1-4 were mapped using underground mapping units established in previous quarterly reports. Units are generally continuous, but they show localized lateral facies changes or pinchouts due to syndepositional processes. Moist patches or weeps are described mainly from ribs. No structural complications were mapped.

Seventeen vertical core holes, about 50 ft in length, have been described to confirm the continuity of units and structure beyond the limits of excavation and help determine suitable anchor depths for geomechanical instruments. Sixteen cores came from 8 locations where cores paired upward and downward were drilled. Thirty units have been distinguished that tend to vary slightly in thickness. Very narrow pipes or local syndepositional dissolution features show in cores. No faults or later dissolution features were detected. DWP

US Department of Energy. 1983c. *DOE Responses to the Public's Comments on "Summary of the Results of the Evaluation of the WIPP Site and Preliminary Design Validation Program" (WIPP-DOE-161)*. WIPP-DOE-173. Albuquerque, NM: US Department of Energy. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: In this report, the Department of Energy (DOE) has summarized and responded to oral and written comments received from the public concerning a report entitled *Summary of the Results of the Evaluation of the WIPP Site and Preliminary Design Validation Program (WIPP-DOE-161)*. The report was made available March 31, 1983, and the public hearing was conducted in Albuquerque, NM, on May 16, 1983. Written comments are included in this document; oral comments were transcribed and are available for review at certain reading

rooms and libraries. The hearing and this document partially fulfill the Stipulated Agreement between the DOE and the State of New Mexico. DWP

ANNOTATION: The report referred to (*WIPP-DOE-161*) is included in this bibliography under US Department of Energy, 1983a.

US Department of Energy. 1983d. *DOE Responses to the State of New Mexico's Comments on "Summary of the Results of the Evaluation of the WIPP Site and Preliminary Design Validation Program" (WIPP-DOE-161)*. WIPP-DOE-174. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Agencies of the State of New Mexico commented extensively on the Department of Energy (DOE) report titled "Summary of the Results of the Evaluation of the WIPP Site and Preliminary Design Validation Program," which was submitted to the State on March 30, 1983, beginning a 60-day period for comment. The reports, comments, and responses are part of the Stipulated Agreement between the State and the DOE which prescribes certain actions before permanent facility construction begins.

Comments were categorized broadly as pertaining to site qualification criteria, site qualification factors, preliminary design validation, general comments, and those beyond the scope of the original document. Comments and responses about geological factors and data are mainly included in subcategories under site qualification factors. DWP

ANNOTATION: The report referred to (*WIPP-DOE-161*) is included in this bibliography under US Department of Energy, 1983a.

US Department of Energy. 1983e. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-177. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Quarterly Geotechnical Field Data Report (GFDR)* presents the significant geotechnical information (Part I) obtained from the Waste Isolation Pilot Plant (WIPP) Site from June 22 through September 15, 1983, as well as all previous geomechanical data. Part II reports drilling and testing for gas in core holes in the roof in underground workings at the WIPP. Data indicate that early responses to excavation may be normalized relative to the time since excavation, though this should be reviewed when more data are available.

Gas-flow rates were monitored for four existing bore holes in the roof of the East 140 Drift, and samples were obtained for analysis. Four new bore holes were drilled, and gas flow rates and shut-in pressure buildups were monitored. Gas samples were obtained for chemical analysis. Flow rates were erratic in existing holes. New holes showed maximum flow rates of over 12 L/min and shut-in pressures up to 120.6 psi. Flow rates decreased to less than half the initial rate within 1 hour. Samples consisted primarily of nitrogen (> 76%), with lesser oxygen, methane, carbon dioxide, and ethane. The reservoirs are limited in volume, but they may be expected in other holes into anhydrites in the roof. DWP

US Department of Energy. 1983f. *Results of Site Validation Experiments*. TME 3177, Rev. 2.0. Albuquerque, NM: US Department of Energy. Vols. 1-2. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Site and Preliminary Design Validation (SPDV) Program was established by the Department of Energy (DOE) in 1980 to obtain more definitive data on in situ geologic conditions through underground observations and tests. It was understood that most of the results that could be obtained productively from the surface had been acquired, and it was desirable to minimize drilling into the proposed facility horizon level.

SPDV consisted of an exploratory shaft, ventilation shaft, and limited underground drift excavation. This report addresses Site Validation Programs (SVP) to determine in situ geological conditions.

Twenty-one site qualification criteria were developed for the Waste Isolation Pilot Plant (WIPP). Twelve were satisfied by surface-based exploration. The remaining criteria were to be satisfied by examining the facility horizon for thickness, continuity, and lateral extent of rock units; brine content and mineralogy; location and characteristics of interbedded materials; potential occurrences of active or capable faults; depth of strata; dissolution features; groundwater and the effect of the facility on aquifers; water-bearing and water-conductive potential; major faults or flow structures; and minerals of unusual compositions or with bound water. Specific experiments and tasks were developed to satisfy SVP objectives.

Underground exploration included drifts over ~5100 ft (north-south) and 750 ft (east-west) and core holes to examine the overlying and underlying 50 ft. Lithologic and stratigraphic features were confirmed. Mineralogical and brine content were extensively examined. All of the nine criteria to be addressed were considered to have been raised to a "complete" level of satisfaction. No site qualification issues remain unsatisfied. DWP

US Department of Energy. 1984a. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-196. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Quarterly Geotechnical Field Data Report (GFDR)* presents information obtained from the geotechnical studies at the Waste Isolation Pilot Plant (WIPP) Site from September 15 through December 15, 1983, as well as all previous data collected from the geomechanical instruments. The principal geotechnical activity was to monitor geomechanical instruments installed in the exploratory shaft and the underground drifts. For the first time, the *GFDR* includes preliminary data analyses.

The instrumental data are reported from the exploratory shaft, key, and shaft station, the ventilation shaft station, the south exploratory drift, north drifts, and test rooms 1-4. In addition to instrumental data, qualitative observations from underground activities are included. Roofs of drifts and test rooms are examined with scaling bars to identify loose areas and remedy them. Minor spalling has occurred since July 1983. Vertical holes in the roof permit clay seams under anhydrites "a" and "b" to be examined; no separation was observed except near the exploratory shaft station.

The exploratory shaft shows seasonal changes in creep rate and greater displacement with depth. Piezometers at the Magenta and Culebra Dolomite Members of the Rustler Formation show pressures consistent with observed heads in these units. Piezometers at the Rustler/Salado Formation contact show little pressure buildup. The ventilation shaft (future waste handling shaft) shows a decreasing rate of extension. The drifts show decreasing closure rates that have not reached steady state. The difference in individual curves is due primarily to the time that elapses between excavation and installation of the instruments. The rate of closure 60 days after excavation is virtually the same for all stations. North drifts are closing at greater rates than the south exploratory drift. The reason for this is not known, though the mechanical situation for these drifts is not identical.

The in situ data collected through 1983 were analyzed numerically using reference stratigraphy and two slip lines above and two slip lines below the drift level. Vertical and horizontal closures five years after excavations are predicted, respectively, to be 13 and 11 in. These values are considerably higher than earlier predictions, and, if they occur, the drift will not meet design requirements.

DWP

US Department of Energy. 1984b. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-199. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Quarterly Geotechnical Field Data Report (GFDR)* presents geotechnical information obtained at the Waste Isolation Pilot Plant (WIPP) Site underground facilities from December 16, 1983, through March 15, 1984, as well as previous data collected from the geomechanical instruments. Data from instruments and analysis constitute most of the report. Geotechnical activities included geologic mapping in the waste shaft, core drilling in the access drifts to the experimental area, and installing new instruments.

The *GFDR* contains all data collected since April 1982, from the geomechanical instruments in the exploratory shaft and underground drifts at the WIPP Site. The data continue to exhibit seasonal fluctuations in closure of the exploratory shaft. The south exploratory shaft continues to show convergence decreasing with time, but not at steady state. North drifts show that steady-state creep has not been reached for all locations and that there is evidence of interaction between different openings. It appears that test rooms 2 and 3 are undergoing identical closure, but rooms 1 and 4 are not apparently the same. Test room 2 shows, approximately, that wall-to-wall convergence is currently 71% of the roof-to-floor convergence. Numerical analysis shows that stress is intensified in the anhydrite in marker bed 139. The roof is predicted to sag, with wall deflection nearly as great. The floor heave is very small. According to current criteria, the walls and corners of the room may fail after 15 years.

Mapping in the waste shaft, being constructed by enlarging the ventilation shaft, shows abundant primary sedimentary structures through much of the Rustler Formation. The so-called "washout" zones exhibit primary depositional features with no evidence of dissolution. The zones were "washed out" during drilling by circulation of drilling fluids. The Magenta Dolomite Member of the Rustler Formation produces little water, while the Culebra Dolomite Member is wet.

DWP

US Department of Energy. 1984c. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-200. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Quarterly Geotechnical Field Data Report (GFDR)* presents information from the geotechnical studies at the Waste Isolation Pilot Plant (WIPP) Site from March 16 through June 15, 1984, as well as previous data. The geotechnical activities included geologic mapping and inspection in the waste shaft, pressure cell and convergence point installation in the waste shaft, core drilling in the experimental area, installing new instruments in drifts and rooms, and monitoring previously installed geomechanical instruments in shafts, underground drifts, and test rooms.

The exploratory shaft continues to show seasonal closure rates, as well as increased closure with depth. Instruments were set in the waste-handling shaft to measure fluid pressure behind

the shaft liner, as well as creep of salt. Convergence points were installed in the experimental area drifts. Visual inspection shows few changes in most areas. Some separation is occurring along a clay seam at the brows of some waste experimental area rooms. Some rock bolts have been installed and some remedial work will be done. Mapping in the waste handling shaft shows stratigraphy as expected, and some zones attributed to dissolution show primary sedimentary structures.

Convergence rates along the exploratory shaft continue to vary seasonally. The south exploratory drift, north drifts, and test rooms continue to converge as in the past.

The vertical convergence rates were examined to try to fit nonlinear equations by regression techniques. Using fitted curves, the vertical convergence for test room 1 is estimated as about 5 ft after 25 years. Predicted steady-state convergence rates vary, however, from one room to another without explanation.

In situ data have been used to calibrate both primary and secondary creep constants to recalculate room responses over time. The calculated storage room responses closely match the in situ data for the period of observation. Predicted closure at 15 years is about 4.7 ft, more than twice the value predicted from laboratory data. The south exploratory drift is predicted to close vertically by about 2 ft over 15 years. These results indicate that the design basis for storage room closure will likely to be exceeded. DWP

US Department of Energy. 1984d. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-202. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Quarterly Geotechnical Field Data Report (GFDR)* presents information from geotechnical studies at the Waste Isolation Pilot Plant (WIPP) during the period June 16 through September 15, 1984, as well as previous data from geomechanical instruments. Activities included geologic mapping in the waste shaft and sump, installing instruments in the waste shaft, drilling and mapping in drifts, and monitoring existing instruments.

The exploratory shaft, now designated the construction and salt-handling (C&SH) shaft, continues to show seasonal apparent convergence rates, as well as convergence, increasing with depth. Piezometer readings also continue their pattern of variable readings with little overall change. Instruments within the waste shaft have only a short history. Instruments have also been installed in south drifts excavated more recently, in new drifts and crosscuts in the north drift area, and in the waste experimental area. Underground inspections show that only minor changes have occurred in rock surface conditions since December 1983. Minor, localized spalling is occurring in some rooms and drifts and around the C&SH shaft. Some separation is occurring along the clay seam at the brows of some waste experimental rooms. Rock bolts have been installed and some remedial mining removed some material. Fractures have developed at some corners of drifts and room intersections. Brine weeps are being sampled and observed, while gas from some bore holes has been sampled.

Data from drift and room areas show that convergence rates are affected by excavations as much as 150 ft away. The creep behavior of rock and interaction with the concrete liner in the C&SH shaft have been modeled. The initial shrinkage of the concrete and predicted beginning tensile strain are consistent with the observed behavior. DWP

US Department of Energy. 1985a. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-210. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office.

(Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The quarterly report presents information obtained from September 16 through December 31, 1984. Activities included collecting data from geomechanical instruments, geologic mapping in various underground areas, installing pressure cells in the exhaust shaft, and maintaining instruments.

Seepage around the Construction and Salt-Handling Shaft (C&SH) and waste shaft liners continues to be very small; the waste shaft yielded about 0.015 gal/min after second stage grouting of Rustler units was completed during the previous quarter. Exhaust shaft construction advanced to a depth of 1663 ft by the end of the quarter, with primary concrete liner advanced to a depth of 907 ft. Geological mapping of the exhaust shaft is concurrent with construction. Underground mapping continues in various underground experimental areas. A borehole inventory is being conducted to support brine testing programs.

Extensometer data from the C&SH shaft continue to show apparent seasonal undulations in extensometer data, probably because of temperature differences in intake air. Convergence data from several drift and shaft locations are reported. Closure rates of the 8 by 25 ft drift differ by 40% between the southern and northern areas. The difference can be partly replicated by refining finite-element models comparing a single drift to a set of intersecting multiple drifts. DWP

US Department of Energy. 1985b. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-213. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The quarterly report presents information obtained from January 1 through March 31, 1985. Activities included collecting data from geomechanical instruments, geologic mapping in Rooms G and H, and coring ten additional holes underground. The exhaust shaft was completed to the facility horizon.

A finite-element program was used to model the mechanical response of Room D (18 by 18 ft cross-section) in the experimental area for periods up to 5 years for comparison with in situ data. Calculations for storage rooms indicate that configurations similar to the existing test room produce results similar to those already obtained. Structural responses are different if more than 4 storage rooms are excavated in a panel or more than 1 panel is excavated. DWP

US Department of Energy. 1985c. *Quarterly Geotechnical Field Data Report*. WIPP-DOE-218. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The quarterly report presents geotechnical information obtained at the site from April 1 through June 30, 1985. Activities included collecting and analyzing data from geomechanical instruments. Underground mapping of Rooms G and H was completed.

The construction and salt-handling shaft continues to show probable seasonal variations in convergence. Fluid accumulating above the lower chemical seal contains chemical seal material, indicating the middle chemical seal is probably ineffective. A finite element code was used to continue modeling of storage room mechanical behavior. DWP

US Department of Energy. 1985d. *Quarterly Geotechnical Field Data Report, December 1985.* WIPP-DOE-221. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office.

ABSTRACT: The quarterly report presents geotechnical information obtained at the site from July 1 through September 30, 1985. Activities included collecting geomechanical data, some underground drilling, and data analysis.

Underground drilling in some rooms intercepted fractures, as noted in previous work, in floor material. Fractures in some areas are being mapped and evaluated. The master inventory of boreholes useful for the brine evaluation program is completed. DWP

US Department of Energy. 1986a. *Waste Isolation Pilot Plant Design Validation, Final Report.* DOE-WIPP-86-010. San Francisco, CA: Bechtel National, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The design validation report consists of an executive summary, twelve chapters, and eleven appendices describing the validation of the Waste Isolation Pilot Plant (WIPP) design. This report is subsequent to the *Preliminary Design Validation Report of March 30, 1983.*

Design validation is "...the process by which the reference design of the underground openings is confirmed by determining the compatibility of the design criteria, design bases, and reference design configurations using site specific information." The information for design validation were behavior of the underground openings, geologic conditions encountered during underground construction, descriptions of core samples from holes in the roof and floor of the underground openings, and geomechanical instrument data.

Elements of design requiring validation were found to be suitable. "The reference design for the storage rooms will be considered to be validated" when one or more of several modifications are incorporated: maintaining reference design storage room dimensions but reducing waste volume and modifying stacking configuration; maintaining storage room dimensions and waste volume, but deleting the requirement for backfill while requiring waste be retrieved before a room exceeds 7 years; maintaining dimensions, waste volume, and backfill while retrieving waste in the order emplaced; changing the dimensions of the room, reducing waste volume, and maintaining backfill; and maintaining current design, waste volume and backfill requirements.

Other design modifications recommended include: the maintenance and trimming of drifts used for waste storage for use near the end of the emplacement period for permanent storage; the addition of rooms to compensate for plugs in the storage area entry drifts; and the installation of instruments to monitor storage room behavior. DWP

US Department of Energy. 1986b. *Interim Geotechnical Field Data Report.* DOE-WIPP-86-012. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant Project Office. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The interim geotechnical field data report covers the period from October 1, 1985 through June 30, 1986. Subsequent data is expected to be reported annually rather than quarterly. The interim report follows the same format as previous quarterly report and

includes data from various geomechanical monitoring programs, continuing underground observations of stability, details of core drilling, and analysis of geomechanical data. DWP

US Department of Energy. 1989. *Draft Plan for the Waste Isolation Pilot Plant Test Phase: Performance Assessment and Operations Demonstration.* DOE/WIPP 89-011. Carlsbad, NM: US Department of Energy, Waste Isolation Pilot Plant.

ABSTRACT: The Department of Energy (DOE) must have reasonable expectation, based upon a performance assessment, that the Waste Isolation Pilot Plant (WIPP) will comply with the Environmental Protection Agency (EPA) Standard, 40 CFR 191, Subpart B, Sections 13 and 15, prior to a determination whether WIPP should become a transuranic (TRU) waste disposal facility. In addition, the DOE is committed to evaluating the safety and effectiveness of the TRU waste management system operations. The intent of the Test Phase is to provide information for assessing whether WIPP complies with the EPA Standard and whether the overall TRU waste management system can operate in a manner consistent with applicable requirements. In both cases, careful assessment of the data, adoption of modifications if necessary, and adherence to a conservative stepwise approach will be the strategy employed. The Test Phase represents a prudent approach consistent with the startup of a first-of-a-kind nuclear facility.

A final report of the Test Phase activities and results will be issued in June 1994. This report will summarize the relevant data from the Performance Assessment and Operations Demonstration Programs and will be available for external, independent review by the EPA, the National Academy of Sciences WIPP Panel, the State of New Mexico's Environmental Evaluation Group, and other appropriate organizations. A decision whether the WIPP should proceed from the Test Phase to the Disposal Phase is scheduled for consideration by September 1994. DWP

US Department of Energy. 1990. *Final Supplement, Environmental Impact Statement, Waste Isolation Pilot Plant.* DOE/EIS-0026-FS. Washington, DC: US Department of Energy, Office of Environmental Restoration and Waste Management. Vols. 1-13. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: In 1980, the Department of Energy (DOE) published the *Final Environmental Impact Statement (FEIS)* for the Waste Isolation Pilot Plant (WIPP). This *FEIS* analyzed and compared the environmental impacts of various alternatives for demonstrating the safe disposal of transuranic (TRU) radioactive waste resulting from DOE national defense related activities. Based on the environmental analyses in the *FEIS*, the DOE published a Record of Decision in 1981 to proceed with the phased development of the WIPP in southeastern New Mexico as authorized by the Congress in Public Law 96-164.

Since publication of the *FEIS*, new geological and hydrological information have led to changes in the understanding of the hydrogeological characteristics of the WIPP Site, as they relate to the long-term performance of the underground waste repository. In addition, there have been changes in the information and assumptions used to analyze the environmental impacts in the *FEIS*. These changes include changes in the composition of the TRU waste inventory; consideration of the hazardous chemical constituents in TRU waste; modification and refinement of the system for the transportation of TRU waste to the WIPP; and modification of the Test Phase.

The purpose of the *Final Supplement, Environmental Impact Statement (SEIS)* is to update the environmental record established in 1980 by evaluating the environmental impacts associated with new information, new circumstances, and proposal modifications. This *SEIS* evaluates and compares the proposed action and two alternatives.

The proposed action is to proceed with a phased approach to the development of the WIPP. Full operation of the WIPP would be preceded by a Test Phase of approximately 5 years, during which time certain tests and operational demonstrations would be carried out. The elements of the Test Phase, tests and operations demonstration, continue to evolve. These elements are currently under evaluation by the DOE based on comments from independent groups such as the Blue Ribbon Panel, the National Academy of Sciences, the Environmental Evaluation Group (EEG), and the Advisory Committee on Nuclear Facility Safety. At this time, the Performance Assessment tests would be comprised of laboratory-scale, bin-scale, and alcove-scale tests. The DOE, in December 1989, issued a revised draft final Test Phase plan that focuses on the Performance Assessment tests to remove uncertainties regarding compliance with long-term disposal standards (*40 CFR 191, Subpart B*) and to provide data confirming that there would be no migration of hazardous constituents (details are available in Subsection 3.1.1.4 and Appendix O). The tests would be conducted to reduce uncertainties associated with the prediction of natural processes that might affect long-term performance of the underground waste repository. Results of these tests would be used to assess the ability of the WIPP to meet applicable Federal standards for the long-term protection of the public and the environment. The operational demonstrations would be conducted to show the ability of the TRU waste management system to certify, package, transport, and emplace TRU waste in the WIPP safely and efficiently. Waste requirements for the Integration Operations Demonstration remain uncertain. A separate document would be developed to describe in detail the Integration Operations Demonstration following the DOE's decision as to the scope and timing of the demonstration.

