SUMMARY OF SCIENTIFIC INVESTIGATIONS
FOR THE
WASTE ISOLATION PILOT PLANT

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ABSTRACT

The scientific issues concerning disposal of radioactive wastes in salt formations have received 40 years of attention since the National Academy of Sciences (NAS) first addressed this issue in the mid-50s. For the last 21 years, Sandia National Laboratories (SNL) have directed site specific studies for the Waste Isolation Pilot Plant (WIPP). This paper will focus primarily on the WIPP scientific studies now in their concluding stages, the major scientific controversies regarding the site, and some of the surprises encountered during the course of these scientific investigations.

The WIPP project's present understanding of the scientific processes involved continues to support the site as a satisfactory, safe location for the disposal of defense-related transuranic waste and one which will be shown to be in compliance with Environmental Protection Agency (EPA) standards. Compliance will be evaluated by incorporating data from these experiments into Performance Assessment (PA) models developed to describe the physical and chemical processes that could occur at the WIPP during the next 10,000 years under a variety of scenarios.

The resulting compliance document is scheduled to be presented to the EPA in October 1996 and all relevant information from scientific studies will be included in this application and the supporting analyses. Studies supporting this compliance application conclude the major period of scientific investigation for the WIPP. Further studies will be of a "confirmatory" and monitoring nature.

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INTRODUCTION

In 1974 the Atomic Energy Commission (AEC) began exploratory investigations for a nuclear waste repository in the salt beds in the southeast corner of New Mexico. Since January 1975 SNL has pursued scientific investigations with the ultimate goal of providing the knowledge base necessary to establish confidence in the ability of the site to safely isolate Defense Transuranic Waste and conform with all applicable waste disposal standards. Some early in-situ tests also evaluated disposal of Defense High Level Waste (DHLW) in salt beds because salt beds in Texas were one of three disposal options. Those studies were terminated when the Congress focused High Level Waste Repository investigations on the Yucca Mountain tuff in Nevada.

During these investigations SNL has been assisted by the U.S. Geological Survey (USGS) and by private contractors, university researchers, and consultants too numerous to individually recognize. It is important to acknowledge the contributions to the WIPP scientific studies provided by the NAS and by the New Mexico Environmental Evaluation Group (EEG). Both organizations have provided valuable scientific oversight and critical review of the scientific studies since 1978. Many of the studies and approaches to the issues were generated by their thoughtful examination of the technical concerns.

Thanks to the efforts of these organizations and many dedicated SNL WIPP staff, the information developed over the past 21 years allows an informed and confident assessment of WIPP’s ability to safely isolate transuranic waste from the biosphere and to comply with EPA repository standards.

The concept of geologic isolation for disposal of radioactive wastes, and in particular, utilization of salt formations, received a primal endorsement from the NAS with the publication of their report in 1957. That recommendation stimulated laboratory and field studies by and for Oak Ridge National Laboratory (ORNL) culminating in the Project Salt Vault experiments (1963 to 1967) in bedded salt at Lyons, Kansas. These tests utilized irradiated nuclear fuel elements, supplemented by electric heaters, to study heat and radiation effects from large-scale experiments in salt. These tests established that salt was an acceptable host rock for radioactive waste disposal but local factors, both technical and potential, resulted in abandonment in 1972 of an AEC proposal to construct a repository at the Lyons, Kansas site.

Subsequently, ORNL and the USGS evaluated existing knowledge regarding salt deposits in the United States and selected the northern portion of the Delaware Basin in New Mexico as having the best prospects of meeting the Site Selection Criteria. By June 1974, two boreholes had explored two corners of the proposed site area when site characterization was suspended in favor of the Retrievable Surface Storage Facility (RSSF) concept. The RSSF was soon abandoned because of objections from intervenor groups and the predecessor to EPA during the environmental hearing process. The concern was that problems created by this generation were being postponed to future generations.

When the Delaware Basin site characterization was resumed in early 1975, the AEC asked SNL to assume responsibility for managing continued site characterization, facility conceptual design,
National Environmental Policy Act (NEPA) studies and scientific studies related to waste disposal in salt beds.

The remainder of the paper will summarize the major geotechnical issues and scientific studies that have occurred within the WIPP program over the past 21 years. The discussion will be divided into the major categories of (1) site selection and characterization, (2) facility seals and rock mechanics, (3) fluid flow in the geologic system, and (4) waste room interactions, (including gas generation). This paper will not address the equally interesting history of the political and policy shifts over this period of time even though they often impacted the scientific program.

SITE SELECTION AND CHARACTERIZATION

SNL formally commenced WIPP studies in January 1975 and received funding in March 1975 to begin exploratory drilling activities and NEPA-related field studies. The first task was to “complete” site characterization by exploratory drilling of the remaining two corners of the 1 1/2 x 2 mile site inherited from the earlier program. The first of these proposed boreholes, ERDA 6, was drilled between June 13, 1975 and September 23, 1975. This exploratory boring unexpectedly encountered steeply dipping and displaced strata in the Salado and Castile formations and a geopressured brine reservoir in the uppermost fractured Castile anhydrite. This unexpected geologic structure and the inability to predict acceptable repository conditions throughout the site area led to an early disqualification of that site. Site selection investigations then focused on finding a more acceptable site within the Delaware Basin (Fig. 1).

Intensive evaluation of existing geologic and geophysical information that had been acquired by the potash and petroleum industries was initiated. This examination was allowed by these companies on a “company proprietary” basis. These studies established that the evaporite deformation zone encountered in ERDA 6 was primarily confined to a belt about five miles wide paralleling the buried Capitan Reef. Drilling data indicated that away from this zone, toward the interior of the Delaware Basin, the Salado Formation was relatively undeformed. The renewed site selection activities, continuing to focus on the Northern Delaware Basin but using more restrictive site selection criteria generated from the evaluation (and a relaxation of borehole stand-off to one mile allowed by improved knowledge of the hydrology), resulted in the same prime alternative site being independently identified by Sandia and USGS teams in December 1975.

The center of this proposed site, about 5 miles southwest of the first location, was core drilled (ERDA 9) by June 1976 and the analyses confirmed the desired bedded salt properties, the anticipated stratigraphy and relatively flat dip. This initial tentative site identification led to a broadly-based geotechnical investigation focused on this region. Between 1975 and 1980, 57 boreholes were drilled and cored to provide basic geologic and hydrologic data, potash resource information, and to aid in interpretation of geophysical surveys. These latter surveys consisted of gravity, aeromagnetics, resistivity, and seismic reflection and refraction surveys. Seismicity evaluations established that the area was basically aseismic and concluded the majority of seismicity in the Central Basic Platform area of west Texas was induced by water-flooding.
activity. The nearest “active” fault, i.e. exhibiting evidence of motion in the last 100,000 years, was determined to be 65 miles to the west on the western slope of the Guadalupe Mountains. Surface mapping and drilling examined features suspected of being breccia pipes, and determined that breccia pipes occurred only over the Capitan Reef and were not, therefore, to be expected at the WIPP site.

Resource evaluations for potash and oil/gas were conducted based on WIPP drill holes and seismic data coupled with knowledge of oil/gas field development and potash exploration. No other significant resources were identified. With this information the site was located to avoid major known petroleum trends and minimized conflict with potash resources to the extent possible. Complete avoidance of potential conflict with hydrocarbons and some potash ore was known to be unattainable in this portion of the Delaware Basin.

Studies conducted by the USGS concluded that salt dissolution rates would not breach the WIPP for millions of years. Surface geology, hydrologic studies, and selected drilling and geophysical surveys ruled out point dissolution and the existence of karst geohydrology at the site.

All this geotechnical information was summarized in a site characterization report in 1978. A generalized geologic cross-section is shown in Figure 2. These characterization studies were conducted prior to the promulgation of EPA standards for nuclear waste repositories. Consequently, the site characterization criteria which governed the studies were based upon the breach scenarios, especially involving natural processes, which were generally regarded by the scientists in the national and international repository programs as being significant to repository integrity and necessary to predict the behavior of a nuclear waste repository in salt. WIPP’s self-imposed criterion for the time duration of repository integrity was 250,000 years, approximately 10 half-lives of Pu-239.