During the Test Phase, National Environmental Policy Act (NEPA) requirements would be reviewed in light of the new information developed, and appropriate documentation would be prepared. In addition, the DOE will issue another *SEIS* at the conclusion of the Test Phase and prior to a decision to proceed to the Disposal Phase. The *SEIS* will analyze, in more detail, the system-wide impacts of the processing and handling at each of the generator/storage facilities, will consider the system-wide facilities, and will consider the system-wide impacts of potential waste treatments.

Upon completion of the Test Phase, the DOE would determine whether the WIPP would comply with US Environmental Protection Agency (EPA) standards for the long-term disposal of TRU waste (i.e., *40 CFR Part 191, Subpart B; 40 CFR Part 268*). The WIPP would enter the Disposal Phase if there was a favorable Record of Decision on the new *SEIS* to be prepared prior to the Disposal Phase and if there was a determination of compliance with the EPA standards and other regulatory requirements. During this phase, defense TRU waste generated since 1970 would be shipped to and disposed of at the WIPP. After completion of waste emplacement, the surface facilities would be decommissioned, and the WIPP underground facilities would serve as a permanent TRU waste repository.

The first alternative, No Action, is similar to the No Action Alternative discussed in the 1980 *FEIS*. Under this alternative, there would be no research and development facility to demonstrate the safe disposal of TRU waste, and TRU waste would continue to be stored. Storage of newly generated TRU mixed waste would be in conflict with the Resource Conservation and Recovery Act (RCRA) Land Disposal Restriction; treatment would be required to avoid such conflict. The WIPP would be decommissioned as a waste disposal facility and potentially put to other uses.

The second alternative to the Proposed Action is to conduct the bin-scale tests at the facility other than the WIPP and to delay emplacement of TRU waste in the WIPP underground until a determination has been made of compliance with the EPA standards for TRU waste disposal

(i.e., 40 CFR Part 191, Subpart B). The bin-scale tests could be conducted outside the WIPP underground facilities in a specially designed, aboveground facility. The implications of this alternative include delays in both the operational demonstrations and alcove-scale tests, the lack of alcove-scale test data for the compliance demonstration, and placing the WIPP facilities in a "standby" mode. The specialized facility for aboveground bin-scale tests could be constructed at any one of the DOE facilities. In order to analyze the environmental impacts of the alternative in the final *SEIS*, the DOE has evaluated the Idaho National Engineering Laboratory in Idaho as a representative facility for the aboveground bin-scale tests.

Unterberger, R.R. 1981. *Final Report on Subsurface Radar Applications in the Delaware Basin, Covering the Period June 1, 1980 through January 31, 1981.* College Station, TX: Texas A&M University, Department of Geophysics. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Radar techniques were experimentally applied underground in the Mississippi Chemical Corporation (MCC) mine to determine whether this method can probe ahead of mining within a potash and salt unit. The tests attempted to show the breccia pipe known to exist in underground workings at MCC, as such a feature at the Waste Isolation Pilot Plant (WIPP) Site would be important to predict. Radar pulses in underground air were unsuccessful in the horizontal direction, but they returned a signal from vertical pulses believed to originate within the rocks. Pulses are reflected from the mine surface and reverberate in the mine air, limiting the utility of radar pulses in air. Antennas were aimed at the the breccia pipe and buried with fine rubble from mining. This greatly improved the radar sensitivity and reduced radar energy in air. No radar signals showed. The modified technique shows promise despite the lack of a specific return radar signal.

Samples measured in the laboratory indicate that low frequency radar or 24 kHz sonar are alternative methods of probing these rocks, with maximum radar range of less than 340 m.

DWP

Van Sambeek, L.L. 1986. "WIPP: Seal Design Calculations," *Working Papers From the US/FRG Workshop on Sealing and Backfilling of a Salt Repository, Albuquerque, NM, September 23-25, 1986*. Comp. R.F. Cook. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-24-1 through II-24-4. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Five parameters related to properties of concrete seals and three parameters related to modeling assumptions were tested by calculations to determine the influence of these parameters on concrete seals in halite. Some parameters were quantified, while others were qualified as included or ignored in the analysis. Young's modulus, Poisson's ratio, seal length, and elapsed time before emplacing the seal were quantifiable. Heat of hydration, chemical expansivity, concrete creep, and the interface between seal and salt were qualified parameters.

Calculated early radial strain is sensitive to the chemical expansivity and hydration of concrete. Later (>5 years), seal length and elapsed time until seal emplacement are significant. Only the heat of hydration and chemical expansivity strongly influence calculated seal behavior. Seal length also becomes more significant with time. Plane strain models may not be appropriate because seal length is assumed to be infinite. DWP

Van Sambeek, L.L. 1987. *Thermal and Thermomechanical Analyses of WIPP Shaft Seals*. SAND87-7039; Topical Report RSI-0324. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Thermal and thermomechanical analyses were performed to provide information on the behavior and stability of concrete seals emplaced in a circular shaft. Two types of concrete were considered, an expansive salt-saturated concrete for seals located in rock salt or other rock and an expansive freshwater concrete for seals located in nonsalt rock.

Thermal analyses were used to determine the temperature rise in the concrete and surrounding rock as a result of the exothermic hydration of the cement in the concretes. The thermomechanical analyses considered time-dependent elastic modulus, thermoelastic expansion, time-dependent chemically induced expansion, and creep of the concrete; thermoelastic behavior of the nonsalt rocks; and thermoelastic and creep behavior of the rock salt. Supplementary analyses were performed to determine the effects of pressure loading on a face of the seal that might result from a static brine head or the swelling of a bentonite backfill; the influence of using a reduced elastic modulus for the rock salt; and the effect of eliminating the chemical expansivity of the concrete.

The primary results of interest from the analyses were the development of radial stress in the seal, the magnitudes of tensile and shear stresses induced in the seal and rock, and the effect of bonding or lack of bonding between the seal and the surrounding rock. The chemical expansivity of the concrete was shown to be important for the development of radial stresses in the seal and at the contact between the seal and the surrounding rock. The shear stresses induced in the seal by the swelling pressure of bentonite become a concern if the radial stresses are not developed. The seals as configured appear to be stable and capable of performing their intended functions.

Van Sambeek, L.L., and J.C. Stormont. 1987. *Thermal/Structural Modeling of Test Series A of the Small Scale Seal Performance Tests*. SAND87-7037. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: In order to ensure effective long-term sealing of nuclear waste repositories, adequate predictive capabilities (i.e., numerical modeling methods) of seal system thermal/structural behavior is required. Such modeling must consider the properties of both the seal material as well as the host rock. In this report, various modeling efforts are described and discussed. Some results are compared to an in situ test on concrete seals (up to 91-cm diameter by 91-cm length) in host rock salt at the Waste Isolation Pilot Plant (WIPP) Facility.

Preliminary efforts included one-dimensional models and limited finite-element models. An experiment design approach, in conjunction with two-dimensional thermomechanical finite-element modeling, determined the relative importance of various concrete and host rock properties on the response of the seal system. In particular, the assumed chemical expansivity of the concrete has a considerable influence on the early-time (180 day) response of the concrete/rock system. Subsequent finite-element modeling of Test Series A produced good comparison between measured and calculated concrete temperatures and strains; fair comparison for concrete stress is obtained. The report concludes by giving present thermal/structural modeling capabilities and limitations, and the direction future development efforts will take.

Vandekraats, J.D. 1986. *Testing of Reconstituted Salt Backfill for Suitability as a Base for the RH TRU Mock Demonstration at the Waste Isolation Pilot Plant, Carlsbad, New Mexico.* [Carlsbad, NM]: Westinghouse Experimental Programs. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Heavy equipment to move and emplace remotely handled (RH) waste may break through reconstituted backfills. A program was developed to test methods of backfilling and characteristics of the reconstituted backfill. Salt pads were laid underground by hand and by machine methods using controlled watering. The lifts (layers) were compacted by rolling with machinery or by using vibrating mechanical tampers. Density and moisture content were measured. The strength and durability of the reconsolidated material were tested by loading salt pads under plate loads and using haul trucks. Salt pads were scuff tested using a loaded haul truck.

Expected stresses range from about 100 to 825 psi. The first plate test added incremental loads of 98 psi as the rate of deflection decreased below 0.002 in./min for 3 min. The cumulative deflection increased with loading, suggesting that the cumulative deflection might increase infinitely at some stress level. At low loads, deflection appears to be insignificant after some initial settling, and at higher stress levels, deflection will be limited by pad thickness and underlying bedrock. Further tests involving initial loads of 98 psi followed by 884 psi for variable times, produced deflections in the range of half an in. in the first half hour. Little rebound was observed after removing loading. Deflections produced by prolonged stress from a parked and loaded haul truck match predictions based on plate bearing tests. Fully loaded haul trucks were used to scuff test pads. "No damage was incurred on either of the large pads although much rubber was left behind as black skid marks." A smaller pad was almost totally destroyed by scuff testing.

It is recommended that areas of drifts prone to breaking should be broken up before placing a crushed salt pad. Thickness of each lift and moisture should be controlled. Use machinery to construct pads where possible. Forklift operators should not make sharp turns or turn wheels while parked, and loaded forklifts should not be parked for more than an hour on a good salt pad until the operational characteristics are determined. Cask loading equipment should be set on solid rock.

DWP

Vandekraats, J.D. 1987. *Quarter-Scale Modeling of Room Convergence Effects on CH TRU Drum Waste Emplacements Using WIPP Reference Design Geometries*. DOE/WIPP 87-012. Carlsbad, NM: US Department of Energy.

ABSTRACT: The Department of Energy (DOE) has agreed to remove any radioactive waste from the Waste Isolation Pilot Plant (WIPP) at the end of a 5-year operations demonstration period if permanent disposal is not appropriate. This study addresses the expected conditions of the waste stacked in disposal room after 5 years, considering room geometry, backfill, waste stack, and room convergence. Modeling at a reduced scale was chosen from various options because of time and budget constraints. Scale model drums were used because this is expected to be the most common waste container. The test plan consisted of three preliminary steps using quarter and full-scale drums to confirm the concept and a final step in which quarter-scale models of drums and rooms, using 900 cans, were tested underground with loads simulating room convergence. Based on these tests, it is expected that load will be completely transmitted through the waste stack within 5 years and all drums will be affected. "Virtually all drums will show some deformation 8 years after emplacement." Some drums, most likely near the center of the room, may breach before 8 years. After 8 years, 1% of the drums are predicted to be breached. After 15 years, about 12% may be breached, and this figure may go higher. Boxes for contact handled waste were not analyzed. Because they are structurally reinforced, contact handled boxes may not deform until adjacent drums have crushed somewhat. The interaction between box designs and drums should be examined. DWP

Wagner, R.A. 1979a. *Viscoelastic Roof-to-Floor Deformations in an Ambient Area of the Pre-WIPP Experimental Area*. Technical Letter Memorandum RSI-0026. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Some of the experiments and/or demonstrations in the Pre-Waste Isolation Pilot Plant (WIPP) Dedicated Area will be performed at ambient temperature conditions. An experiment is being designed to provide easily measurable room-and-pillar deformations at ambient temperature over a period of a few years. The configuration is not characteristic of any specific structural member that would appear in a repository, but rather is designed to be easily simulated with a two-dimensional numerical model.

Two constitutive laws were utilized in modeling the creep behavior of the salt in this Pre-WIPP experiment: 1) an empirical transient law and 2) an empirical steady-state law. The numerical modeling was performed with the finite element code SPECTROM-21.

The steady-state creep law is highly sensitive to changes in effective stress. "As the extraction ratio is increased, the zone of relatively high deviatoric stress in the pillar is correspondingly increased." So "...one would...expect the steady-state creep rate, and accumulated creep strain, to considerably overshadow that of the totally transient situation." At high extraction ratios, steady state creep of narrow pillars results in greater roof-to-floor closure than does transient creep.

For extraction ratios greater than 60%, roof-to-floor closures will greatly increase. For extraction ratios of about 60%, centerline roof-to-floor closure within 3 years should not exceed 25 cm. Most closure in cases analyzed was due to pillar shortening rather than from roof sag or floor heave. DWP

Wagner, R.A. 1979b. *Ambient Drillhole Closure in a Mined Drift*. Technical Letter Memorandum RSI-0037. Rapid City, SD: RE/SPEC, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Closures have been simulated numerically for hypothetical boreholes ranging in diameter from 10.1 cm to 40.6 cm., and drilled below a drift in rock salt. The finite-element code SPECTROM-21 used in the simulation incorporates both transient and steady-state empirical constitutive laws. Model conditions include: 30° C (86° F) ambient temperature, elevation of borehole collar of 305 m (1000 ft), and a borehole depth of 6.1 m (20.0 ft). Mechanical properties of salt were taken as the following: density of 2.16×10^3 kg/m³, modulus of elasticity of 1.38×10^3 MPa, and Poisson's ratio of 0.40.

Closures across the diameter for the steady-state creep law are considerably less than for the transient creep law. The largest radial closures occur between 1 and 5 m depth. Closure across the diameter after 100 and 400 days appears to taper off for boreholes greater than 40.6 cm (16 inches). Field measurements of larger boreholes should be measurable within 1 month of drilling. Calculated effects using the transient creep law are significantly greater than for the steady-state creep law, which is highly sensitive to effective stress. DWP

Wagner, R.A., and J.L. Ratigan. 1979. *Thermo/Viscoelastic Analysis of a Heated Room With Crushed-Salt Backfill in the Pre-WIPP Dedicated Area*. Technical Memorandum Report RSI-0081. Rapid City, SD: RE/SPEC, Inc.

ABSTRACT: Finite-element codes SPECTROM-21 and SPECTROM-41 have been used to simulate numerically an experiment in the Pre-Waste Isolation Pilot Plant (WIPP) Dedicated Area to determine consolidation of crushed-salt backfill in a heated room in rock salt. The analysis determines power requirements and consolidation for various room and pillar geometries to obtain 10% consolidation after 1 year.

The design was constrained by room width not less than 4 m, height no greater than 5 m, total power of 50 kW, temperatures not above 100° C (212°F), and a time limit of 1 year. Both transient and steady-state creep constitutive laws based on laboratory tests were used.

The baseline case (Model 1) produces about 6% volumetric room closure, less than desired. Model 2, with unheated rooms adjacent to the created room, results in extraction ratios of about 50%. Extending the heating period results in about 17% closure after three years. This violates both time and temperature constraints. Lowering thermal loading reduces temperatures, but also reduces closure. It is recommended that extraction ratios be maximized, time of the experiment be extended, and backfill salt be "preconsolidated" in one part of the heated section while another section is allowed to consolidate naturally. Preconsolidated salt will benefit numerical simulations and will help to evaluate mineability of consolidated salt.

DWP

Wahi, K.K., and D.K. Rudeen. 1981. *WIPP Benchmark II Computations With Stealth 2D: Structural Response of an Isothermal and a Heated Drift*. SAI-207-FR-696-1. Albuquerque, NM: Science Applications, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: STEALTH codes are finite-difference numerical codes that have been applied to the Benchmark II problem to compare results among several numerical codes. The isothermal drift case at 10 years shows maximum closure of 0.474 m. Horizontal displacement on the drift wall at pillar midheight has a maximum displacement of 0.174 m. The heated drift case shows a relatively constant convergence rate after 2 years because of the steady-state creep model. The vertical closure at 10 years is 0.538 m. Temperature histories show the code does not properly compute heat conduction across slidelines in the most general case, though the changes are not large. Changes in temperature are not expected to greatly influence stresses or closure

General conclusions from the exercise are: 1) the problem was challenging and realistic, exercising the code to nearly full capability; 2) results differ significantly when stratigraphy is included; 3) the Benchmark II design appears quite safe regarding retrievability. More specific conclusions included: stiff anhydrite layers support the deforming rock mass and limit drift closure; a realistic thermal radiation model for a closed cavity requires a very modest effort; slip at sliplines is significant, warranting inclusion of sliplines in future models and study of friction as a parameter; anhydrite layers build up relatively high stress, which could be relieved by including plasticity; and heat conduction across sliplines needs to be developed and verified.

Sliplines can be accommodated, though frictional sliding has not been verified. Ten or more slip lines can be included, mainly by changing array sizes to store boundary data. STEALTH already includes the ability to describe radiation in a closed cavity, and it was used for the heated drift case for Benchmark II. Thin geological layers may be handled within the code, but certain applications may be very costly. Modulus scaling for certain thermal or thermomechanical applications may be helpful, as the shear modulus can be lowered and thickness increased to maintain relatively consistent mesh scale. It is recommended that the following be considered to avert possible Benchmark III problems: 1) include a simple elastic-perfectly plastic model for anhydrite layers, 2) include friction at slidelines as a parametric

variation, and 3) use identical drift configurations to assess directly the contribution of the thermal load. DWP

Wakeley, L.D. 1986. "Development of Grouts and Concretes for Use at the WIPP, 1975-1986," *Working Papers From the US/FRG Workshop on Sealing and Backfilling of a Salt Repository, Albuquerque, NM, September 23-25, 1986*. Comp. R.F. Cook, Columbus, OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-11-1 through II-11-8. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Freshwater and saltwater grouts were developed and used in bore hole plugging at the Waste Isolation Pilot Plant (WIPP) during 1970s. Through 1984, grouts first used for the Bell Canyon tests (1979-80) were modified but did not achieve the performance criteria considered necessary for the small-scale seal performance tests at the WIPP beginning in 1985.

Waterways Experiment Station developed a new expansive salt-saturated concrete in 1985. This concrete had a 4-hour working time and was self-leveling and nonsegregating in commercial and lab operations. The concrete was expansive in lab tests. It was nonshrinking when emplaced in instrumented or noninstrumented bore holes, either horizontal or vertical, and up to 3 ft in diameter at the repository horizon. Temperature and retarders affect its expansivity. DWP

Wakeley, L.D. 1987a. *Dependence of Expansion of a Salt-Saturated Concrete on Temperature and Mixing and Handling Procedures*. Technical Report SL-87-20. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: In experiments with an Expansive Salt-Saturated Concrete (ESC), the time of setting was controlled by the amount of sodium citrate used. The rheological and physical properties required of ESC were determined by its intended use in an underground repository for radioactive wastes in bedded rock salt. These properties, including a long working time and low air content, could not be achieved using conventional high-range water-reducing admixtures such as melamine and naphthalene formaldehyde condensates. Within a fixed range of citrate percentages, expansivity of the concrete was proportional to the amount of citrate used.

The desired level of expansion resulted from delaying formation of ettringite until after formation of a rigid structure in the paste. Expansive potential was diminished by warmer temperatures of mixing curing and by repeated episodes of mixing or disturbance during the extended period of workability (up to 4 hr). These variables should be considered in plans for field placement of this or any expansive concrete.

The potential for durability of this concrete in the environment for which it was formulated cannot be gauged by those properties commonly used as indicators of durability for conventional concrete in surface environments. Low permeability and minimal reaction to brine are interrelated factors that may better indicate durability than do traditionally cited properties such as compressive strength or resistance to cyclic phenomena.

Wakeley, L.D. 1987b. "Relationships Among Retardation, Expansion, Microstructure, and Phase Composition for a Salt-Saturated Expansive Grout," *Scientific Basis for Nuclear Waste Management, Materials Research Society Proceedings X, Boston, MA, December 1-6, 1986*.

Eds. J.K. Bates and W.B. Seefeldt. Pittsburgh, PA: Materials Research Society. Vol. 85, 283-290.

ABSTRACT: A salt-saturated and sulfate-expansive grout was formulated with four levels of sodium citrate to determine effects on workability and setting time. Linear expansion of restrained grout prisms increased with the amount of citrate used, apparently a function of the extent of retardation of the grouts. This relationship was observed both for grouts cured for at least 53 days and for a concrete formulated from the same cementitious materials cured for at least 180 days.

The microstructures of the grouts at 28 days old showed notable increases in the extent of reaction of the sulfate phases and in the formation of ettringite with increasing citrate content, thus with increasing retardation of the set. X-ray diffraction also revealed an increase in well-crystallized ettringite and decrease in gypsum with greater retardation. These observations provide a microstructural and compositional link between retardation and the expansion of cementitious materials formulated to be expansive.

Wakeley, L.D., and J.P. Burkes. 1986. "Distribution of Chloride in a Salt-Saturated Grout in Contact with Halite Rock," *Cement and Concrete Research*, Vol. 16, 267-274.

ABSTRACT: The shear strength of a sodium chloride-saturated grout to rock salt suggested chemical bonding existed across the interface. Chemical analyses using SEM/EDX of various locations in the grout showed a significantly greater quantity of chloride near the interface than near the perimeter of specimens. The resultant concentration of chloride is at least partially controlled by the proximity of rock salt.

Wakeley, L.D., and T.S. Poole. 1986. *Posttest Analysis of a Laboratory-Cast Monolith of Salt-Saturated Concrete*. Miscellaneous Paper SL-86-13. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: A salt-saturated concrete was formulated for laboratory testing of cementitious mixtures with the potential for use in the disposal of radioactive wastes in a geologic repository in halite rock. Cores were taken from a laboratory-cast concrete monolith on completion of tests of permeability, strain, and stress. The cores were analyzed for physical and chemical evidence of brine migration through the concrete and other features with potential impact on the installation of concrete plugs at the Waste Isolation Pilot Plant (WIPP) in New Mexico.

The post-test analyses of the cores provided evidence of brine movement along the interface between concrete and pipe and little indication of permeability through the monolith itself. There may also have been diffusion of chloride into the monolith without actual brine flow.

Wakeley, L.D., and T.S. Poole. 1987. *Studies of the Geochemical Stability of a Salt-Saturated Expansive Grout*. Miscellaneous Paper SL-87-10. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: This report describes laboratory experiments on several aspects of durability of grout in the special environment of a repository for radioactive wastes in bedded halite rock.

The variables tested include solubility of grout components, phase changes, and mobility of chloride relative to interfaces with rock and brine or freshwater.

The grout tested had large percentages of both chloride and sulfate. Chloride was more mobile when the grout was exposed to freshwater and sulfate when exposed to brine. Removal of chloride from the grout accompanied the loss of the chloroaluminate phase, rather than simply the dissolution of NaCl. However, chloride gradients were not apparently related to an interface between grout and halite rock.

With extended exposure to brine or freshwater, calcium represented the largest fraction of mass loss, as determined by analyses of exposure solutions. Sulfate loss was the second largest. This effect increased with time and temperature of exposure. Volume increase of test specimens indicated continued or renewed expansion, even after the initial curing or storage period (28 days or 9 months), when the grout was exposed to water or brine. The combination of volume increase with mass loss suggests a density decrease, but this did not cause the loss of physical integrity of specimens. Analyses of phase compositions and changes will be reported in a subsequent document.

Wakeley, L.D., and D.M. Walley. 1986. *Development and Field Placement of an Expansive Salt-Saturated Concrete (ESC) for the Waste Isolation Pilot Plant (WIPP)*. Technical Report SL-86-36. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: An Expansive Salt-Saturated Concrete (ESC) was proportioned for placement underground in halite rock at the Waste Isolation Pilot Plant (WIPP) Site, near Carlsbad, NM. Requirements for this concrete were to be chemically compatible with the host rock, to remain pumpable for 4 hours, to give net volume increase beginning at an early age and continuing until creep closure of the salt assures sealing at the rock interface, and to cure to a solid with extremely low permeability and fairly high strength.

ESC was proportioned and placed underground at the WIPP in two successful field tests during FY85 and FY86. This report is the first of three reports about this concrete. It describes the development of ESC in the laboratory and the mixture properties prior to final set. It summarizes field placement activities in July 1985 and February 1986, when ESC was placed in test holes underground at the WIPP for two series of Small-Scale Seal Performance Tests (SSSPT). It also gives data from tests of expansive behavior of the concrete at early ages and under simulated repository conditions.

The second report will describe expansive behavior of ESC relative to several variables that could have an impact on its field performance and long-term stability, as determined during laboratory testing. It also will discuss possible explanations of the rather extraordinary suite of properties exhibited by ESC, as controlled by its chemical composition. The third report will describe laboratory studies of the mechanism of set retardation in a grout derived from this concrete.

Wakeley, L.D., D.M. Walley, and A.D. Buck. 1986. *Development of Freshwater Grout Subsequent to the Bell Canyon Tests (BCT)*. Miscellaneous Paper SL-86-2. Vicksburg, MS: Waterways Experiment Station, Corps of Engineers. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Freshwater grouts are among the cement-based materials developed and studied at the US Army Engineer Waterways Experiment Station (WES) for sealing a radioactive waste

repository in bedded evaporite rocks. The grout most studied was first developed for the Bell Canyon Tests (BCT) at the Waste Isolation Pilot (WIPP) Project in southeastern New Mexico.

This salt-free grout, designated BCT-1FF, was placed in the field in 1981 (site and preliminary design validation, or SPDV) and again in 1983 (B-25 bore hole). Casting of specimens for laboratory study at WES accompanied both of these field events. Specimens were tested to ages of nearly four years for such properties as expansion, compressional wave velocity, compressive strength, static and dynamic elastic moduli, and phase composition.

Most properties achieved the values for which this mixture was developed. Changes in some parameters, such as increases in density and expansion, can be related directly to phase composition and microstructure. The BCT-1FF grout is the baseline candidate freshwater grout for future studies and development of the WIPP as a demonstration geologic repository.

Wallace, M., J. Pletz, J. Case, D. Deal, and B. Lauctes. 1990. "Coupled Fluid-Flow Modeling of Brines Flowing Through Deforming Salt Around the Excavations for the Waste Isolation Pilot Plant (WIPP), in the Permian Salado Formation," *Waste Management 90, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 25-March 1, 1990*. Ed. R.G. Post. Tucson, AZ: University of Arizona. Vol. 2, 873-880.

ABSTRACT: Small brine weeps have been observed on the exposed surfaces of the otherwise dry repository horizon excavations at the Waste Isolation Pilot Plant (WIPP). Furthermore, it is known that creep of the surrounding salt will enhance permeabilities and porosities in the region encompassing the excavations, offering the potential for increased brine inflow. This study is part of an ongoing effort through the Brine Sampling and Evaluation Program (BSEP) to evaluate the coupled processes of salt creep and brine inflow. The previous phase of this project involved the development of a comprehensive mathematical formulation of multiphase (brine and nitrogen), temperature-dependent flow through deforming rock. Aspects of that formulation were employed in the current implementation of a salt creep brine-inflow simulator. The coupled processes were investigated through the integration of a finite-element rock mechanics code with a finite-element groundwater flow code. Preliminary analyses applied to a hypothetical circular excavation showed the development of a zone of disturbed rock having enhanced permeability and porosity. This development was accompanied by the outward propagation of an unsaturated zone. For the excavation geometry considered, the development of this unsaturated zone appears to be primarily sensitive to strain rates.

Walter, G.R. 1983. *A Three-Well Technique for Determining Formation Anisotropy at the Waste Isolation Pilot Plant (WIPP) Southeast New Mexico*. SAND83-7011. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The traditional methods used by hydrologists for determining the principal components of transmissivity in anisotropic aquifers are based on techniques developed by Papadopoulos and Hantush. Their procedures are based on the assumption that an aquifer test will be performed with one pumped well and require a minimum of three observation wells to completely define the direction and magnitude of the principal components of transmissivity. The theory and techniques described in this report represent an extension of the techniques presented by Papadopoulos and Hantush in support of the theory that more than one well in a well array can be pumped. In this case, the transmissivity tensor can be completely defined using a three-well array, if two aquifer tests are performed sequentially pumping two of the wells.

Walter, G.R., H.W. Bentley, J.J. Ward, and D.D. Gonzalez. 1983. "Continuum and Non-Continuum Aspects of Groundwater Movement at the Waste Isolation Pilot Plant, Southeastern New Mexico," *EOS Transactions, American Geophysical Union*. Vol. 64, no. 45, 713. (Abstract Only).

ABSTRACT: Both pumping and tracer tests on the Culebra Dolomite Member of the Rustler Formation near the Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico have shown that both types of tests are necessary to describe the physics of groundwater flow in these rocks. Based only on pumping test results, the Culebra Dolomite appears to be a nearly ideal anisotropic porous medium with a ratio of the principal components of transmissivity of about 2.7:1. Groundwater tracer tests, however, have shown order of magnitude differences in travel times, depending on the direction of tracer movement. The solute-transport results suggest that groundwater movement takes place through discrete channels or fractures. These results also raise fundamental questions about the meaning and determination of "effective" porosity values used in solute-transport modeling. Numerical models are currently being developed to determine the formation characteristics which will reconcile the continuum and noncontinuum aspects of flow in the Culebra.

Ward, D.B., and D.G. Brookins. 1990. "Rb-Sr and Uranium Geochemical Constraints on Actinide Migration at the Waste Isolation Pilot Site, New Mexico," *Abstracts with Programs, Geological Society of America, Dallas, TX, October 29-November 1, 1990*, Vol. 22, no. 7, A100. (Abstract Only).

ABSTRACT: In the Culebra Dolomite of the Rustler Formation, the most probable conduit for the long-term release of radionuclides to the biosphere is transport by groundwater. We have examined clay minerals from fracture surfaces in the Culebra which overlies the Waste Isolation Pilot Plant (WIPP) repository in the Salado Formation.

Whereas clay minerals in the WIPP repository proper (Salado Formation) are dominantly illitic and illitic smectite and yield pre-depositional ages of 428 ± 7 Ma, the clay minerals in the fractures of the Culebra formation are predominantly Mg-rich varieties such as corrensite, saponite, and chlorite and complex mixed layered species. These clay minerals from throughout the Rustler Formation yield Rb-Sr ages ranging from 290 Ma (minus 2 micron fraction) to 250 Ma (minus 0.125 micron fraction), suggesting that much of the water-rock interaction and fracture filling occurred during or very soon after the Late Permian. The Rb-Sr ages do not, however, reflect ion-exchange processes occurring on clay surfaces because normal laboratory cleaning removes most sorbed ions.

We have examined this problem further by attempting field distribution coefficient (K_d) measurements. Using water data from wells studied for uranium series disequilibrium systematics coupled with neutron activation analysis of clay minerals from the same horizons allows us to determine a range in K_d values from 80 to 800 ml/g. Despite the uncertainties involved in precise water/rock behavior, these K_d values imply only limited mobility of uranium in the Culebra samples.

Ward, J.J., G.R. Walter, and D.D. Gonzalez. 1983. "Heterogeneity and Anisotropy of a Groundwater System in Carbonate Rocks at the Waste Isolation Pilot Plant (WIPP Site), New Mexico," *EOS Transactions, American Geophysical Union*. Vol. 64, no. 45, 713-714. (Abstract Only).

ABSTRACT: Numerous aquifer tests have been performed on the Culebra Dolomite Member of the Permian Rustler Formation in the vicinity of the Waste Isolation Pilot Plant (WIPP) Site.

These tests included determination of transmissivity, storativity, and, at several locations, anisotropy. The similarity of the principal directions and the ratio of the major to minor components of transmissivity implies a regional control mechanism, the most plausible being the approximate north-south fracture alignment inferred from the regional stress history of the Delaware Basin. A very high degree of aquifer heterogeneity is evidenced by the more than five orders of magnitude variation in measured transmissivity within the study area. The values and trends of transmissivity appear to be controlled primarily by an eastwardly migrating halite dissolution front and not to the factors controlling the anisotropy.

Wawersik, W.R. 1979. *Indirect Deformation (Strain) Measurements and Calibrations in Sandia Triaxial Apparatus for Rock Testing to 250°C*. SAND79-0114. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Indirect procedures for axial and radial strain measurements on rock in triaxial tests to 250°C are presented. The description of techniques includes discussions of all calibrations and of the accuracies of measurements. In addition, two examples are given to show how the techniques are implemented in triaxial compression and triaxial extension experiments.

Wawersik, W.R. 1981. "New Comparisons of Creep Rates for Rock Salt as a Function of Temperature to 160°C ($T = 0.4 T_m$)," *EOS Transactions, American Geophysical Union*. Vol. 62, no. 45, 1029. (Abstract Only).

ABSTRACT: Salt creep measurements as a function of temperature are needed to simulate salt mass motions around underground structures. They are also sought to identify governing deformation mechanisms for data extrapolation.

Temperature-dependent creep rates were determined for a natural rock salt in differential temperature tests under compression between 23 and 160°C. Results were compared in terms of the quantity $S = -R[\ln(e_{i+1}/e_i)/(1/T_{i+1} - 1/T_i)]_T$ where e_i denotes natural strain rate at temperature T_i , R is the gas constant and T is shear stress. With few exceptions, S lay between 67 and 96.4 kJ/mole. The high values pertain to some strain rates just before and after the temperature had been changed (instantaneous values). The lower values correspond either to strain rates at the end of each test stage or to constant strain rates throughout a pair of stages (asymptotic values). Differences in the instantaneous and asymptotic values of S are attributed to transients because steady-state creep had not been reached in the preceding test stage.

If the lower values of S are assumed to equal an effective activation energy for steady-state creep, Q_{eff} , then the present data lie noticeably above published values $Q_{eff} = 50.2$ kJ/mole for the same temperature and stresses. This fact suggests that earlier data may have been biased by short-term measurements which did not extend into the steady-state regime. It also implies that earlier exponents in power-law stress formulations may have been underestimated.

Wawersik, W.R. 1982. "Low Temperature Creep Mechanisms in Rock Salt," *EOS Transactions, American Geophysical Union*. SAND82-2071A. Vol. 63, no. 45, 1095. (Abstract Only).

ABSTRACT: Based on adequate power-law fits, low-temperature creep of rock salt ($0.27 \leq T/T_m \leq 0.44$) is often assumed to be controlled exclusively by the climb of edge dislocations. This suggestion is then used to justify the extrapolation of measurements to lower stresses and longer times than can be realized in the laboratory.

The assumption that the low-temperature creep of rock salt is entirely governed by diffusion is at odds with measured low-activation enthalpies. It was shown that this assumption is also at variance with alternate fits to creep rates by exponential stress functions; activation areas on the order of $100 b^2$ (b = Burgers vector); glide bands in addition to subgrain structures in virgin specimens, laboratory-deformed samples, and in salt which was taken from the walls of old mine workings; and normal and inverse transients following changes in applied temperature in laboratory creep experiments. These observations, along with previously established high-temperature creep properties and with measurements of low-temperature flow stresses, τ_{II} , all suggest that the low-temperature creep of rock salt is determined by the simultaneous action of climb and cross-slip. Substantiating measurements of activation enthalpies as a function of stress are pending.

Wawersik, W.R. 1984a. "Comparison of Creep and Creep Models for Rock Salt," *Second Conference on the Mechanical Behavior of Salt, Hannover, Germany, September 24-29, 1989*, SAND84-0888A. Albuquerque, NM: Sandia National Laboratories. (Abstract Only; Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Creep data will be presented for four domal salts and one bedded salt. The measurements furnish credible upper and lower bound steady-state creep estimates. The upper and lower bounds were distinguished by the association of creep with normal and inverse transients. This new approach to the determination of steady-state creep rates of salt at low temperature requires shorter test times than conventional methods. Possible errors in steady-state creep measurements using the old and new approaches will be demonstrated by a comparison of two relatively large data sets for bedded salt from the Salado Formation, New Mexico.

The different groups of steady-state creep estimates of this study were fitted by a power law model,

$$\dot{\epsilon}_{1s} = C \exp(-Q/RT) \left(\frac{\tau}{\mu} \right)^n \quad (1)$$

and by several alternate models for cross-slip, Eq (2), and dislocation glide, Eq (3)

$$\dot{\epsilon}_{1s} = D \exp \left(-\frac{Qcs}{RT} \right) \ln \left(\frac{\tau_0}{\mu_0} \right) - \ln \left(\frac{\tau}{\mu} \right), \quad (2)$$

$$\dot{\epsilon}_{1s} = B_1 \left(\frac{\tau(1 - B_7)}{\mu} \right)^{B_2} \exp \left(-\frac{1}{RT} (B_3 - V\tau(1 - B_6)) \right) \quad (3)$$

where

$$V = B_4 \exp \left(-\frac{B_5}{RT} \right).$$

As a further alternative, $\tau(1 - B_6)$ was replaced by $(\tau(1 - B_6))^{B_8}$.

C, D, and n are constants. μ denotes the shear modulus, T is temperature and $\tau = (\sigma_1 - \sigma_3)$ is the shear stress. τ_0 and μ_0 are the flow stress and the shear modulus at absolute zero. The

quantities Q_{CS} , B_3 and B_5 are activation energies. V denotes an activation volume. In addition to these expressions, a dual mechanism model for climb and cross-slip was considered.

The best and mechanistically most credible fit to the models in eqs. (1)-(3) was obtained for cross-slip with excellent agreement between the fitted activation energies and activation energies for cross-slip in the literature. This conclusion is supported by activation analyses including some correlations between the effective activation energy and the stress exponent of the power law model, on one hand, and stress and temperature, on the other. This conclusion is also consistent with some large power law stress exponents and with limited substructural observations that showed no subgrain development. No satisfactory fit could be obtained for a two-mechanism model for dislocation climb and cross-slip, especially when the activation energies were constrained to known values. If cross-slip can be proven to be the dominant creep mechanism, then a rationale would be available to extrapolate the existing steady state creep measurements beyond the range of laboratory conditions of stress and temperature. Such extrapolations appear justified also by equivalent salt viscosities of the order of 10^{19} poise or less that are predicted by the cross-slip model for geologic stresses, $0.7 \leq \tau \leq 1.75$ MPa, and corresponding temperatures $70 \leq T \leq 120^\circ\text{C}$.

Although the present data suggest that cross-slip may be the rate controlling step during the low temperature creep of salt, there is good agreement between the cross-slip and power law fits. Therefore, the power law fits appear to be good empirical approximations to the true creep processes despite the fact that the fitted power law creep parameters cannot be interpreted mechanistically.

Creep measurements on different salts yielded differences in steady-state creep estimates between one and two orders of magnitude. The reasons for unusually low creep rates for salt from the Bryan Mound dome remain unknown. Several chemical studies were inconclusive, while arguments concerning variations in initial subgrain sizes proved inadequate. Work on compositional and textural variations is continuing.

Wawersik, W.R. 1984b. "On the Evolution of Texture and Microstructure in Laboratory Deformed Rock Salt," *Second Conference on the Mechanical Behavior of Salt, Hannover, Germany, September 24-29, 1984*. SAND84-0889A. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Textural and microstructural studies for rock salt are important for the selection and extrapolation of creep models that are based on laboratory measurements at constant stress or at constant strain rate. For example, a well-developed subgrain structure suggests that steady-state creep is governed by dislocation climb. On the other hand, glide bands, diffuse glide bands, and wavy slip are indicative of glide and cross-slip. Microstructural observations are also relevant to the interpretation of creep measurements following stress drops. While recovery in such tests is indicated by inverse transients, available observations do not suffice to determine whether recovery is always complete. Such judgement is particularly difficult when the associated microstructures are not dominated by subgrain formation.

The evolution of texture and microstructure is being studied in rock salt from the Asse Mine anticline and from the Salado Formation, New Mexico. The first part of this study consisted of creep tests on layered samples at two stresses and at 100 and 160°C. The resulting histories of seven samples are indicated. The induced strains varied between 0.2 and approximately 8%. Associated textural and microstructural measurements are now in progress, beginning with observations of grain-boundary sliding. Additional observations are being made on Salado salt to evaluate substructural changes that were associated with the recovery tests. These tests supplemented the recovery tests. All observational studies will be completed by August 1984.

Wawersik, W.R. 1984c. "Fracture Patterns Induced By Hydraulic Fracturing in a Bedded Rocksalt," *EOS Transactions, American Geophysical Union*. Vol. 65, no. 45, 1118. (Abstract Only).

ABSTRACT: Hydraulic fractures were induced in a 130-m long horizontal drill hole in bedded salt of the Salado Formation in southeastern New Mexico, 675 m below the surface. The relevant salt stratigraphy contains almost pure salt, polyhalitic salt, and argillaceous salt with distinct clay partings. The induced fractures were decorated with fluorescent dye that had been added to the hydraulic fracturing fluid earlier. As a result, all fracture patterns could be mapped in detail as a drift was advanced along the axis of the drill hole in which hydraulic fracturing had been conducted.

The observed fracture patterns can be divided into four groups: fractures with preferred orientations due to the effect of nearby, 15-month old mine openings; fracture patterns that are interpreted to be characteristic for isotropic stress states; fracture patterns and fracture process zones that are typical for argillaceous salt with intervening clay partings; and fracture patterns near the ends of a pair of 1.7-m long sliding packers. Especially large fracture process zones in argillaceous salt correlate well with low fluid recoveries immediately following hydraulic fracturing.

Based on published analyses of the stress distribution around an isolated mine opening in rock salt, it is inferred that preferred fracture orientations are indicative of maximum principal stress differences $\sigma_1 - \sigma_3 \geq 1.25$ MPa.