Certain site characterization issues became the focus of much oversight scrutiny during the ‘70s and early ‘80s. Chief among these were the salt dissolution aspects of which there were four. Regional dissolution of salt, both at the top of the salt section and within the salt beds themselves was one of the first issues addressed. The former was addressed by geologic studies conducted by the USGS determining both horizontal and vertical rates of dissolution over the past million years. This information established that the WIPP would not be threatened by this process for a far longer time than the 250,000 years then used as a criterion. The inter-bed locus for salt dissolution, particularly within the Castile and at the base of the Salado, had been suggested as a cause of some of the local lithologic and structural features in the Castile salt beds and as the cause of Castile salt bed thickness variations. This issue was directly addressed for suspect areas near the WIPP site by borehole drilling and core examination. This evaluation showed no evidence of dissolution features and, together with regional isopach and structural interpretations, led to the present concept of anhydrite foundering in the salt to explain the Castile variations in salt thickness. The third dissolution issue addressed “point source” dissolution as evidenced by features termed “collapse breccia pipes”. These breccia pipes were cylindrical collapse structures, about 1000 feet in diameter, caused by dissolution of soluble rock at depth, ultimately resulting in
collapse of overlying rock into the solution cavity with the chimney action progressing to the surface. The concern for the repository was that since these features were known to occur north of the site, they might also be developed at the WIPP, providing a permeable waterflow path through the repository horizon and leading to a breach of repository integrity. Studies by the USGS, based on drilling of known breccia pipes and other suspect features, surface mapping and one underground mining intercept, concluded that breccia pipes were not a threat to WIPP because: (1) they occur only over the Capitan Reef—a source of water for dissolution, and (2) the examination of existing breccia pipes revealed they were not a long-term permeable path for water flow.

The fourth dissolution issue dealt with the issue of karst hydrogeology. Karst was known to be well developed to the west of WP, in the Nash Draw topographic depression. This karst expression was postulated by some critics to extend to the WIPP site with the associated consequence of extremely rapid hydrologic transport of any radioactivity release to the Pecos River. Subsequent geologic studies, geophysical surveys and expanded hydrologic testing failed to find any evidence of karst development over the WIPP site or along the indicated hydrologic flow path. Peer reviews of the extensive hydrogeologic database, conducted by the EEG and the NAS WIPP Panel, concluded that karst development was not a threat to the WIPP.

The final stage of the site characterization phase commenced with the Site and Preliminary Design Validation (SPDV) in July 1981. This underground excavation explored the core of the site area and enabled extensive geologic mapping for one mile in the north-south and east-west directions as well as mapping of the exploratory and exhaust air shafts. As a result of this geologic investigation and the accompanying mineralogical analyses, it was concluded that the site met the previously established siting criteria. DOE accepted the site and proceeded to full facility construction in July 1983.

FACILITY SEALS AND ROCK MECHANICS

A primary attribute of a salt repository is the ability of the salt to deform or creep over time thereby sealing man-made access and intrusions into the repository and preventing natural processes from causing permeable fractures or faults which could allow entry of water. This creep attribute is utilized in the sealing of repository access shafts and in predicting closure of the waste rooms and resultant encapsulation of the waste placed therein. To allow quantification of this behavior an extensive rock mechanics program has been carried out in the laboratory and in-situ at the WIPP site. Additionally, evaluation of numerous materials, both cementitious and native materials (salt and/or clay), which are candidate seal materials, has been completed.

Prior to gaining access to the WIPP underground, laboratory tests were conducted on rock salt core obtained from surface drilling. The constitutive data thus acquired were used in existing rock mechanics models to predict salt creep in the WIPP. The SNL models SANCHO and JAC were then benchmarked in a program that compared nine different codes from throughout the National and International communities. This exercise revealed that similar results could be obtained from the more sophisticated codes but only if great care was given to assuring the same problem specification. Code operator set-up of the problem could significantly alter the results.
Prior to implementing in-situ tests, an in-situ test plan\textsuperscript{(5)} was prepared which outlined the tests to be conducted in the WIPP underground. The rock mechanics tests in the WIPP ranged in size from single borehole to full simulation of disposal room, configured respectively for TRU and DHLW disposal. Defense High Level Waste experiments in salt were conducted to provide early information about issues that could face a proposed High Level Waste repository in a west Texas salt site.

Measurements were begun in 1983 and the final tests have only recently been terminated. These tests, which span a decade in some instances, relied primarily upon strain and displacement measurements although some tests required extensive thermocouple data. Some stress gauges were emplaced but difficulty in interpreting their results because of the "plastic" nature of the rock limited their utility. At the peak of the in-situ test program, about 5000 channels of data, most of it for rock mechanics, were being continuously recorded. Figure 3 displays the location of the WIPP in-situ tests.