Wawersik, W.R. 1985a. "Alternatives to a Power-Law Creep Model for Rock Salt Below 160°C," *EOS Transactions, American Geophysical Union*. Vol. 66, no. 46, 1084. (Abstract Only).

ABSTRACT: Upper and lower bound estimates of the steady-state strain rates of rock salt from five locations were analyzed. The measurements were obtained in triaxial creep tests, including systematic changes in stress and temperature to 160°C. The various data sets were correlated in activation analyses and fitted by models for power-law creep (dislocation climb), cross-slip, dislocation glide, and combined climb and cross slip. In addition, measurements were made to evaluate the importance of grain-boundary sliding. It was determined that a cross-slip model yields the mechanistically most credible fit with activation energies and activation areas matching those published for NaCl single crystals. Grain-boundary sliding contributed less than 18% of the total strain at 160°C. Good fits for cross-slip and high power-law stress exponents rule out the possibility that pressure solution affected the data in a major way to the lowest recorded strain rates of order 10^{-10} s⁻¹.

The conclusion concerning cross-slip as the rate-controlling step during creep of rock salt below 160°C is consistent with many glide related microstructural features in samples deformed in the laboratory at or below 110°C. It is emphasized, however, that the role of cross slip does not imply the absence of dislocation climb and subgrain formation, but merely suggests that climb is not dominant.

Wawersik, W.R. 1985b. "Determination of Steady State Creep Rates and Activation Parameters for Rock Salt," *Measurement of Rock Properties at Elevated Pressures and Temperatures, College Station, TX, June 20, 1983*. Eds. H.J. Pincus and E.R. Hoskins. SAND82-2731C. Philadelphia, PA: American Society for Testing and Materials. 72-92.

ABSTRACT: Measurements of steady-state creep rates and activation parameters are described for rock salt at low-temperature ($T \leq .4T_m$; $T_m \equiv$ melting temperature) and low-strain rates. The determinations of steady-state creep rates rely on the evaluations of upper and lower bounds based on the characteristics of transients following changes in stress and temperature. First order activation analyses make use of correlations between the steady-state creep rates, stress, and temperature. More rigorous activation analyses result from comparisons of creep rates right before and after temperature and stress changes. Selected experimental results are given for rock salts from two locales deformed between 40 and 160°C. Based on measured values of activation enthalpies, activation areas, correlations between steady-state creep rates by means of a power law, and some temperature-induced transients, it is suggested that the low-temperature creep of rock salt is affected by large, independent contributions from glide mechanisms besides dislocation climb.

Wawersik, W.R. 1986. "Microstructures in Deformed Rock Salt From Around Old Mine Workings," *EOS Transactions, American Geophysical Union, San Francisco, CA, December 8-12, 1986*. SAND86-2187A. Vol. 67, no. 44, 1202. (Abstract Only).

ABSTRACT: Microstructures were observed in deformed rock salt from around old workings in Hutchinson, Kansas; Hallstatt, Austria; Wieliczka, Poland; and from the Asse Mine, Federal Republic of Germany. Samples from Hutchinson included core from the rib and from the center of an approximately 50-year-old pillar. The microstructures were compared with those in virgin salt and in single and polycrystalline salt deformed in laboratory creep experiments. The microstructural data are used to test mechanistic interpretations of laboratory creep measurements and to evaluate whether the current models for the low-temperature creep of rock salt can be extrapolated to lower in situ stresses and to longer times.

Most of the samples exhibited both straight and wavy slip. Homogeneous, regular subgrain structures were found only in the Asse salt from the vicinity of an in situ heater experiment at 280°C. Slip-related features produced at ambient temperature are consistent with microstructures induced by laboratory tests to 100°C. However, salt from around mine workings exhibited many additional features. The most developed of these, besides pure glide bands, are coexisting subgrains and glide bands; local polygonization; accelerated, apparently stress-assisted recovery around brine inclusions; and recrystallization. Indicators of recrystallization are similar to microstructural manifestations after stress drops and after gradual, previously unexplained creep accelerations in some laboratory creep tests. Although some of the observed features, such as recrystallization, may not be caused by steady-state processes, their random development over large volumes could be important and might contribute to systematic underpredictions of salt deformations measured in situ.

Wawersik, W.R. 1988a. *The Mechanical Behavior of Salt, Proceedings of the Second Conference, Hanover, Federal Republic of Germany, September 24-28, 1984*. Eds. H.R. Hardy, Jr. and M. Langer. SAND85-2453C. Clausthal-Zellerfeld, Germany: Trans Tech Publications. 103-128.

ABSTRACT: Five sets of steady-state creep estimates for rock salt were analyzed to compare the results of power-law fits for dislocation climb with the fits by models for cross-slip, glide, and a combination of cross-slip and climb. It was determined that a cross-slip model yields the mechanistically most credible fit with activation energies and activation areas matching those published for NaCl single crystals. High power-law stress exponents also ruled out the possibility that pressure solution and recrystallization played a major role to the lowest recorded strain rates on the order of 10^{-10} s^{-1} .

The conclusion concerning cross-slip as the rate controlling step during creep of rock salt below 160°C is consistent with many glide related microstructural features in samples deformed in the laboratory at or below 110°C. It is emphasized, however, that the role of cross-slip does not imply the absence of other mechanisms, including dislocation climb and subgrain formation, but merely suggests that they are not dominant.

Wawersik, W.R. [1988b.] "Using Hydraulic Fracturing and Mineback to Determine In Situ Stresses in Rock Salt," *ASME/SES Joint Applied Mechanics Conference, Berkeley, CA, June 20-22, 1988*. SAND88-1113A. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Hydraulic fracturing was applied in horizontal drill holes in the Salado salt formation at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. Tests were performed approximately 650 m below the surface primarily to determine whether the virgin in situ stress state is isotropic and whether the magnitude of the virgin in situ stresses corresponds to the weight of the overburden. Additionally, measurements were made to evaluate the usefulness of hydraulic fracturing under anisotropic stress conditions in rock salt and in other rocks that exhibit creep and stress relaxation. To achieve these objectives, hydraulic fracturing tests were carried out in orthogonal drill holes at distances from 14 to 560 m from existing mine panels, up to 50 m from the face of an isolated drift, and in a 3-year-old mine pillar. Several tests were followed by observations of the hydraulically induced fracture patterns during mining of a drift at a later date. Field measurements were aided by finite-element analyses to infer the likely shape of the pressure-time records of hydraulic fracturing operations in rock salt for comparison with the corresponding pressure-time records in approximately linearly elastic "hard" rock.

The main results obtained were as follows: the existence of an isotropic virgin in situ stress state at the WIPP Site could be demonstrated solely by means of very characteristic, randomly oriented fracture patterns distant from the effects of prior mining, as opposed to preferentially aligned fracture patterns near existing excavations; isotropic or nearly isotropic in situ stresses resulted in stable pressure-time records with little loss in pressure after primary breakdown, contrary to observations in competent hard rock. The attendant peak pressure, fracture reopening pressure, and fracture driving pressure were consistent with numerical predictions; fracture pinching under isotropic or nearly isotropic stress conditions produced a characteristic pressure rise during fracture reopening and appeared to raise the fracture driving pressure. It also obscured the identification of the instantaneous shut-in pressures; anisotropic stress states were qualitatively indicated by unstable pressure-time records. However, the effect of rock-salt creep under these conditions appeared to preclude unique interpretations of hydraulic fracturing tests in rock salt, at least in initially traction-free, open drill holes and up to far-field principal stress ratios of 1:4.

Wawersik, W.R., and D.W. Hannum. 1979. *Interim Summary of Sandia Creep Experiments on Rock Salt from the WIPP Study Area, Southeastern New Mexico*. SAND79-0115. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Triaxial creep experiments were performed on relatively large samples of salt, mainly from drillholes AEC-7 and ERDA-9. Samples were taken from two horizons between 2000-2100 ft and 2600-2800 ft depth (625-650 m and 810-875 m). Most tests were conducted

at a mean slow loading rate $30 \text{ psi/min} (0.21 \text{ MPa/min}) \leq d(\sigma_1 - \sigma_3)/dt \leq 60 \text{ psi/min} (0.41 \text{ MPa/min})$.

Some experiments used loading rates to about 20,000 psi/min (0.14 MPa/min). Results compare behavior as a function of principal stress difference, temperature, and confining pressure. Samples exhibited all known stages of creep: primary, secondary, and tertiary creep followed by creep fracture.

New Mexico rock salt is very nonlinear in behavior under all loading conditions, having an initial elastic limit ($\sigma_1 - \sigma_3$) of about 0, and this behavior is not affected by hydrostatic pressures to 5000 psi (34.5 MPa) before deviatoric loading. Core damage may cause the low initial elastic limit, but the stress history of samples is unknown. New Mexico rock salt can be accurately evaluated only if load/unload/reload cycles are used, "...provided the imposed loading rate is sufficiently high, or the ranges of stresses, either hydrostatic pressure p or ($\sigma_1 - \sigma_3$), is well below the previously attained peak stress." When characterized under these conditions, Young's modulus (E) and Poisson's ratio (ν) range from $4.3 \times 10^6 \leq E \leq 5.3 \times 10^6$ psi ($29.6 \leq E \leq 36.5$ MPa) and $0.17 \leq \nu \leq 0.26$, respectively, comparing favorably to calculated ranges based on in situ geophysical log data.

Practically all nonelastic rock salt deformation is permanent, and elastic deformation under deviatoric loading is a very small part of total deformation. Time-dependent and time-independent components of permanent deformation have not been separable even at higher loading rates. At low confining pressures, rock salt exhibits regimes of nearly isovolumetric deformation and regimes of large dilatancy due to local fracturing. Low deviatoric stress, higher confining pressure, and/or higher temperatures favor nearly isovolumetric, ductile behavior.

Strength and/or ductility of rock salt depend on temperature and pressure. At ambient temperature, the greatest compressive strain (ϵ_1) ranged between 12.5 and 14% at 500 psi (3.5 MPa) confining pressure. At a confining pressure of 3000 psi (20.7 MPa), macroscopic failure was not observed below 8800 psi (60.7 MPa) ultimate principal stress difference and compressive strain of 20%. Macroscopic failure occurred with large strain ratios (ϵ_3/ϵ_1). Increased temperature reduced ultimate stress and extended rock salt ductility. At ambient temperature, fracture appears brittle.

In contrast to earlier results, primary creep data appear independent of pressure within experimental scatter. Steady state creep ratios of interest to the Waste Isolation Pilot Plant (WIPP) vary from less than 10^{-10} s^{-1} to about 10^{-8} s^{-1} . "Tertiary creep and creep fracture were observed at ambient temperature and at 100°C. Creep fracture was not observed in a limited number of experiments at 200°C and is deemed unlikely except, possibly, at very low confining pressure" ($\leq 100 \text{ psi}$; 0.7 MPa).

Creep fractures may be predicted using an empirical procedure correlating "permanent time-dependent strains (damage) with limiting damage...established from complete quasi-static stress-strain curves including pre- and post-failure records." DWP

Wawersik, W.R., and D.W. Hannum. 1980. "Mechanical Behavior of New Mexico Rock Salt in Triaxial Compression up to 200°C," *Journal of Geophysical Research*. SAND77-1192J. Vol. 85, no. B2, 891-900.

ABSTRACT: Experiments were conducted to determine the 'quasi-static' mechanical behavior of rock salt in support of the structural design of a waste isolation pilot plant. The salt studied was from the Salado formation in the Delaware Basin, southeastern New Mexico. Three groups of tests are discussed to identify the relative and site-specific importance of deviator stress, confining pressure (mean stress), temperature, time (loading rate), and stress path. The three

groups of experiments consist of (1) hydrostatic loading, (2) triaxial compression tests ($\sigma_1 > \sigma_2 = \sigma_3 = \text{const}$), and (3) variable stress path tests including experiments at approximately constant σ_1 and at constant mean stress. The range of parameters considered was $0 \leq p$ (hydrostatic pressure) ≤ 34.5 MPa, $0 \leq \sigma_2 = \sigma_3 \leq 20.7$ MPa, $0 \leq (\sigma_1 - \sigma_3) \leq 62$ MPa, $23 \leq T$ (temperature) $\leq 200^\circ\text{C}$, and $1.7 \leq d(\sigma_1 - \sigma_3)/dt \leq 3.5$ kPa/s. All data were generated on 100-mm diameter specimens. The rock salt exhibited nonlinear response under all loading conditions, a low initial elastic limit ($\sigma_1 - \sigma_3$) ≤ 0.7 MPa, and an apparent inseparability of permanent deformations into time-independent and time-dependent components. Pressure and temperature did not alter the elastic constants over the range $29.6 \leq E \leq 36.5$ GPa and $0.17 \leq \nu \leq 0.26$, depending on core lithology. Pressure and temperature affected the principal strain ratio, the ratio of volumetric to shear strain, rock salt ductility, and the ultimate stress. In particular, low pressure and temperature permitted pronounced dilatancy and loss in load bearing ability. Under such conditions, the volumetric strains reached sizable fractions of the shear strains, $|\epsilon/(\epsilon_1 - \epsilon_3)| \geq 0.2$. Pressure remained important even at 200°C temperature because it influenced the rate of shearing at constant loading rates. Load path and stress history may be significant under deviatoric loading conditions and for large variations in pressure.

Wawersik, W.R., and H.S. Morgan. 1987. "Evaluating Design Procedures for Structures in Rock Salt," *Rock Mechanics: Proceedings of the 28th US Symposium, University of Arizona, Tucson, AZ, June 29-July 1, 1987*. Eds. I.W. Farmer, J.J.K. Daemen, C.S. Desai, C.E. Glass, and S.P. Neuman. SAND86-2597C. Boston, MA: A.A. Balkema. 107-115.

ABSTRACT: Validating design procedures for structures in salt masses can be accelerated by suitable laboratory or bench-scale experiments where in situ loading conditions with inhomogeneous stress fields and heating are simulated, controlled, and repeated. Design validations, especially data and model extrapolations, can also be supported by identifying microstructures as manifestations of the governing deformation processes. The laboratory tests described here use externally and internally pressurized, heated, thick-walled hollow cylinders. Microstructural studies presented entail observations on rock salt after laboratory testing and on salt from around old mine workings.

Wawersik, W.R., and D.S. Preece. 1984. "Creep Testing of Salt - Procedures, Problems and Suggestions," *The Mechanical Behavior of Salt: Proceedings of the First Conference, Pennsylvania State University, University Park, PA, November 9-11, 1981*. Eds. H.R. Hardy, Jr. and M. Langer. SAND81-1116C. Clausthal-Zellerfeld, Federal Republic of Germany: Trans Tech Publications. 421-449.

ABSTRACT: Apparatus and procedures are described for salt testing to 70 MPa confining pressure and 250°C with emphasis on rock-salt creep. Data reduction and fitting methods are discussed together with difficulties which bear on the validity and interpretation of creep measurements. Problems of particular concern include the identification of steady-state creep and the consequence of overload hardening.

Difficulties of salt creep measurements lead to suggestions for reference tests under standardized conditions to facilitate the comparison and use of data from different sources.

Wawersik, W.R., and C.M. Stone. 1983. "Small-Volume Hydraulic Fracturing Tests in Salt--A Progress Report," *EOS Transactions, American Geophysical Union*. Vol. 64, no. 45, 850. (Abstract Only).

ABSTRACT: Small-volume hydraulic fracturing tests in horizontal drill holes in salt at depth are discussed and compared with three sets of hydraulic fracturing data of other studies. Emphasis is placed on the description of repeatable, stable pressure-time records with no clear shut-in signatures during the initial and subsequent pressurization of 1.3-m long intervals in 1.54-cm diameter drill holes. The observations presented are based on tests with two frac fluids (viscosities 4 cs and 45 cs), pumping rates between 0.1 gpm and 2.5 gpm, and visual observations during mineback of one fracture interval. The results are then qualitatively related to the computed stresses around a drill hole in both isotropic and anisotropic stress fields, treating both the elastic and the creep properties of salt with transient and steady-state creep.

Wawersik, W.R., and C.M. Stone. 1984. "Hydraulic Fracturing Tests in Salt," *Second Conference on the Mechanical Behavior of Salt, Hannover, Germany, September 24-29, 1984*. SAND84-0890. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Small-volume hydraulic fracturing tests were carried out to determine the virgin in situ stresses at the site of a radioactive waste isolation pilot plant in southeastern New Mexico. To measure stresses by means of hydraulic fracturing it was necessary to consider the effects of salt creep on the stress distribution around the drillholes in which the frac jobs were conducted. This leads to a departure from traditional interpretations of hydraulic fracturing data.

In situ measurements consisted of eleven hydrofracs spaced between 3 m and 14 m apart in a 140 m long horizontal drillhole. The hole coincided with the axis of a drift that will be mined later. Therefore, it will be possible to inspect and map the fractures to correlate pressure-time signatures with fracture patterns and fracture directions. To try relevant procedures, the eleven main fracs were preceded by five trial experiments using different packer setting pressures, pumping rates, injection volumes, dies for fracture mapping, etc.

The pressure histories obtained were extremely consistent, regardless of distance from the drillhole collars and irrespective of pumping rates between 31.5 cc/s (.5 pgm) and ≈ 100 cc/s (1.5 gpm) and fluid viscosities between 5 and 50 cs. Typical pressure-time records and flow-records are shown together with the characteristic pressures P_b , P_p , P_f , P_s , etc. The pressures P_b and P_{bs} are first estimates of the initial breakdown and fracture reopening pressures, respectively. P_{p1} , P_{ps} and P_{fs} are the observed peak and the approximate driving pressures. P_s denotes instantaneous shut-in pressure with one exception: the pressure-time records were stable showing only weak peaks and no distinct, readily identifiable shut-in pressures although the interval pressures were monitored downhole. Also, fracture reopening at or below P_{bs} was followed by a steady increase in driving pressures, P_f and P_{fs} , during all first and subsequent pumps differed by less than 0.7 MPa.

It was mentioned before that fracture patterns and fracture directions are determined by means of visual observations during excavation into each fracture interval. Accordingly, more or less small multiple fractures were created in the immediate vicinity of the drillhole. Longer cracks were located at about 120 degrees. The longest fracture consisted of a conjugate, vertical pair extending to at least 1.3 m. Fracture mapping of all main hydraulic fracturing intervals is planned for July 1984.

To assist in the interpretation of the field results, finite element and laboratory hydraulic fracturing tests were conducted. Finite element analyses determined the tangential stress distribution around a drillhole subjected to isotropic and anisotropic far-field stresses. The tangential stress at the drillhole wall relaxes very rapidly to between 80% and 90% of the far-field stress. Also, at times after drilling when hydraulic fracturing might be practicable, the greatest induced tangential stress lies between 2 and 8 radii away from the drillhole wall.

Laboratory hydraulic fracturing tests were performed under confining pressure with emphasis on the relationship between confining pressure and fracture reopening pressure, preferred fracture directions, and size of fracture process zones.

The combination of hydraulic fracturing activities has led to the following preliminary conclusions. (1) Stable pressure-time signatures might be the direct consequence of stress relaxation in isotropic, far-field stress fields. (2) Regardless of creep, it should be possible to determine minimum principal stresses from driving pressures or instantaneous shut-in pressures even in short hydraulic fractures (fracture lengths 2 to 6 m; injection volumes 5000 to 8000 cc). (3) Multiple fracturing must be anticipated at the walls of hydraulic fracturing intervals. Therefore, borehole observations of fractures and inferences concerning principal stress directions should be viewed with caution. (4) Multiple fracturing must be considered in the interpretation of peak pressures and fracture reopening pressures. (5) The absence of distinct shut-in pressures remains puzzling. Possible causes include adverse thermal effects, equality between driving pressure and far-field stresses, and fluid seepage into large fracture process zones. (6) Based on finite element analyses completed to date, measured ratios $p_{bs}/p_{fs} < 1$ ($p_{bs}/p_s < 1$) are indicative of isotropic stress fields, $p_{bs}/p_{fs} > 1$ ($p_{bs}/p_s > 1$) of anisotropic stress states. (7) Elastic analyses will be misleading even if hydraulic fracturing were possible only a few hours after drilling. (8) The combination of measured pressure-time records, observed fracture patterns during one mineback operation, and analytical results suggest that the virgin in situ stress field at the site of interest is nearly isotropic. (9) The consistency of all pressure-time records during hydraulic fracturing indicate that the influence of mining on the stress state at the radioactive waste isolation pilot facility in New Mexico does not reach nearly as far as anticipated.