Fig. 3 goes here

The early in-situ observations of salt creep revealed that strain rates and room closure were proceeding at about three times the rate that had been predicted by pre-test modeling. This accuracy was not sufficient for sealing and room-closure prediction requirements. Several laboratory and modeling studies were implemented to establish what modifications were required to our predictive model and to our understanding of the creep process to better predict the observed behavior.

To be certain that errors were not introduced into the two-dimensional model by the geometric abstractions necessary to represent the 3-D world, a large (108-foot diameter) circular test room (Room H) with a cylinder of undisturbed salt 36 feet in diameter at the center was constructed. After acquiring data at ambient temperature for about one year (1985), strip heaters around the pillar were activated to raise the pillar temperature from 50\degree to 70\degree C, near the center and at the pillar wall respectively. This greatly accelerated the creep rate so that greater strains could be accumulated during the measurement span than would otherwise be possible but assured the strain mechanisms would not be changed. Laboratory tests on salt core containing impurities and from the anhydrite marker beds permitted the model to incorporate a more detailed description of the stratigraphy within and above and below the excavation. Other improvements to the model were incorporated with the realization that transient strain could not be neglected, even long after excavation, because the continuing creep and consequent stress changes, although small at long times after excavation, were enough to cause continued transient creep behavior. The other major change was to the stress generalization, from Von Mises to a Tresca formulation. This change was supported by results from hollow cylinder, salt core tests in the laboratory. Incorporating these modifications to the model and database resulted in agreement between prediction and observation to within 10 to 15 percent--satisfactory for repository modeling purposes.

Full-scale simulation of DHLW, as well as a thermal overtest, were conducted in two test rooms, A and B. Room B and Room D provided data for identical geometry excavations, thermal effects
in Room B being the only difference. In a later test a 36-inch diameter borehole 100 feet long, drilled between two-mined drifts, was instrumented to be certain that the creep phenomena observed in the large room tests and that the model adaptations to predict their behavior, were not the result of scale effects. The newly developed model has shown it can predict different scales, geometries, heated and unheated, with equal precision. Prediction of salt creep is now considered to be a resolved issue.\(^6\)

Discreet rock mechanics phenomena, such as fracture development and healing, have presented a challenging problem. The healing of salt fractures at stresses typical of the repository has been demonstrated in laboratory experiments. These experimental results support the logic that the disturbed rock zone that forms in salt around excavations will return to nearly in-situ values of density and permeability. This is an essential element in the design of effective long-term seals for the repository. Modeling has developed to the point that stress conditions and locations conducive to fracturing can be predicted as a rough function of time as an excavation deforms. Precise prediction of the time of failure is still not possible from modeling although deformation rates obtained on failed rooms gives reasonable time estimates for rooms of the same geometry.

Response of the salt beds to internal room gas pressures caused by decomposition of the emplaced waste is still another concern to be addressed by the rock mechanics program. In-situ hydrofracture tests revealed the salt, remote from the excavation, behaves isotropically. The induced fractures don’t show a preferred direction on this relatively small scale. Since the salt is layered on a larger scale, with the interbeds of anhydrite containing pre-existing fractures and with clay partings at the base of the anhydrites, these layer features will provide paths of least resistance to propagation of fractures on a large scale. These horizontal bedding features prevent fractures from developing upward through the salt, but they must be considered as potentially more permeable paths when evaluating propagation of fluids horizontally to the site boundary. Detailed calculation of discrete fracture development over large distances is not yet realistic because of natural heterogeneities in the rock. Consequently bounding approaches are taken to model this issue.

Sealing Systems\(^7\)

Sealing systems proposed for the WIPP depend strongly upon the knowledge obtained from the rock mechanics program. The principal seals, those upon which isolation depends, will be in the access shafts into the WIPP and will consist of physically different modules which are designed to be most effective over different time scales (Fig. 4). WIPP in-situ experiments have demonstrated that cementitious seals can be very effective as soon after emplacement as the disturbed rock zone (DRZ) heals. Materials evaluation has permitted development of tailored cements that are relatively compatible with a salt environment and with the non-halite rock of the overlying aquifers. However it is difficult to prove that interface degradation will not occur over the millennia that are required of seals. Thus the WIPP will use materials natural to the WIPP environment, i.e., salt and clay, which will not be chemically foreign to the surroundings and will therefore remain stable for as long as the salt beds survive.