Wawersik, W.R., and C.M. Stone. 1985. *Application of Hydraulic Fracturing to Determine Virgin In Situ Stress State Around Waste Isolation Pilot Plant - In Situ Measurements.* SAND85-1776. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Hydraulic fracturing tests were carried out in horizontal drill holes in rock salt in the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM. It was determined that the virgin in situ stress field is isotropic or nearly isotropic. The inferred magnitude of the isotropic in situ stress falls between bounds of 14.28 and 17.9 MPa for the average breakdown reopening pressures and driving pressures. The best estimate from instantaneous shut-in pressures is 16.61 MPa. Given some uncertainties about the interpretation of hydraulic fracturing data in salt, all of the foregoing values are in acceptable agreement with an average calculated isotropic in situ stress of 14.9 MPa at an average depth of 657 m below surface. Interpretations of breakdown and reopening pressures are based on finite-element analyses of the relaxed stress field around a bore-hole in salt. The stress field varies little between approximately 50 and 200 days after drilling. The finite-element analyses were also used to interpret the observed stable pressure-time signatures with little or no pressure drops during primary breakdown of the salt formation. The conclusion about the isotropic nature of the virgin in situ stress held is supported by observations of the induced fracture patterns. The report includes a comparison of the hydrofrac data in the WIPP with the published results of hydraulic fracturing tests in salt at three other locations.

Wawersik, W.R., and C.M. Stone. 1986a. "Stress Measurements in Rock Salt Using Hydraulic Fracturing," *Solution Mining Research Institute Meeting, Hydrofracture Tests of US Salt, Spring Meeting, Baton Rouge, LA, April 20-22, 1986.* SAND86-1034C. Woodstock, IL: Solution Mining Research Institute. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Comparison of creep and creep models for rock salt creep data will be presented for four domal salts and one bedded salt. The measurements furnish credible upper and lower bound steady-state creep estimates. The upper and lower bounds were distinguished by the association of creep with normal and inverse transients. This new approach to the determination of steady-state creep rates of salt at low temperatures requires shorter test times than conventional methods. Possible errors in steady-state creep measurements using the old and new approaches will be demonstrated by a comparison of two relatively large data sets for bedded salt from the Salado Formation, New Mexico.

A credible model was obtained for cross slip with excellent agreement between the fitted activation energies and activation energies for cross slip in the literature. This conclusion is supported by activation analyses including some correlations between the effective activation energy and the stress exponent of a power law model, on one hand, and stress and temperature on the other. This conclusion is also consistent with some large power law stress exponents and with limited substructural observations that showed no subgrain development. No satisfactory fit would be obtained for a two-mechanism model for dislocation climb and cross slip, especially when the activation energies were constrained to known values. If cross slip can be proven to be the dominant creep mechanism, then a rationale would be available to extrapolate the existing steady-state creep measurements beyond the range of laboratory conditions of stress and temperature. Such extrapolations appear justified also by equivalent salt viscosities of the order 10^{19} poise or less that are predicted by the cross slip model for geologic stresses, $0.7 \leq T \leq 1.75$ MPa, and corresponding temperature $70 \leq T \leq 120^\circ\text{C}$.

Although the present data suggest that cross slip may be the rate controlling step during the low temperature creep of salt, there is good agreement between the cross slip and power law fits. Therefore, the power law fits appear to be good empirical approximations to the true creep processes despite the fact that the fitted power law creep parameters cannot be interpreted mechanistically.

Creep measurements on different salt yielded differences in steady state creep estimates between one and two orders of magnitude. The reasons for unusually low creep rates for salt from the Bryan Mound dome remain unknown.

Several chemical studies were inconclusive, while arguments concerning variations in initial subgrain sizes proved inadequate. Work on compositional and textural variations is continuing.

Wawersik, W.R., and C.M. Stone. 1986b. "Experience with Hydraulic Fracturing Tests for Stress Measurements in the WIPP," *Rock Mechanics: Key to Energy Production, Proceedings of the 27th US Symposium on Rock Mechanics, Tuscaloosa, AL, June 23-25, 1986*. Ed. H.L. Hartman. SAND85-2273C. Littleton, CO: Society of Mining Engineers, Inc. 940-947.

ABSTRACT: Hydraulic fracturing experiments were conducted in rock salt at 650 m depth in the Waste Isolation Pilot Plant to determine if virgin in situ stress at the site is isotropic and if the magnitude of such stresses corresponds to overburden weight. Horizontal drillholes, 10 cm in diameter, were drilled near the corner of an underground panel and tested at 11 locations from 23 to about 135 m from the nearest room.

The virgin in situ stress is isotropic and stress magnitude corresponds to overburden weight. Hydraulic fracturing in rock salt does not yield stress measurements directly, however, because creep influences test pressures. Fracture pressures and in situ stresses were correlated by finite element analyses and by observing hydraulic fracture patterns. Pressure-time records of rock salt differ in shape from records of hydraulic fractures in competent rock because of creep. "In particular, 1) stable pressure-time signatures with no distinct change from breakdown to driving pressures are obtained under isotropic far-field loading, 2) instantaneous shut-in pressures are likely to be obscured by fracture pinching, 3) pressure-time signatures will

change with delay time between drilling and hydraulic fracturing for approximately the first 50 days. After that time, a relatively long window appears to open up during which the predicted stress fields around the drillhole are approximately constant." DWP

Wawersik, W.R., and C.M. Stone. 1989. "A Characterization of Pressure Records in Inelastic Rock Demonstrated by Hydraulic Fracturing Measurements in Salt," *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, SAND87-2569J, Vol. 26, no. 6, 613-627.

ABSTRACT: The use of hydraulic fracturing in inelastic rock is described in terms of comprehensive hydraulic fracturing observations in rock salt in the Salado Formation in southeastern New Mexico. Inelastic rock behavior involves both rate-independent and rate-dependent permanent deformations. A combination of small-volume tests in initially open, horizontal drill holes, finite-element analyses, and in situ fracture observations demonstrate that the pressure-time data in inelastic rock can differ fundamentally from those typically recorded in competent hard rock. Stable pressure-time signatures with little or no pressure drop between peak and driving pressure are obtained in isotropic stress fields. Increasingly unstable records appear to be characteristic for anisotropic stress conditions. Qualitatively, the shapes of the pressure-time records of hydraulic fracturing tests in rock salt appear to be remarkably sensitive to the ratio of the in situ principal stresses normal to the fractures. Obtaining quantitative estimates of in situ stress magnitudes in rock salt and other highly inelastic rocks, however, hinges on the existence of reliable rate-dependent constitutive models in conjunction with relatively complex numerical analyses. Exaggerated contrasts in the greatest and the least in situ compressive stresses are inferred from applications of classical elasticity solutions. Time-dependent effects on the characteristic of hydraulic fracturing in rock salt and associated difficulties in data interpretations arise, even if hydraulic fracturing is performed almost immediately after drilling.

Wawersik, W.R., and D.H. Zeuch. 1986. "Modeling and Mechanistic Interpretation of Creep of Rock Salt Below 200°C," *Tectonophysics*, Vol. 121, 125-152.

ABSTRACT: Upper and lower bound estimates of the steady-state strain rates of rock salt from five locations are analyzed. The measurements were obtained in triaxial creep tests, including systematic changes in stress and temperature. The various data sets are correlated in activation analyses and fitted by models, and combinations of models, for power-law creep, cross-slip, and dislocation glide to show that a cross-slip model yields the best, mechanistically most credible fit. Good fits for cross-slip and high power-law stress exponents rule out the possibility that pressure solution affected the data in a major way to the lowest recorded strain rates of order 10^{-10} s^{-1} .

Wawersik, W.R., W. Herrmann, S.T. Montgomery, and H.S. Lauson. 1984. "Excavation Design in Rock Salt - Laboratory Experiments, Material Modeling and Validations," *ISRM Symposium on Rock Mechanics: Caverns and Pressure Shafts, Aachen, Germany, May 26-28, 1982*, Ed. W. Wittke, SAND81-1167C, Boston, MA: A.A. Balkema, 1345-1356.

ABSTRACT: A cycle of laboratory measurements, constitutive modeling and validation calculations are described as a basis for excavation design in rock salt. The results of triaxial creep tests were fitted by a creep model with exponentially decaying transients and power law thermally activated steady state creep which are functions only of deviatoric stress and temperature. The corresponding three-dimensional constitutive equation, including elastic

terms, is then applied in finite element simulations of the known closure of an isolated mine drift.

Wayland, J.R., and L.D. Bertholf. 1980. *A Comparison of Thermomechanical Calculations for Highly Non-Linear Quasistatic Drift Deformations*. SAND80-0149. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The results of code calculations for the November 14, 1979, Waste Isolation Pilot Plant (WIPP) Code Benchmark Workshop are compared. The results from five different codes (COUPLEFLO, JAC, SANCHO, SPECTROM, and STEALTH) are given for a problem involving the creep closure of an underground drift. The basic features of the codes are summarized, and the codes are evaluated in terms of their applicability to WIPP problems. The codes predicted essentially the same response for this problem, and they appear to be nearly equally applicable to problems of this type. Also, a new benchmark problem is suggested along with a more realistic creep model for bedded salt.

Weart, W.D. 1976. "New Mexico Waste Isolation Pilot Plant: A Status Report," *Proceedings of the Symposium on Waste Management, Tucson AZ, October 3-6, 1976*. Ed. R.G. Post. SAND76-5992; CONF-761020. Tucson, AZ: University of Arizona. 173-187.

ABSTRACT: More than twenty years of investigation on radioactive waste disposal in salt will be implemented in the development of a Waste Isolation Pilot Plant (WIPP) in southeast New Mexico. The WIPP will accommodate [Energy Research and Development Administration] ERDA-generated transuranic (TRU) and intermediate level (ILW) waste. The facility will also be used to conduct retrievable high-level (HLW) waste experiments. Site selection and WIPP conceptual design have been conducted with a view toward possible future utilization of the area by a HLW pilot plant.

Extensive site evaluations in an area of the Delaware Basin about 50 km east of Carlsbad, New Mexico, indicate the area is acceptable from the viewpoint of short-and long-term repository integrity. The magnitude of the potential conflict with potash and petroleum resources is now under evaluation. If this site is selected by ERDA, horizons at 640 and 800-m depth will be developed for the TRU and the ILW/HLW waste experiments, respectively.

Present schedules call for the start of construction in 1979 with first waste acceptance in 1983. A *Draft Environmental Impact Statement (DEIS)* for the WIPP is being prepared by Sandia and will be issued by ERDA in late 1977. Public information programs within the State of New Mexico and in the local area are being conducted by Sandia and ERDA project personnel and are considered to be an essential part of the WIPP Program.

Weart, W.D. 1977a. "Beneficial Uses and Disposal of Radioactive Wastes," *AEC Conference on Beneficial Uses of Radioactivity, Albuquerque, NM*. SAND77-0375. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Radioactive by-products of nuclear power generation and US Defense activities include materials that have, or may have, beneficial uses, as well as waste materials that must be isolated. Beneficial applications generally require separation of isotopes. Applications fall into three categories: radiation processes, heat sources, and miscellaneous. Radiation processes, commonly using ^{137}Cs , can be used to sterilize sewage or to reduce spoilage of food and disinfect seed foods. Heat sources from radioisotopes are useful for reliable long-term,

automatic operations such as space vehicles, unmanned weather stations, and cardiac pacemakers. Heaters for arctic regions have been developed. Miscellaneous applications include industrial radiography, well logging, tracers, and medical uses. Beneficial uses have not progressed rapidly because supplies are not readily available and future availability is uncertain.

Wastes are created at various stages of both commercial and defense programs. The Energy Research and Development Agency (ERDA) has separate programs for managing and disposing of these wastes in geologic formations. A repository site for defense waste is being investigated in southeastern New Mexico in salt beds more than 200 million years old. Geological, hydrological, and geophysical investigations show that the site meets selection criteria. An environmental impact statement is being prepared for public hearings. ERDA programs to develop a repository for commercial waste involve 36 states and are aimed at identifying 6 locations for possible repositories. The first 2 repositories for commercial radioactive waste are expected to be in rock salt. DWP

Weart, W.D. 1977b. *New Mexico Waste Isolation Pilot Plant Mid 1977 Status Report*. SAND77-0994. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: More than twenty years of investigation on radioactive waste disposal in salt will be implemented in the development of a Waste Isolation Pilot Plant (WIPP) in southeast New Mexico. The WIPP will accommodate [Energy Research and Development Administration] ERDA-generated transuranic (TRU) waste, both remote and contact handled. The facility will also be used to conduct retrievable, high-level waste (HLW) experiments. Site selection and WIPP conceptual design have been conducted with a view toward possible future utilization of the area by a HLW pilot plant.

Extensive site evaluations in an area of the Delaware Basin about 50 km east of Carlsbad, New Mexico, indicate the area is acceptable from the viewpoint of short- and long-term repository integrity. The magnitude of the potential conflict with potash and petroleum resources is now under evaluation. If this site is selected by ERDA, horizons at 640 and 800-m depth will be developed for the low-level contact waste and the remote handled higher level waste experiments, respectively.

Present schedules call for start of construction in 1979 with first waste acceptance in 1983. A *Draft Environmental Impact Statement (DEIS)* for the WIPP has been prepared by Sandia and will be issued by ERDA in late 1977. Public information programs within the state of New Mexico and in the local area are being conducted by Sandia and ERDA project personnel and are considered to be an essential part of the WIPP Program.

Weart, W.D. 1978. "Evaluation of Salt Beds in New Mexico as a Geologic Repository for Nuclear Waste," *Environmental Control Symposium*, Washington, DC, November 28-30, 1978. SAND78-2086. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Department of Energy (DOE) is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The WIPP will serve as a permanent repository for defense generated transuranic (TRU) contaminated waste and will also be used as a facility in which experiments and demonstrations with all radioactive waste types can be conducted. Rock salt has been the leading candidate for geologic disposal of nuclear waste since the National Academy of Science recommended, in 1957, that salt for repositories receive further evaluation. Subsequent studies have failed to reveal any phenomena which would disqualify

salt beds as a repository medium. The present area being proposed for the WIPP is the second such location in the Delaware Basin for which new site data have been developed; the first site proved geologically unacceptable. Ecologic and socioeconomic aspects have been investigated, and extensive geophysical, geologic, and hydrologic studies have been conducted to allow an evaluation of site acceptability. This paper will deal principally with the geotechnical aspects of site characterization. These studies are now sufficiently complete that the site can be recommended for further development of the WIPP.

Weart, W.D. 1979a. "WIPP: A Bedded Salt Repository for Defense Radioactive Waste in Southeastern New Mexico," *Radioactive Waste in Geologic Storage, Miami Beach, FL, September 11-15, 1978*. Ed. S. Fried. ACS Symposium Series No. 100; SAND78-0934C. Washington, DC: American Chemical Society. 13-36.

ABSTRACT: The Department of Energy (DOE) is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The WIPP will serve as a permanent repository for defense generated transuranic (TRU) contaminated waste and will also be used as a facility in which experiments and demonstrations with all radioactive waste types can be conducted. A conceptual design has been completed and an environmental report on actual and possible impacts will soon be released. There are many technical issues that must be pursued in connection with the WIPP. Many of these involve natural geologic and hydrologic phenomena. The introduction of radioactive wastes into this environment raises more issues that are being investigated in the laboratory and which, in many instances, must also be studied in situ. The WIPP will be an underground laboratory where large-scale experiments on thermal effects and waste/rock interactions will be examined. Some of these physical and chemical problems will be summarized in this paper.

Weart, W.D. 1979b. "Evaluation of the Proposed WIPP Site in Southeast New Mexico," *87th National Meeting, American Institute of Chemical Engineers, Boston, MA, August 19-22, 1979*. SAND79-1113. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Five years of earth science characterization of the proposed Waste Isolation Pilot Plant (WIPP) Site provide a high-level of assurance that the area is satisfactory for development of a geologic repository. Ecological investigations and socioeconomic studies have indicated only relatively benign impacts will occur from construction, operation, and long-term aspects of the repository.

Weart, W.D. 1979c. "Geotechnical Evaluation of the Proposed WIPP Site in Southeast New Mexico," *Waste Management 79, The State of Waste Disposal Technology and the Social and Political Implications, Proceedings of the Symposium on Waste Management, Tucson, AZ, February 26-March 1, 1979*. Ed. R.G. Post. SAND78-2194C. Tucson, AZ: University of Arizona. 217-239. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Department of Energy (DOE) is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The WIPP will serve as a permanent repository for defense generated transuranic (TRU) contaminated waste and will also be used as a facility in which experiments and demonstrations with all radioactive waste types can be conducted. The present area being proposed for the WIPP is the second such location in the Delaware Basin for

which new site data have been developed; the first site proved geologically unacceptable. Ecologic and socioeconomic aspects have been investigated, and extensive geophysical, geologic, and hydrologic studies have been conducted to allow an evaluation of site acceptability. This paper will deal principally with the geotechnical aspects of site characterization. These studies are now sufficiently complete that the site can be recommended for further development of the WIPP.

Weart, W.D. 1979d. "WIPP - A Repository for Defense Radioactive Waste in Southeastern New Mexico Salt Beds," *American Chemical Society Symposium, Richland, WA, June 14, 1979*, SAND79-1207, Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Department of Energy (DOE) is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The current mission proposed for the WIPP by the DOE is geologic isolation of defense transuranic (TRU) waste, experimental investigation of interactions between salt and various high-level waste (HLW) forms, and provision of an option for demonstrating isolation of a limited number (<1000) of spent fuel assemblies.

This latter option is presently opposed by the cognizant congressional committees and is under discussion between the DOE and Congress.

All wastes in WIPP will be retrievable for a period of time, 5 to 10 years for TRU waste and 15 to 20 years for spent fuel. The HLW for experiments will be retrieved upon conclusion of the associated experiments. The present schedule calls for start of construction in late 1981 and waste acceptance in 1986.

The TRU waste will be placed in rooms mined in salt at a depth of 2100 ft. These rooms will be several hundred ft long and have a nominal cross section 45 ft wide by 17 ft high. The remote-handled wastes will be placed into holes drilled into the floor of rooms mined in salt at a depth of 2600 ft. Most of the RH wastes will be placed in sleeved holes to assure easy retrievability.

Site selection for the WIPP was narrowed to the present Los Medaños area in December, 1975. Subsurface structure, hydrology, and dissolution have been evaluated using geophysical techniques (primarily seismic reflection and resistivity) and more than 55 bore holes. To date only one of these holes penetrates to the depth of the repository within the waste disposal zone.

The site investigations show that the desired depth, thickness, and lithology are present at the Los Medaños site. The structure and stratigraphy are acceptable. No unacceptable salt flow structures are known to be present in the WIPP Site and no Recent or Quaternary faults of tectonic origin have been identified closer than about 65 mi. The area is also relatively aseismic.

The hydrologic regime in the WIPP Site is favorable. The region is near a hydrologic divide so recharge to the aquifers over the site is low. The aquifers have relatively low transmissivities and flow velocities. Aquifers at the WIPP Site do not produce significant volumes of water, and that which is available is not potable.

Geologic studies indicate the regional dissolution front west of the site area is progressing eastward at a rate less than 6 to 8 mi/million years and is moving downward at a rate less than about 500 ft/million years. These conservatively determined values indicate the repository beds will not be breached by regional dissolution for many millions of years. Local dissolution features called collapse chimneys or breccia pipes are known to exist in portions of the basin

that have experienced extensive dissolution activity. Seismic and resistivity surveys can detect these features, but application of these techniques to the site area indicate an absence of breccia pipes. Studies are in progress to better understand the genesis of breccia pipes and to evaluate their physical properties.

Some potash and potentially some hydrocarbons exist within the buffer zones established for WIPP. The estimated amount of these resources within WIPP zone III, which might not be exploited if the WIPP is built, is 13.1 million tons of potash product (K_2O); 23.5 billion ft^3 of gas; and 42.5 thousand barrels of oil. These resource values are small compared to United States resources but may be considered as an enticement for future generations. Studies now underway may show that these resources can be developed without jeopardy to the repository and/or significant hazard to mankind.

One scenario, for example, assumes an open, unplugged bore hole penetrates through the TRU repository and connects aquifers above and below the salt. Using the hydrologic parameters experimentally established for the WIPP Site, the dissolution of salt by water flow in the bore hole and transport of the various radioisotopes through the aquifers has been calculated, and concentrations and/or possible body burdens of radioactivity determined. Using extremely conservative assumptions that the waste dissolves as rapidly as the salt and that the maximum permeability of the measured range of values exists throughout the site area, the transport of TRU isotopes through the Rustler aquifers to the exit point on the Pecos River, about 14 mi away, is such that it requires about 100,000 years for uranium isotopes to reach their maximum concentration. At this time, a hypothetical man who daily ingested the amount of radioactivity contained in 20 l. of Pecos River water would, over a 50-year lifespan, accumulate a whole-body dose less than the annual whole-body dose acquired in one year because of natural causes. There is negligible contribution to the radioactive burden from plutonium isotopes because of their high sorption and retardation in the aquifer system.

Thus, the data available to date indicate the WIPP Site satisfies all the desirable factors with the exception of some conflict with natural resources. While it is possible that future repository mining or improved understanding of geological processes could reveal aspects undesirable for a repository, these prospects are unlikely and a recommendation can now be made to proceed with the WIPP planning based on a site in the Los Medanos area of southeast New Mexico. A potential breach of the repository through penetration by human activity cannot be dismissed and is believed to be more likely to occur than natural failures of the geologic barriers. Calculations made to evaluate the consequences of such repository breaches indicate that the potential hazard to the general population because of human penetration of the repository in the future is very slight—less than that caused by naturally occurring radiation.

Weart, W.D. 1979e. "Status of the WIPP: A Bedded Salt Repository for Defense Radioactive Waste in Southeastern New Mexico," *1979 Fall Meeting, Rio Grande Chapter, Health Physics Society, Santa Fe, NM, October 18-19, 1979*. SAND79-1904. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The Department of Energy (DOE) is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The WIPP will serve as a permanent repository for defense generated transuranic (TRU) contaminated waste and will also be used as a facility in which experiments with high-level radioactive waste types can be conducted. A conceptual design and preliminary engineering have been completed, and a draft environmental report on actual and possible impacts has been released. There are many technical issues that must be pursued in connection with the WIPP. Many of these involve natural geologic and hydrologic phenomena. The introduction of radioactive wastes into this salt environment raises additional issues which are being investigated in the laboratory and that, in many instances, must also be

studied in situ. The WIPP will be an underground laboratory where large-scale experiments on thermal effects and waste/rock interactions will be examined. Some of these physical and chemical problems will be summarized in this presentation and the present status of the WIPP program will be discussed.

Weart, W.D. 1979f. "Status Report on the Waste Isolation Pilot Plant," *Transactions of the American Nuclear Society Annual Meeting, Atlanta, GA, June 3-8, 1979*. SAND79-0323A. La Grange Park, IL: American Nuclear Society. 367-368. (Published in summary form only).

ABSTRACT: The Department of Energy is proposing to demonstrate the acceptability of geologic disposal of radioactive waste by locating a Waste Isolation Pilot Plant (WIPP) in the salt beds 26 mi east of Carlsbad, NM. The current mission proposed for the WIPP is geologic isolation of defense transuranic (TRU) waste, experimental investigation of interactions between salt and various high-level waste forms, provision of an option for demonstrating isolation of a limited number (<1000) of spent fuel assemblies.

All wastes in WIPP will be retrievable for a period of time, 5 to 10 years for TRU waste and 15 to 20 years for spent fuel. The high-level waste for experiments will be retrieved upon conclusion of the associated experiments. The present schedule (which assumes NRC licensing) calls for start of construction in late 1981 and waste acceptance in 1986.

The TRU waste will be placed in rooms mined in salt at a depth of 2100 ft. These rooms will be several hundred ft long and have a cross-section 45 ft wide by 17 ft high. The remote-handled (RH) wastes will be placed into holes drilled into the floor of rooms mined in salt at a depth of 2600 ft. Most of the RH wastes will be placed in sleeved holes to assure easy retrievability.

Site selection for the WIPP was narrowed to the present Los Medaños, area in December 1975. Subsurface structure, hydrology, and dissolution have been evaluated using geophysical techniques (primarily seismic reflection and resistivity) and more than 55 boreholes. Only one of these holes penetrates to the depth of the repository within the waste disposal zone.

The site investigations show that the desired depth, thickness, and lithology are present at the Los Medaños site. The structure and stratigraphy are acceptable. No unacceptable salt flow structures are present in the WIPP Site, and no recent or Quaternary faults of tectonic origin have been identified closer than about 65 mi. The area is also relatively aseismic.

The hydrologic regime in the WIPP Site is favorable. The region is near a hydrologic divide, so recharge to the aquifers over the site is low. The aquifers have relatively low transmissivities and flow velocities. Aquifers at the WIPP Site do not produce significant volumes of water, and that which is available is not potable.

Geologic studies indicate the regional dissolution front west of the site area is progressing eastward at a rate of less than 6 to 8 miles per million years and is moving downward at a rate of less than about 500 ft (152.4 m)/million years. These conservatively determined values indicate the repository beds will not be breached by regional dissolution for many millions years. Local dissolution features, called collapse chimneys or breccia pipes, are known to exist in portions of the basin that have experienced extensive dissolution activity. Seismic and resistivity surveys can detect these features, but application of these techniques to the site area indicates an absence of breccia pipes. Studies are in progress to better understand the genesis of breccia pipes and to evaluate their physical properties.

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gas; and 42.5 thousand barrels of oil. These resource values are small compared to United States resources, but may be considered as an enticement for future generations. Studies now underway may show that these resources can be developed without jeopardy to the repository and/or significant hazard to mankind.

One scenario, for example, assumes that an open, unplugged borehole penetrates through the TRU repository and connects aquifers above and below the salt. Using the hydrologic parameters experimentally established for the WIPP Site, the dissolution of salt by water flow in the borehole and transport of the various radioisotopes through the aquifers have been calculated, and concentrations and/or possible body burdens of radioactivity determined. Using extremely conservative assumptions that the waste dissolves as rapidly as the salt and that the maximum permeability of the measured range of values exists throughout the site area, the transport of transuranic isotopes through the Rustler aquifers to the exit point on the Pecos River, about 14 miles away, is such that it requires about 100,000 years for uranium isotopes to reach their maximum concentration. At this time, a hypothetical man who daily ingested the amount of radioactivity contained in 20 liters of Pecos River water would, over a 50-year lifespan, accumulate a whole-body dose less than the annual whole-body dose acquired in 1 year because of natural causes. There is negligible contribution to the radioactive burden from plutonium isotopes because of their high sorption and retardation in the aquifer system.

Thus, the data available to date indicate the WIPP Site satisfies all the desirable factors with the exception of some conflict with natural resources. While it is possible that future repository mining or improved understanding of geologic processes could reveal aspects undesirable for a repository, these prospects are unlikely and a recommendation can now be made to proceed with the WIPP planning based on a site in the Los Medaños area of southeast New Mexico. A potential breach of the repository through penetration by human activity cannot be dismissed and is believed to be more likely to occur than natural failures of the geologic barriers. Calculations made to evaluate the consequences of such repository breaches indicate that the potential hazard to the general population due to human penetration of the repository in the future is very slight, less than that due to naturally occurring radiation.

Weart, W.D. 1980a. "Status of the Waste Isolation Pilot Plant Project," *American Institute of Mining Engineers Meeting, Carlsbad Potash Section, Carlsbad, NM, January 22, 1980*. SAND80-0134. Albuquerque, NM: Sandia National Laboratories. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The technical investigations in support of the Waste Isolation Pilot Plant (WIPP) have not identified any geologic or environmental issues that would rule out safe development of the WIPP. The socioeconomic impacts, while subject to individual interpretation, would not place undue strain on the capacity of the cities of Carlsbad and Hobbs to support the project activities. The future of the WIPP and its role within the nation's waste management program has been debated at length within Congress, the Administration, and with the State of New Mexico. The present status of the WIPP mission will be discussed.

Weart, W.D. 1980b. "Technical Issues in the Geologic Disposal of Radioactive Wastes," *Institute of Environmental Sciences 1980 Proceedings, 26th Annual Technical Meeting, Life Cycle Problems and Environmental Technology, Philadelphia, PA, May 12-14, 1980*. SAND80-0323C. Mt. Prospect, IL: Institute of Environmental Sciences. 439-443. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Although underground disposal in geologic formations is the most likely solution to the problem of radioactive waste, several technical issues are still being addressed. Geologic

problems include: 1) obtaining information to determine if site characteristics are suitable, and 2) understanding processes well enough to determine if unacceptable events are likely to occur in the near geologic future. The first problem is generally overcome with current technology, given sufficient time and money. The second problem is more difficult, as the isolation period required is not agreed upon and confidence in predictions is varied and decreases with the length of the isolation period. Conservative standards about the effects of and likelihood of processes may be adopted to help deal with this problem. Other technical concerns relate to the phenomena associated with placing waste in a repository. Interactions between host rock and waste will depend on the materials involved, including the waste form, canister materials and stability, backfill, and the thermal-structural behavior of the rocks and waste under the stresses of heat and radiation. The waste form and canister materials may be effective as part of the system of barriers to radionuclide migration. Brine migration is an issue only for salt repositories, while creep deformation of the host rock is of concern for both salt and shale. Mechanical behavior of surrounding rocks will be of concern in all repositories. Borehole/shaft plugging and sealing will be of concern for all repositories, and safety assessment will be required to establish confidence in long-term isolation.

Salt repository knowledge is more advanced, and knowledge of other rock types is improving rapidly. It is possible to proceed now, with sufficient confidence, to develop a bedded salt repository. Extensive in situ testing in salt and other rock types will be necessary to resolve the general issues facing specific rock types as well as all geologic repositories.

DWP

Weart, W.D. 1981. "Technical Developments in the WIPP Program," *Bulletin of the Association of Engineering Geologists*. SAND80-1599C. Vol. 18, no. 4, 423-436.

ABSTRACT: More than five years of site specific studies have led to the conclusion that radioactive wastes can be safely isolated in the bedded salt of the Delaware Basin in southeast New Mexico. Aspects of particular concern for site integrity, such as regional or local dissolution processes and salt deformation, have been thoroughly evaluated and are not believed to present hazards to the repository. Hydrology of the site area has been shown to possess many desirable features with respect to transport of radioisotopes to the biosphere in the event of a repository breach. Natural resources, potash, and hydrocarbons, are present in the area of the site, but can be exploited with appropriate precautions. Safety analyses have considered the consequences of their possible attraction to future man. Repository behavior and interactions between waste and the host rock have been studied in the laboratory, in field tests, and by calculational methods. In particular, such issues as brine migration and canister corrosion may be shown to have little detrimental impact if modest and practical engineering measures are adopted. Calculated salt deformation and room closure rates indicate that a salt repository must be carefully designed in order to assure ready retrieval of emplaced waste over long periods of time. Safety assessment calculations, performed to determine the consequences of assumed repository failure scenarios, showed that even the most dire credible (but improbable) natural failure scenarios are benign in their consequences to man. Direct penetration by unknowing, future man could result in significant exposures to the specific individuals involved but would not cause significant population effects.

Weart, W.D. 1982. "Geophysical Applications to Characterization of the Waste Isolation Pilot Plant (WIPP) Site," *EOS Transactions, American Geophysical Union*. SAND82-2123A. Vol. 63, no. 45, 1101-1102. (Abstract Only).

ABSTRACT: Since 1974, the northern Delaware Basin in New Mexico has been the focus of intensive geotechnical investigations to locate and characterize the Waste Isolation Pilot Plant (WIPP) Site. The WIPP is the Department of Energy's (DOE's) geologic facility that will

demonstrate the safe disposal of defense transuranic (TRU) wastes and enable conduct of in situ research on questions related to disposal of defense high-level waste (DHLW) in salt.

Geophysical investigations were applied initially to reconnaissance mapping of subsurface structure and subsequently to investigate areas and aspects of particular concern. Seismic reflection and precision gravity surveys have proven particularly useful in mapping subsurface structures in the site area. Electrical resistivity surveys have been utilized to search for local and regional dissolution features at the top of the evaporite sequence. Magnetic surveys have less general mapping value but were useful in ruling out certain geologic and man-made features. Recent application of electromagnetic techniques to delineate "brine reservoirs" within the evaporites has been conducted. Radar has been used underground to detect the location of fluid pockets and other discontinuities in the salt as an aid to mining operations. Geophysical well logs are very useful in correlation of stratigraphy among more than 100 bore holes in the immediate site vicinity.

Weart, W.D. 1983a. "WIPP: The Solution to Disposal of Defense Transuranic Waste," *Transactions of the American Nuclear Society, Detroit, MI, June 12-16, 1983*. SAND83-0062A. La Grange Park, IL: American Nuclear Society. Vol. 44, 182-183. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) was authorized by Congress in 1980 after more than five years of site evaluation and environmental studies culminated in a *Final Environmental Impact Statement*. The WIPP will provide an unlicensed research and development (R&D) facility to demonstrate the safe disposal of radioactive wastes arising from the defense activities and programs of the United States. It is being constructed in southeast New Mexico utilizing salt beds ~2150 ft below the surface of the ground. WIPP construction is separated into two phases. The first phase, the Site and Preliminary Design Validation (SPDV), was recently completed. This phase began with drilling of a 12-ft diameter shaft in June 1981. The SPDV now consists of a second, 6-ft diameter, unlined ventilation shaft, exploratory drifts extending 5100 ft in length, and typical transuranic (TRU) waste rooms. This mining, about 170,000 tons, will be completed in the summer of 1983, and no detrimental conditions were observed. The second phase, construction of the full WIPP facility, will commence in September 1983 with the mining of a third shaft after the state of New Mexico has reviewed the results of the SPDV Program. The full WIPP facility will occupy 160 underground acres and will involve excavation of 1.5 million tons of salt. The surface facility will occupy 27 acres plus an additional 10 acres for salt tailings. Mining will be done by continuous miners and salt tails will be transported by rubber-tired diesel trucks. Contact TRU waste will be stacked in rooms 13 x 33 x 300 ft. The remote-handled (RH) TRU waste will be placed in horizontal holes drilled into the sides of the rooms. Storage and mining will occur on separate shifts, permitting a 500,000 ft³ annual capacity. The construction phase will be complete in June 1988, with first receipt of TRU waste in April 1989.

The geotechnical investigations of the WIPP Site have now been essentially completed. Aspects that received much discussions over the past several years were local and regional dissolution of salt, deformation within evaporites in the Northern Delaware Basin, adequacy of hydrologic modeling, significance of brine reservoirs in the Castile anhydrites, and the presence of hydrocarbons and natural gas resources at and near the WIPP Site. These issues have been addressed in topical reports, with the conclusion that a threat to site integrity is very unlikely. While breach of the facility by natural geologic processes over the required lifetime of the facility is not considered realistic, breach by action of man (i.e., drilling deep holes), though prevented in the near term (a few hundred years) by administrative controls, cannot be ruled out in the more distant future. Safety analyses show that such failure scenarios have benign consequences and should not represent a significant concern even if such breaches occur.

The WIPP research and development (R&D) activities, which address the concerns presented by both TRU waste and defense high-level waste (DHLW) disposal stages, are being pursued in three stages. The first stage, now nearly complete, includes the modeling and laboratory studies of salt and the possible interactions of the waste package with a salt medium. These studies also include small-scale, nonradioactive tests in existing salt and potash mines. These investigations have provided a high degree of confidence in geologic disposal of TRU waste and DHLW in bedded salt. Such issues as brine migration and salt creep do not appear to pose significant problems in a properly designed repository. Practical waste packages can be designed to provide assured containment for DHLW for several hundred to a thousand years should that be required.

The second stage of the R&D Program will involve large, full-scale operations demonstrations and in situ, nonradioactive experiments in the WIPP Facility. Implementation of this phase will begin in the late summer of 1983, with the excavation of an experimental test area and installation of instrumentation to monitor rock mechanics parameters in the salt surrounding the drifts. Studies will address the thermal/structural interactions that occur, not only in the WIPP, but in a possible future salt repository for DHLW. Electric heaters will be used to simulate thermal loadings of 12 W/m², a likely repository design. Overtests at higher temperatures will be used to accelerate a range of rock mechanics behavior, such as room and hole closure and backfill consolidation. Modeling and prediction of phenomena have been done to guide experiment design, and more definitive calculations will occur prior to testing in order to acquire confidence in the applicability of the models. Waste package performance and near-field effects comprise another category of investigation. Canister corrosion and backfill behavior will be examined, and brine migration models will be validated under actual repository conditions. The third stage of the WIPP R&D Program, starting in 1989, will be to confirm our existing knowledge when actual radioactive sources are used to approximate repository conditions. These tests will involve mostly waste package and near-field performance.

The WIPP is an unlicensed facility but it must, however, meet US Environmental Protection Agency (EPA) standards and has fulfilled the requirements of the National Environmental Policy Act. The state of New Mexico and the US Department of Energy (DOE), on July 2, 1982, entered into an *Agreement for Consultation and Cooperation Between Department of Energy and the State of New Mexico on the Waste Isolation Pilot Plant* that formally provides the state an opportunity to review and comment on the WIPP Program at key milestone points. The agreement has also resulted in resolution of many issues of interests to the state. Prior to this consultation and cooperation (C&C) agreement, the state of New Mexico conducted technical oversight and review, started in 1974 with an ad hoc part-time review committee. In July 1978, the DOE agreed to fund a full-time technical state group to review the WIPP in matters related to public safety. This has proved to be a valuable mechanism to the State in establishing their own confidence in WIPP safety in the absence of US Nuclear Regulatory Commission review.

Weart, W.D. 1983b. "Conclusions Regarding Geotechnical Acceptability of the WIPP Site," *Waste Management 83, Waste Isolation in the US, Technical Programs and Public Education, Tucson, AZ, February 27-March 3, 1983*. Ed. R.G. Post. SAND83-0226C. Tucson, AZ: University of Arizona. Vol. 2, 373-376.

ABSTRACT: Site evaluation studies for the Waste Isolation Pilot Plant (WIPP) are essentially complete. These studies have made extensive use of existing data, geologic mapping, exploration geophysics, and bore holes. The issues that have been most contentious and that have now been thoroughly investigated are salt dissolution, deformation of the Castile salt beds and associated phenomena (i.e., brine reservoirs), definition of the hydrologic regime, and the potential conflict with natural resources. The first two phenomena have been shown not to present a significant threat to the WIPP during its required lifetime. The hydrologic regime

has been adequately characterized, and it is very favorable with respect to its role in possible breach scenarios. There is a potential for natural resources at the WIPP Site, but all promising resources can be exploited without jeopardy to the WIPP. Future breaches by human activity cannot be ruled out but consequences of such activities are relatively benign.

Weart, W.D. 1983c. *Summary Evaluation of the Waste Isolation Pilot Plant (WIPP) Site Suitability*. SAND83-0450. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Geotechnical studies oriented toward selecting a radioactive waste disposal site began in southeast New Mexico in 1972. These geological studies have focused on the present Waste Isolation Pilot Plant (WIPP) Site since November 1975 and have been accompanied by investigations of the ecologic and socioeconomic environment. Surface-based geotechnical investigations have relied heavily on geologic mapping, on geophysical exploration techniques, and on drill holes for confirmation of interpretation, core examination, and acquisition of hydrologic parameters. These studies have now been supplemented by direct examination and measurement of the subsurface geology in two shafts and in several thousand feet of mined drift at the depth selected for the WIPP. Additional studies are not likely to change significantly the level of confidence that now exists with regard to the suitability of the WIPP Site. Consequently, Sandia National Laboratories (SNL) has now evaluated the information available on the WIPP Site and, in this report, summarizes the information and judgments reached for each of the 21 site qualification criteria. The site satisfies the intent of all the site criteria. SNL recommends, without reservation, the use of the Los Medaños site for the WIPP.

Weart, W.D. 1986. "Status of the WIPP - A Defense Transuranic Waste Isolation Facility," *Proceedings of the Twenty-First Annual Meeting of the National Council on Radiation Protection and Measurements, Washington, DC, April 3, 1985*. SAND85-0736J. Bethesda, MD: National Council on Radiation Protection and Measurements. 94-121.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is being constructed in bedded salt deposits east of Carlsbad, NM, as a research facility to develop and demonstrate safe disposal of radioactive waste. The WIPP is expected to become operational in October 1988 with the first receipt of radioactive waste.

Site evaluation studies are generally complete. Broader issues examined include dissolution of salt, deformation, hydrology, and natural resources. Though dissolution has occurred in the Delaware Basin, regional and local dissolution are no threat to the integrity of the WIPP over the next 10,000 years. Evaporite deformation and related pressurized brine reservoirs in the northern Delaware Basin do not appear to pose a natural threat to the WIPP; the consequences of a scenario connecting the repository to a brine reservoir are also relatively benign. The general hydrologic conditions of fluid-bearing units above and below the repository indicate lengthy transit times to areas of normal human access. Karst has been proposed to affect the hydrology of the Rustler Formation and continues to be investigated, though it is not found at the site and appears to have relatively benign consequences. The WIPP Site has both potash and hydrocarbon potential within its boundaries. Both resources may potentially be extracted without effect on the WIPP, given current technology. The consequences of other exploration or development of resources, perhaps after the WIPP has been "forgotten," have been examined and are believed not to be significant.

In situ tests continue in four general areas: thermal-structural interaction experiments, waste package interactions, plugging, and sealing. In addition to several experiments to obtain information about the deformation of salt when heated, hydrofracture experiments have been conducted which found information that the in situ stress is nearly lithostatic and isotropic away from room excavations. Waste package interaction tests with simulated defense high-

level waste packages use heaters and nonradioactive glass. If salt temperatures are kept at less than 100°C around actual waste, brine is not expected to migrate. The plugging and sealing experiments test the effectiveness of engineered barriers and will also quantify salt bed permeability. Changes in permeability will be measured as backfill is compressed by accelerated closure of the overtest room.

The WIPP is far along in construction and provides a test facility for concepts derived from laboratory experiments. Experiments with simulated and actual defense high-level waste should demonstrate that salt beds can be used to isolate such waste. In October 1988, the WIPP is expected to begin receiving defense transuranic waste, "...finally closing the last link in the waste management chain governing this category of waste." DWP

Weart, W.D. 1989. "Status and Future Prospects for the Waste Isolation Pilot Plant," *Nuclear Materials Management, 30th Annual Meeting Proceedings, Orlando, FL, July 9-12, 1989*. SAND89-0760. Northbrook, IL: Institute of Nuclear Materials Management. 640. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) in southeast New Mexico has been constructed and is physically ready to receive transuranic (TRU) wastes generated by Department of Energy (DOE) defense programs. But before radioactive wastes can be received at WIPP, the site land must be withdrawn from public domain, either by legislative action or administrative withdrawal; the waste transporter TRUPACT must be certified by the NRC; the WIPP plan for activities leading to determination of compliance with the Environmental Protection Agency (EPA) standard for geologic disposal must be reviewed by the State of New Mexico and the National Academy of Science; and the EPA/New Mexico mixed waste regulations must be satisfactorily addressed. The DOE anticipates these hurdles will be surmounted and that a *Supplemental Environmental Impact Statement (SEIS)* will be issued in time to allow the WIPP to receive waste in September 1989.

Technical and engineering issues that are now being addressed relate to seal design for the repository, the brine seepage from the salt, gas generation from the waste, the radioactive source term, and the ultimate state of the waste rooms after salt creep consolidation. The efficacy of engineered modifications is also being examined in the experimental program. Results of these and earlier studies will be incorporated into performance assessment of the WIPP in order to determine compliance with the EPA standard for geologic disposal before the end of 1994. All these issues will be discussed in this presentation.

Weart, W.D., and D.W. Powers. 1980. "Geologic Issues for the Waste Isolation Pilot Plant (WIPP)," *Abstracts with Programs, Geological Society of America, 1980 Annual Meeting, Atlanta, GA, November 17-20, 1980*. SAND80-1269C. Vol. 12, no. 7, 546. (Abstract Only).

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) has been pursued for disposal of defense radioactive waste in bedded salt of the Salado Formation about 30 mi east of Carlsbad, NM.

Two recurring issues which have broader implications than for the WIPP are dissolution and natural resources. Any repository in salt or other somewhat soluble rock will be scrutinized for effects on a repository. Natural resources are an issue because of their intrinsic value and because of their potential attraction for exploration. This aspect is addressed by consequence assessment.

Dissolution in the Delaware Basin occurs as a wedge at the top of and low in the evaporites and also as point source exemplified by features commonly called "breccia pipes." Dissolution of salt at the WIPP Site occurs mainly in the Rustler Formation; some dissolution has occurred at the Rustler/Salado contact on the western side of the site. The Rustler thins as much as 150

ft across the site. The overlying Mescalero caliche does not reflect Rustler thinning and indicates dissolution is not now occurring at the site.

Dissolution of the lower evaporites is not known at the site though it occurs elsewhere in the basin. Several geophysical anomalies at the site have been investigated by drilling and are not breccia pipes. A recent hypothesis of origin restricts their occurrence to the basin margin; we are drilling these features to elucidate their genesis.

Wells, J.G., and S.L. Drellack, Jr. 1982. *Geologic and Well-Construction Data for the H-8 Borehole Complex Near the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Water-Resources Investigations 82-4118. Albuquerque, NM: US Geological Survey. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The H-8 bore hole complex, a group of three closely spaced bore holes, is located 9 mi south of the proposed Waste Isolation Pilot Plant (WIPP) Site in southeastern Eddy County, New Mexico. The holes were drilled during July, August, and September 1979 to obtain geologic and hydrologic data to better define the regional groundwater-flow system. The geologic data presented in this report are part of a site characterization study for the possible disposal of defense-associated radioactive wastes within salt beds of the Salado Formation of Permian age. The geologic data include detailed descriptions of cores, cuttings, and geophysical logs.

Each bore hole was designed to penetrate a distinct water-bearing zone: H-8a (total depth 505 ft) was completed just below the Magenta Dolomite Member of the Rustler Formation of Permian age; H-8b (total depth 624 ft) was completed just below the Culebra Dolomite Member of the Rustler Formation; and H-8c (total depth 808 ft) was completed just below the Rustler Formation-Salado Formation contact. The geologic units penetrated in borehole H-8c are surficial alluvium and eolian sand of Holocene age (0-4 ft); the Mescalero caliche (4-10 ft) and Gatuña Formation (10-153 ft), both of Pleistocene age; and the Dewey Lake Red Beds (153-399 ft), the Rustler Formation (399-733 ft), and part of the Salado Formation (733-808 ft), all of Permian age. The upper 41 ft of the Salado Formation penetrated by borehole H-8c is composed of residue from dissolution of halite and associated rocks and the hydration of anhydrite to gypsum, indicating that the eastward-moving dissolution on top of the Salado, found west of the WIPP Site, has reached the H-8 site.

Wells, J.G., and S.L. Drellack, Jr. 1983. *Geologic and Well-Construction Data for the H-10 Borehole Complex Near the Proposed Waste Isolation Pilot Plant Site, Southeastern New Mexico.* Water-Resources Investigations Report 83-4124. Albuquerque, NM: US Geological Survey. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The H-10 bore hole complex, a group of three closely spaced bore holes, is located 4 mi southeast of the proposed Waste Isolation Pilot Plant (WIPP) Site in west-central Lea County, New Mexico. The holes were drilled during August and October 1979 to obtain geologic and hydrologic data to better define the regional groundwater-flow system. The geologic data presented in this report are part of a site characterization study for the possible disposal of defense-associated radioactive wastes within the salt beds of the Salado Formation of Permian age. The geologic data include detailed descriptions of cores, cuttings, and geophysical logs.

Each bore hole was designed to penetrate a distinct water bearing zone: H-10a (total depth 1318 ft) was completed just below the Magenta Dolomite Member of the Rustler Formation of

Permian age; H-10b (total depth 1398 ft) was completed just below the Culebra Dolomite Member of the Rustler Formation; and H-10c (total depth 1538 ft) was completed below the Rustler Formation/Salado Formation contact. The geologic units penetrated in borehole H-10c are surficial alluvium and eolian sand of Holocene age (0-5 ft); the Mescalero caliche (5-9 ft) and the Gatuña Formation (9-90 ft) of Pleistocene age; formations in the Dockum Group (Chinle (?) Formation, 90-482 ft and Santa Rosa Sandstone, 482-658 ft) of Late Triassic age; and the Dewey Lake Red Beds (658-1204 ft), the Rustler Formation (1204-1501 ft), and part of the Salado Formation (1501-1538 ft), all of Permian age. The sections of the Rustler and Salado Formations penetrated by borehole H-10c are complete and contain little or no evidence of dissolution of halite and associated rocks, indicating that the eastward-moving dissolution within the Rustler or on top of the Salado, found west of the WIPP Site, has not reached the H-10 site.

Westinghouse Electric Corporation. 1988. *Geotechnical Field Data and Analysis Report, July 1986-June 1987*. DOE/WIPP 87-017. Carlsbad, NM: Westinghouse Electric Corporation. Vols. 1-2.

ABSTRACT: "Shaft convergence, liner and key stresses, and piezometric data confirmed that the three shafts and associated keys were performing in accordance with the pertinent design criteria." Average fluid inflow through the lined section in the waste handling shaft averaged about 0.2 gallons/minute during the reporting period. Inflow in the lined part of the exhaust shaft is observable but not measurable. Stations for both the construction and salt-handling and waste-handling shafts show fracturing and excess creep requiring enlarging and modifying the shaft station areas. Access drifts meet design criteria, with one exception. The principal waste haulageway will require enlarging and periodic trimming. Opening maintenance, including rock bolting, increased considerably during this reporting period and should be expected to increase further as new facilities are excavated and existing facilities become older.

Test rooms show gradually decreasing displacement with time, possibly approaching a "steady-state" rate. Vertical closure rates in test rooms ranged from 2.18 to 2.85 inches/year while horizontal closure rates ranged from 1.27 to 1.74 inches/year. The average vertical-to-horizontal closure ratio is 1.65. Fracturing has also developed around test rooms.

Excavation for waste storage areas began during the reporting period. Permeability and geomechanical testing for waste storage areas are insufficient to date to evaluate.

Displacements in boreholes, minor spalling, and vertical displacements show that changes continue and maintenance will be required; "...there is no evidence at this time that the long-term stability of these areas is compromised."

Three gas occurrences were observed in the first waste storage panel. Brine occurrences continue to be documented and monitored, though none of the gas or brine occurrences adversely affect development or operations. Advance drillholes allow safe development. DWP

Westinghouse Electric Corporation. 1989. *Geotechnical Field Data and Analysis Report, July 1987-June 1988*. DOE/WIPP 89-009, Carlsbad, NM: Westinghouse Electric Corporation. Vols. 1-2.

ABSTRACT: The *Geotechnical Field Data and Analysis Report* provides a timely assessment and formal documentation of the Waste Isolation Pilot Plant (WIPP) geotechnical status, additional information for design evaluation, guidance for design modifications and remedial actions, and geotechnical data to assess the performance of underground openings in salt rocks. The two volumes provide a summary/evaluation and documentation/data.

Data continue to confirm that the three shafts and keys are performing in accordance with design criteria. Stations at the construction and salt-handling (C&SH) and waste handling shafts were enlarged; the work destroyed most of the geomechanical locations, which will be replaced as appropriate after construction. Access drifts continue to meet design criteria, with openings maintenance increasing as the facility ages. Test rooms show steady or increased displacement during this reporting period. Data from the previous period suggested displacements were approaching a "steady state." The first waste storage panel was completed, though long-term structural performance cannot yet be predicted. Mapping confirms the stratigraphy in the vicinity of the first storage panels, with units locally showing evidence of syndepositional dissolution and reprecipitation of halite from channel cutting of subaerial mud flats. Observation boreholes showing normal displacements increased during the year, as fractures in boreholes and exposed surfaces continued. DWP

Westinghouse Electric Corporation. 1990a. *Waste Isolation Pilot Plant No-Migration Variance Petition*. DOE/WIPP 89-003, Revision 1. Carlsbad, NM: Westinghouse Electric Corporation, Waste Isolation Division.

ABSTRACT: Stringent new laws enacted by Congress in 1984 prohibit land disposal of hazardous wastes unless certain standards are met (e.g., concentrations or treatment by a requires method approved by the Environmental Protection Agency [EPA]). The EPA determined in 1986 that hazardous waste components of radioactive waste are also subject to the regulation. An EPA approved variance or exemption may be obtained if it can be demonstrated with reasonable certainty that hazardous constituents will not migrate from the site as long as the waste remains hazardous. The EPA relies on health-based standards, as well as other stringent criteria, to evaluate petitions for variance or exemption.

Only transuranic (TRU) wastes from defense programs will be accepted at the Waste Isolation Pilot Plant (WIPP). However, this waste is also contaminated with regulated hazardous waste including toxic metals, halogenated organic compounds, and nonhalogenated compounds.

To obtain a variance, the petition includes information in five categories: waste information, site characterization, facility information, environmental impacts, including modeling of waste mobility, and analysis of uncertainties. Information is presented in the main body of the petition and appendices, and an extensive addendum was published in October 1989 with a revision date of March 1990.

"The WIPP Facility relies on both the inherent characteristics of the salt in which the repository is constructed and engineered barriers, such as backfill and seals, to permanently isolate the wastes that will be emplaced, as well as operational procedures that protect workers and the public during waste emplacement activities. The Department of Energy (DOE) believes that the *Waste Isolation Pilot Plant No-Migration Variance Petition* demonstrates, to the necessary degree of certainty, that there will be no releases of hazardous constituents from the WIPP Facility." DWP

Westinghouse Electric Corporation. 1990b. *Geotechnical Field Data and Analysis Report, July 1988-June 1989*. DOE/WIPP 90-006. Carlsbad, NM: Westinghouse Electric Corporation. Vols. 1-2. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Geotechnical Field Data and Analysis Report* documents the geomechanical data collected at the Waste Isolation Pilot Plant (WIPP) up to June 30, 1989 and describes the conditions of underground openings from July 1, 1988 to June 30, 1989. The data are

required to understand performance during operations and do not include data to support performance assessment.

The underground openings have performed satisfactorily during the reporting period. This analysis is based primarily on the instrumental data, in particular the measured convergence compared to predictions, and the observations of exposed rock surfaces. The main concerns during this period have been the deterioration found in site and preliminary design validation (SPDV) test rooms 1 and 2 and some spalling found in panel 1.

Ground conditions in the facility were maintained by routine scaling and rock bolting. In panel 1, "drummy" areas of the roofs, floors, and walls of the rooms were scaled or supported, where necessary, with rock bolts as part of normal activities.

Convergence data from throughout the underground indicate that the only locations in which measured closure rates consistently exceed predictions are in the SPDV test rooms 1 and 2. These rooms are among the largest and oldest WIPP excavations and are about 7 years old (as of June 30, 1989). Aging of the excavations is accompanied by increased closure rates in some parts of the rooms and the development of fractures in the roof, floor, and ribs. Fracture mapping and instrumental data have allowed conditions to be assured on a timely basis, and appropriate action to be taken. Based on the conditions that had developed, access into these test rooms was restricted in May 1989. DWP

Westinghouse Electric Corporation, 1990c. *Final Safety Analysis Report, Waste Isolation Pilot Plant, Carlsbad, New Mexico*. WP 02-9, Rev. 0. Carlsbad, NM: Westinghouse Electric Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: The *Final Safety Analysis Report (FSAR)* has been prepared "...to document that a systematic analysis of the potential hazards associated with operating the WIPP facility has been performed, that potential consequences have been analyzed, and that reasonable measures have been taken to control or mitigate the hazards. Specific potential hazards that were analyzed include credible natural hazards such as flood, weather (tornado, wind, etc.) and earthquake; and credible manmade hazards such as fire, explosion, radiation, and mining hazards. Mitigating measures include facility design and construction, operational controls, and administrative limits." The *FSAR* has also been prepared to meet part of the requirements of the Consultation and Cooperation Agreement between the Department of Energy (DOE) and the State of New Mexico; it is the most comprehensive document concerning the Waste Isolation Pilot Plant (WIPP) in general as related to public health and safety.

Though the WIPP is not required to prepare a safety analysis report, the *FSAR* was considered appropriate because the WIPP is a first-of-a-kind facility justifying a conservative approach and because agreements with the state require "final facility amendments" to the *SAR* to be published.

The design basis for WIPP is a 25-year operating life with a 5-year test phase. The WIPP will be converted to a permanent repository for transuranic (TRU) wastes after demonstrating the facility can meet standards in 40 CFR Part 191. TRU waste placed in the WIPP during the test phase will be readily retrievable.

Performance assessment methodology is described in the *FSAR*, but the long-term performance of the facility is not revised for this document. This activity is carried out separately through a performance assessment program.

"This *FSAR* represents a statement and commitment by the DOE that the WIPP facility can be operated safely and at minimum risk, if operated in accordance with this *FSAR*.

Consequently, this *FSAR* has been prepared to document that systematic analysis of the potential hazards associated with operating the WIPP facility has been performed...; that potential consequences have been analyzed...; and that reasonable measures have been taken to eliminate, control, or mitigate the hazards... In addition, this *FSAR* documents the implementation of commitments made in the environmental impact statement regarding the mitigation of adverse impacts to the environment..."

The *FSAR* consists of 3 volumes with 12 chapters and a glossary of terms.

DWP

Wicks, G.G., and M.A. Molecke. 1988. "WIPP/SRI. In Situ Testing Program: MIT Update 1988," *Waste Management 88, Waste Processing, Transportation, Storage and Disposal, Technical Programs and Public Education, Tucson, AZ, February 28-March 3, 1988*, Ed. R.G. Post. SAND87-2654C. Tucson, AZ: University of Arizona. Vol. 2, 383-392.

ABSTRACT: The first series of in situ, high-level waste form leaching tests to be conducted in the United States was started on July 22, 1986. This effort, the Waste Isolation Pilot Plant (WIPP) Materials Interface Interactions Tests (MIT), involves the underground test emplacement of almost 1900 (nonradioactive) waste form, metals container, and geologic samples in the bedded salt at the Waste Isolation Pilot Plant (WIPP) Facility, near Carlsbad, NM. Samples were supplied from seven countries and are being analyzed by laboratories and universities in the United States, Canada, France, Germany, Belgium, Japan, the United Kingdom, and Sweden. Post-test analyses of samples removed after 0.5 and 1 year of testing are in progress. The MIT data complement other laboratory and international in situ efforts involving underground field testing of Savannah River Laboratory simulated nuclear waste glasses. The MIT international program is a joint effort conducted and managed by Sandia National Laboratories (SNL) and Savannah River Laboratory at the WIPP and is sponsored by the US Department of Energy (DOE).

Wicks, G.G., and M.A. Molecke. 1989. "WIPP/SRI. International In Situ Testing Program—MIT," *Testing of High Level Waste Forms Under Repository Conditions, Cardache, France, October 17-21, 1988*, Ed. T. McMenamin. SAND88-2838C; EUR 12017. Luxembourg: Commission of the European Communities. 49-66.

ABSTRACT: On July 22, 1986, the largest and most cooperative international effort directed at in situ testing of simulated nuclear waste glasses was officially begun. This program, called the Materials Interface Interactions Tests (MIT), involves the underground emplacement of almost 2000 simulated high-level waste samples, package components, and geologic samples in the bedded salt site at the Waste Isolation Pilot Plant (WIPP), near Carlsbad, NM. Samples were supplied by researchers in the United States, France, Germany, Canada, Belgium, Japan, and the United Kingdom. Data and sample performance are being assessed and analyzed by laboratories and universities in each of the participating countries and additional nations. Samples have been retrieved after 0.5, 1, and 2 years of burial with only the 5-year samples still in test. There are hundreds of samples available for study, and many analyses are currently in progress. At present, even though only a small portion of all the data available has been obtained and analyzed, important effects and trends are already emerging. An overview of the MIT program will be presented along with a summary of preliminary findings on performance of Savannah River waste glass in the WIPP MIT.

Widdicombe, R.E. 1979. *Quaternary Surficial Features in the Delaware Basin, Eddy and Lea Counties, New Mexico*. MS thesis. Albuquerque, NM: University of New Mexico.

ABSTRACT: Quaternary eolian deposits in the eastern Delaware Basin, Eddy and Lea Counties, New Mexico, including gypsum clay dunes (or "lunettes"), gypsum sand dunes, and quartzose sand dunes, provide evidence for paleoclimate and age of associated collapse events. Gypsum clay dunes are found at Bell Lake Sink, Slick Sink, and Willow Lake; gypsum sand dunes occur at Nash Well Sink. Quartzose sheet or "cover" sands (the Old Mescalero and Mescalero sands) blanket approximately 62% of the basin and represent both fossil and active dune fields. Stratigraphic relationships between these and other Quaternary deposits are used to determine the effects of different climatic episodes on dissolution in the Delaware Basin.

Early Holocene gypsum clay dunes formed under specific climatic conditions intermediate between a wet, cool glacial episode (Wisconsin) and an arid, hot interval (Altithermal). Gypsum sand dunes, representing semi-arid to arid conditions, probably formed during the Altithermal. The youth of these deposits and evidence of lake sands in Bell Lake Sink and Slick Sink indicate that collapse of the sinks was a late Wisconsin dissolution event.

Relationships between Quaternary deposits and collapse features in the Delaware Basin indicate that collapse events may have been significantly influenced by past pluvial episodes that caused acceleration of both local and regional dissolution in the Delaware Basin.

Wieduwilt, W.G. 1977. *Electrical Geophysical Surveys of the Los Medanos Site and Surrounding Areas for Waste Isolation Pilot Plant Program, Eddy and Lea Counties, New Mexico.* [Tucson, AZ]: Mining Geophysical Surveys, Inc. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Mining Geophysical Surveys conducted resistivity surveys in the area of the Waste Isolation Pilot Plant (WIPP) from May 9 through November 15, 1977. About 37 square miles, including the site and some adjacent areas, were covered using a gradient array with measuring points 200 ft apart in most areas and 400 ft apart along the east and west boundaries of the surveyed area. About 9750 data points were generated in the gradient array survey. Specific target areas and physical features were investigated in the site area and Nash Draw with 20 Schlumberger soundings and 4 pole-dipole profiles. Schlumberger soundings used current dipole (AB) width up to 20,000 ft. Ratios of current dipole half-width (AB/2) to potential dipole half-width (MN/2) were between 5 and 200. For pole-dipole profiles, the spacing ("a") to the potential or receiver dipole was 100 ft and the current electrode (pole) was a multiple ("n") of 5 times the distance from the potential dipole to the nearest potential electrode. The reference current electrode was a distance greater than 1 mile from any station of the pole-dipole array. DWP

ANNOTATION: The report by Wieduwilt presents the basic program of resistivity investigations during early site characterization. It includes various calibration, production, and personnel data. The data from the survey were reported and interpreted by C.L. Elliot under separate contract (Elliot, 1977a, b, f, g). The extensive coverage by resistivity combined with seismic reflection data (e.g., Hern et al., 1979), provided basic information that led to specific drilling programs and further geophysical work as part of site characterization. One example of a target from this survey is WIPP-13, drilled to explore a low resistivity area northwest of the site center; low resistivity is also a characteristic of breccia pipes - collapse features known to exist over the Capitan reef near the Mississippi Chemical Corporation potash mine. Such resistivity and other surface geophysical techniques were an important and efficient means of directing drilling as part of site characterization.

Winslow, C.D. 1981. *The Sorption of Cesium and Strontium From Concentrated Brines by Backfill Barrier Materials.* SAND80-2046. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The sorption of radionuclides from potentially intruding groundwater at a nuclear waste repository is a major chemical function of backfill barriers. In this study, various materials (including clays, zeolites, and an inorganic ion exchanger) were screened for the sorption of the fission products cesium and strontium in concentrated brines. Representative brines A and B for the Waste Isolation Pilot Plant (WIPP), a proposed radioactive waste repository and test facility in bedded salt were used. Sorption properties were quantified using empirical distribution coefficients, K_d . Of the materials examined, sodium titanate had the highest K_d for the sorption of Sr(II) in both brine A (K_d 125 mL/g) and brine B (K_d = 500-600 mL/g). A mordenite-type zeolite was the most effective getter for Cs(I) in brine A (K_d 27 mL/g), while illite yielded the highest K_d for Cs(I) in brine B (K_d 115 mL/g). The relative merit of these K_d values is evaluated in terms of calculated estimates of breakthrough times for a backfill barrier containing the getters. Results show that a backfill mixture containing these getters is potentially an effective barrier to the migration of Sr(II) and Cs(I), although further study (especially for the sorption of cesium from brine A) is recommended.

Winstanley, D.J., and R.C. Carrasco. 1986. *Annual Hydrogeologic Data Report: 1985-1986 for the Waste Isolation Pilot Plant*. DOE-WIPP-86-004. Carlsbad, NM: Westinghouse Electric Corporation. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Hydrologic data collected at the US Department of Energy's (DOE's) Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico are presented. Two compiled topographic maps are also included at a scale of 1 in. equals 1 mi. The first map covers approximately 1400 mi² and the second covers approximately 450 mi² and includes selected hydrologic well location information.

Water-level measurements collected from 56 wells during the first half of calendar year 1986 are presented. A number of wells are completed in multiple zones separated by production-injection packers, allowing measurements to be taken from more than one zone. Nine water-level measurements were collected of the Magenta Dolomite Member of the Rustler Formation, 45 of the Culebra Dolomite Member of the Rustler Formation, 3 of the Rustler-Salado contact residuum, 2 of the Bell Canyon Formation, 1 of the Castile Formation, and 2 from unknown zones.

Pressure recovery and flow-rate data are presented from pumping at well H-12 during August 1985. Pumping continued for 9 days at an average flow rate of approximately 17 gal/hour. Recovery data was collected for 5 days after termination of pumping. No data interpretation is provided.

Well configuration data are provided for 67 wells in the vicinity of the WIPP Site. The information is compiled from published reports, memos, field notes, and other documented sources of which a detailed listing is provided. Each well record includes general well information, casing/hole/screen data, completion interval data, packer or plug installations, and comments.

Geophysical logs from 22 hydrologic test wells were reinterpreted, and the picks are presented for the following stratigraphic markers: the Rustler-Salado contact residuum, the base and top of the Culebra Dolomite, and the base and top of the Magenta Dolomite.

Winstanley, D., R.[C.] Carrasco, and J. Zurkoff. 1986. "Pressure and Density Measurements of Selected Fluid-Bearing Zones at the Waste Isolation Pilot Plant (WIPP)," *Waste Management 86, Waste Isolation in the US, Technical Programs and Public Education*, Tucson, AZ, March 2-6, 1986. Ed. R.G. Post, Tucson, AZ: University of Arizona. Vol. 2, 217-220.

ABSTRACT: A field effort is presently being conducted at the Waste Isolation Pilot Plant (WIPP) to collect accurate pressure and density information from the Culebra and Magenta Dolomite Members of the Rustler Formation. The spatial variation of fluid density that occurs in these water-bearing units requires the use of numerical models to accurately solve for flow direction and velocity. The groundwater regime is a vital element in possible release scenarios of radionuclide-bearing fluid from the repository.

Field tests were conducted on four wells utilizing a testing apparatus composed of two pressure and temperature monitoring systems and a point water sampler. Pressure versus depth plots are linear with a correlation coefficient of 0.999 or greater. Comparison of the calculated density and measured density of water obtained at depth agree within 2% of density measurements obtained after continuous pumping of the formation for several days before sampling. The temperature gradients ranged from 0.4° to 0.6°C/100 ft. The data presented here are preliminary and serve as developmental information for the detailed operating plan currently under preparation.

Wofsy, C. 1980. *The Significance of Certain Rustler Aquifer Parameters for Predicting Long-Term Radiation Doses From WIPP*. EEG-8. Santa Fe, NM: Environmental Evaluation Group.

ABSTRACT: The *Safety Analysis Report (SAR)* for the Waste Isolation Pilot Plant (WIPP) includes modeling of the radiological consequences of breach events of the WIPP and radionuclide transport through the Rustler Formation to the Pecos River near Malaga Bend. Some plausible changes to parameters used in the *SAR* have been examined to determine if radionuclides may move significantly faster than predicted and if radionuclides may be more concentrated in the Pecos River, resulting in higher calculated doses than predicted. Three to four orders of magnitude change in certain parameters is necessary to reduce the travel times calculated in the *SAR* to 10^4 to 10^5 years or less, a range considered to result in peak Pu-239 concentrations.

It does not seem credible that the hydraulic gradient parameter should change by even an order of magnitude. Hydraulic conductivity near the site might plausibly change by an order of magnitude. The distribution coefficient for radionuclides is highly variable within experiments as well as for differing rocks and chemical conditions. For some conditions, plutonium may not be retarded at all. Given the factors concerning radionuclide retardation, it is considered a plausible worst case to assume 1% of the plutonium entering the Rustler moves unretarded through the aquifer to the Pecos River.

The whole body 50-year dose commitments from 1-year ingestion of plutonium from Pecos River water (730 l/yr) by a maximally exposed adult were calculated: 3.2×10^{-2} mrem for a specified travel time of 10^5 yr for Pu-239 and 5.1×10^{-3} mrem if 1% of Pu is not retarded but the "natural" travel time is longer. These doses are comparable to computed radium-226 doses reported for the *SAR*, indicating plausible changes in hydrologic parameters do not result in doses significantly greater than those reported for the *SAR*.

DWP

Wood, B.J., R.E. Snow, D.J. Cosler, and S. Haji-Djafari. 1982. *Delaware Mountain Group (DMG) Hydrology-Salt Removal Potential, Waste Isolation Pilot Plant (WIPP) Project, Southeastern New Mexico*. TME 3166. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: There are some concerns that salt could be dissolved and effect isolation of waste at the Waste Isolation Pilot Plant (WIPP). Fluids in the underlying Delaware Mountain Group (DMG) have been considered the agent of salt dissolution and the medium to transport radionuclides. In this study, DMG hydrologic data were compiled and reviewed, salt dissolution hypotheses and potential were assessed, a hydrological model for salt removal through the DMG was established, dissolution rates and solution cavity dimensions were assessed, and the sensitivity of salt dissolution rates to hydrologic and geochemical parameters was evaluated.

Diffusion and very weak convection (brine density flow) from halite layers to the Bell Canyon Formation (upper DMG) and Capitan may remove Castile halite overlying the DMG. convection may be significant adjacent to the Capitan reef aquifer. DMG hydrogeologic and geochemical conditions indicate diffusion would advance the dissolution front by only 0.3 cm in 10,000 years and would not significantly affect the integrity of the facility. A potential increase in flow rate of an order of magnitude for the Bell Canyon would not increase removal of salt from the Castile by more than 17%; this unlikely occurrence is not anticipated to have any effect on repository integrity. The "...implausible worst-case dissolution rates associated with both diffusive and convective dissolution at the Bell Canyon aquifer - Castile Formation interface suggest that the structural integrity of the WIPP facility located more than 400 meters above would not be affected." Also, "...the theoretical maximum cavity radius would be 7 m over a fracture and 1 m above a circular porous zone in a period of 10,000 years." DWP

Woolfolk, S.W. 1982. *Radiologic Consequences of Brine Release by Human Intrusion Into WIPP*. TME 3151. Albuquerque, NM: US Department of Energy, Waste Isolation Pilot Plant. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Pressurized brine reservoirs have been encountered in the Castile Formation at boreholes ERDA-6 and WIPP-12. The radiological consequences of inadvertent human intrusion into a brine reservoir connecting with the waste repository are evaluated in two scenarios considered to take place 250 years after closure of the repository. Intrusions based on knowledge of the site are not evaluated. Both scenarios involve 15-in. boreholes through the facility, intercepting a pressurized brine pocket below the facility. The first scenario involves 24 hrs. of flow to the surface before the borehole is plugged. The consequences are based on initial exposure and further exposure to dispersed residue from evaporation of the drilling fluids on the surface. The second scenario results in filling the repository with brine, after which the initial borehole is plugged. A second borehole intercepts the repository after the brine has come to equilibrium with plutonium dioxide. The brine flows to the surface for 24 hrs., with subsequent events similar to the first scenario.

The radiological consequences of both scenarios are considered not significant compared to the existing natural background of the area. The events are considered rather improbable based on DOE plans to permit extraction of resources using slant drilling techniques. A drilling crew may be unwilling to continue operations in striking an obviously unusual situation, and the second scenario involves drilling two boreholes into unusual conditions. Thus, "... it is apparent that the presence of a brine pocket beneath the site does not significantly increase the risk associated with the disposal of radioactive waste at WIPP." The analysis also indicates that WIPP meets the draft standard for release limits in the first 10,000 years after closure, as proposed in draft 21 of 40 CFR 191. DWP

Wowak, W.E. 1979. *Early In-Situ Measurements Program for the Waste Isolation Pilot Plant*. SAND79-0362. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The technical basis and description of measurements for the early in situ measurements program at the Waste Isolation Pilot Plant (WIPP) are described and a proposed organizational structure is presented. Measurements are needed for verification of design predictions and also for a prelude to the main experiment program. The design verification measurements will be concentrated in the first shaft and the underground support and access areas. Early experiments will be concentrated in the test drifts on the storage horizons. Recommendations are made to Department of Energy (DOE) for appropriate division of responsibility among Bechtel, the technical support contractor, the instrumentation contractor, and Sandia National Laboratories.

Yost, F.G. 1986. "Salt Consolidation Mechanism Studies," *Working Papers from the US/FRG Workshop on Sealing and Backfilling of a Salt Repository, Albuquerque, NM, September 23-25, 1986*. Comp. R.F. Cook. Columbus, OH: Office of Nuclear Waste Isolation, Battelle Project Management Division. II-8-1 through II-8-20. (Copy on file at the Waste Management and Transportation Library, Sandia National Laboratories, Albuquerque, NM).

ABSTRACT: Any mechanism to explain crushed salt compaction must be consistent with two experimental observations: moisture accelerates creep; and compaction continues after a stress decrement. Pressure solution and the Joffe effect are two mechanisms consistent with these observations. Pressure solution describes "a wide range of phenomena in which solids, immersed in liquids containing one or more components of the solid, have higher solubility when stressed. The Joffe effect is the facilitation of glissile dislocation nucleation at the surfaces of salt particles due to the presence of brine." It is not clear whether the moisture, which is necessary for the operation of these mechanisms, must be condensed or absorbed brine. Our experiments have shown that moisture adsorption on crushed Waste Isolation Pilot Plant (WIPP) salt can be described by a BET (Brunauer, Emmett and Teller) type III isotherm with brine droplets nucleating above 70% relative humidity. This corresponds to approximately 0.2% added moisture. The effect of moisture on the kinetics of crushed salt compaction investigated experimentally by Holcomb included moisture significantly greater than 0.2%. A simple model for creep compaction of crushed salt was derived by solving the continuity equation. The model, valid for both of the above mentioned mechanisms, was found to fit the experimental data of Holcomb extremely well. DWP

ANNOTATION: The experiments by Holcomb discussed by Yost are those reported by Holcomb (1986) and included in the annotated bibliography.

Yost, F.G., and E.A. Aronson. 1987. *Crushed Salt Consolidation Kinetics*. SAND87-0264. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The compaction of crushed salt is an important process in the sealing of a salt repository for nuclear wastes. Reported here is a simple phenomenological model of crushed salt compaction kinetics. The model is compared to experimental data and it is shown that very good least-squares fits can be made. The model allows correlation of experimental data, comparison with physical mechanisms for compaction, and the prediction of long-term compaction behavior.

Z

Zand, S.M., 1982. "Dissolution of Evaporites and Its Possible Impact on the Integrity of the Waste Isolation Pilot Plant (WIPP), New Mexico, USA," *Scientific Basis for Nuclear Waste Management V, Materials Research Society Proceedings, Fifth International Symposium on the Scientific Basis for Nuclear Waste Management, Berlin, Germany, June 7-10, 1982*. Ed. W. Lutze. New York, NY: North-Holland. Vol. 11, 439-448.

ABSTRACT: "The radiological consequences of a breach of the Waste Isolation Pilot Plant (WIPP) transuranic (TRU) waste repository, as a result of dissolution processes were shown to be in two broad classes. Most of the possible scenarios that could happen as a result of the deep dissolution processes were shown to be addressed by the scenarios already presented elsewhere or are being investigated at the present. The remaining possible scenarios, except one, showed that the possible release of radionuclides through the geosphere to the biosphere would take periods of time orders of magnitude longer than the half-life of plutonium-239. The one not specifically addressed, a postulated hydrologic pathway with the characteristics of the Salado/Castile interface aquifer, appears unlikely. However, it should be quantified when more data become available. To obtain a better understanding of the radiological health effects of the deep dissolution-caused breach of the repository, emphasis must be placed on better evaluation and refinement of the existing mathematical models and associated parameters.

"In the majority of the existing scenarios, the most significant pathway of the radionuclide through the geosphere to the biosphere is the dolomitic Magenta and Culebra aquifers. Because these formations are fractured, mathematical modeling of radionuclide transport is subject to a large degree of uncertainty. Other uncertainties that relate to this pathway which need further study are: a) the possibility of having more permeable abandoned mined potash tunnels as a part of the radionuclide flow path and b) the possibility of discharges to the biosphere occurring at the outcrops of the Magenta and Culebra Formations in Nash Draw, 11 km (7 mi) before the outlet to the Pecos River at Malaga Bend. The problems associated with the quantifications of these uncertainties as well as the effects of long-term climatic and hydrologic changes and hydrogeological data requirements of the models should be further addressed." DWP

Zeuch, D.H. 1989. *Isostatic Hot-Pressing Mechanism Maps for Pure and Natural Sodium Chloride: Applications to Nuclear Waste Isolation in Bedded and Domal Salt Formations*. SAND88-2207. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: The Waste Isolation Pilot Plant (WIPP) is a US Department of Energy (DOE) research and development facility that is intended to demonstrate the safe geologic disposal of transuranic (TRU) wastes. The mechanical behavior of crushed rock salt is of interest to the WIPP Project because the mined WIPP salt is a candidate material for use as backfill around the waste packages and in the underground openings during and after the operational phase. It is anticipated that, in response to the convergence of the mine openings, the crushed salt will compact sufficiently to serve as an effective component in WIPP seal systems. In this report, the model for isostatic hot-pressing, which was developed by Helle, is applied to the problem of compaction of both pure sodium chloride and natural (WIPP) salt to develop a model capable of predicting densification rates as a function of temperature and applied pressure. Calculations for pure dry salt suggest that under conditions in situ, the contribution to densification by diffusional processes is negligible; all compaction will occur by dislocation creep. Assuming then that compaction will occur only by dislocation processes, the model is extended to nominally dry WIPP salt. Model predictions are shown to agree favorably with limited test data, and the kinds of laboratory tests that may be done to validate the model are

discussed. Hot-pressing mechanism maps for dry WIPP salt, under anticipated repository conditions, indicate that fractional densities in excess of 0.95 are attained in about 30 years. At this density, connected porosity and hence, permeability, diminish rapidly and the recompacted salt can begin to serve as an effective seal material. This prediction is conservative because moist salt will compact even more rapidly. Work is in progress to extend the model to include the effects of brine on densification rates.

Zeuch, D.H., and D.J. Holcomb. 1984. "Analysis of Creep Consolidation of Crushed Rocksalt Using a Plastic Flow Model for Isostatic Hot-Pressing," *EOS Transactions, American Geophysical Union*. SAND84-1599A. Vol. 65, no. 45, 1108. (Abstract Only).

ABSTRACT: Recent, short-term experiments (~3.5 days in duration) on the creep consolidation of crushed, natural rocksalt indicate that compaction occurs very slowly. Since waste repositories sited in naturally occurring salt formations are likely to use crushed, native rocksalt as "backfill" to encapsulate waste packages, it becomes necessary that we understand this unexpected result in order to predict densification rates in situ over long time intervals. The problem of consolidation of powdered aggregates using heat and pressure is a relatively old one in the fields of ceramics and powder metallurgy, and an extensive body of literature exists on the theory and practice of sintering and hot-pressing. A simple model for isostatic hot-pressing to the test results has been applied. The model fits the individual test results quite well, and further investigation is clearly warranted.

The model which we used was that of McClelland, which derives from the early sintering theory of MacKenzie and Shuttleworth. The particles are assumed to behave as a Bingham solid, deforming elastically below a yield stress, τ , and viscously above the yield stress as described by the other material constant, η . The model also accounts for the difference between the applied pressure, P_c , and local contact stresses. At constant applied pressure

$$\frac{dD}{dt} = \frac{3P_c(1 - D)}{4\eta} \left[\frac{1}{1 - (1 - D)^{2/3}} + \frac{\sqrt{2}\tau}{P_c} \ln(1 - D) \right],$$

where D = fractional density, i.e., actual density normalized to theoretical density and t = time at pressure. Individual creep consolidation tests can be fit quite well using this model. The parameters τ and η show little systematic variation with temperature. This may be the result of a limited temperature range used in our tests. On the other hand, these parameters increase monotonically with P_c , showing a strong correlation. This provides a qualitative explanation for the slow consolidation rates: the salt hardens rapidly with applied pressure, so the yield stress is always approximately equal to the applied stress. The particular model used here predicts an "endpoint density" beyond which no further compaction will occur. Further experimentation will be required to develop a better understanding of the relationships between τ and η and test temperature before this model will allow prediction of material response from test conditions.

Zeuch, D.H., D.J. Holcomb, and H.S. Lauson. 1985. *Analysis of Consolidation of Granulated Rocksalt Using a Plastic Flow Model for Isostatic Hot-Pressing*. SAND84-1106. Albuquerque, NM: Sandia National Laboratories.

ABSTRACT: Since waste repositories sited in naturally occurring salt formations are likely to use crushed rock salt as "backfill" to encapsulate waste packages, it becomes necessary to understand the behavior of this material in order to predict densification rates. The problem of consolidation of powdered aggregates using heat and pressure is an old one in the fields of

ceramics and powder metallurgy, and an extensive body of literature exists on the theory and practice of hot-pressing. In this report, it is shown that a simple model for hot-pressing fits the results for individual creep consolidation tests reasonably well. This leads us to believe that hot-pressing models are appropriate to the problem in the laboratory. The particular model used predicts an endpoint density beyond which no further densification will occur. However, the current data base is insufficient to fully justify either adoption of the model or long-term extrapolation of material response. Further laboratory testing is required to better define the model parameters as functions of temperature, applied pressure, and time.

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