Fig. 4 goes here
Utilization of natural materials requires compaction to near in-situ salt densities. Experiments demonstrate that compacting crushed salt to >95% of natural density will achieve the desired permeability. This desired compaction can be initiated by tamping the emplaced material. Tests show that densities of about 90% can be attained by tamping but final compaction will rely on additional compression obtained over time from natural creep of the salt. Densification of crushed salt by applied pressure has been quantified in laboratory testing. Another advantage of tamping to achieve high emplacement density is that it decreases the time interval required to reheal the DRZ since resistive forces to creep closure build more quickly. Shaft seals relying on natural materials can be emplaced in the WIPP which will provide satisfactory seals within 100 to 200 years. During this time span, while natural material seals are becoming effective, sealing will be provided by cementitious seals at other locations higher in the shafts. Conservative properties attainable for the WIPP seals are presented in Repository Seals Program baseline position paper. A third component, clay, either separately or in conjunction with crushed salt has also been evaluated. Clay may be useful to provide low permeability when water may be expected before salt creep has made the salt seals effective. Compacted clay will expand when wetted and intrude into openings and crevices, helping to reduce permeability. Another attribute of clay (but for which the WIPP does not take credit in calculating performance assessment) is its ability to sorb radionuclides should they be present in any fluid moving through a clay seal component.

Should it become desirable to enhance sealing of individual waste rooms or panels or to maximize sealing of the water bearing shaft intervals, a special injection technique was developed and demonstrated in the WIPP Marker Bed 139. This development utilized a specially ground microfine cement and fluidizers to allow penetration into microfractures. The demonstration test defined the degree of penetration and the reduction in flow by comparing pre- and post-grouting flow tests.

Fluid Flow in the Geologic System

The hydrology of the WIPP site has been a subject of study since the initial site selection. Ground water flow is a possible dissolution threat as well as the primary transport mechanism for any breach scenario which may be postulated. Consequently it is important that the hydrologic system be known well enough to predict not only its present behavior but the response to future natural variations in climate as well.

Fluid Flow in the Rustler Formation

The earliest studies, in the late 1970s, established that the Culebra Formation, with an average thickness of 7.7 m, is the principal aquifer overlying the WIPP site and the aquifer of concern when modeling radionuclide transport. Numerous hydrologic test holes indicated the transmissivity over the WIPP area varied by several orders of magnitude with transmissivity generally decreasing to the east. Further testing which employed larger scale, long-term pumping tests, detected a "channel" of higher transmissivity (1-20 ft²/day), running north-south, on the east side of the site. This feature altered the water flow patterns somewhat but the general flow path
from the repository to the site boundary is still generally southward. There has been much speculation about the cause of the general trends of transmissivity over the area and for the origin of the higher transmissivity channel. The most commonly accepted explanation for the general trend is the striking correlation with the extent of apparent salt dissolution from below the Culebra in the Rustler Formation. The more salt missing the greater is the observed transmissivity. The eastern edge of the WIPP site has all the salt still present in the section and the transmissivity is very low \(10^{-3} - 10^{-1}\) \(\text{ft}^2/\text{day}\). The explanation for the channel is less obvious—there are no apparent structural or stratigraphic features that provide an explanation. Resistivity surveys help to provide additional spatial definition of this feature. Since geologic processes which could extend this feature or cause similar new ones are unlikely over 10,000 years, it is not critical that its origin be understood—only that we can incorporate its effect into our hydrologic model (Fig. 5).

Fig. 5 goes here.

One of the most useful tools in the hydrologic test program was the implementation of the large-scale, multiwell pump test. This test could be implemented with or without the utilization of conservative tracers to accomplish several objectives. As a purely hydraulic test it has been used to establish effective transmissivity over intervals between pumping and observation wells that range from tens to thousands of feet. By performing these tests at selected WIPP locations a much better approximation of the transmissivity field has been established. When used as a tracer test it has provided additional information on dispersivity, fracture characteristics and matrix diffusion, all important parameters in modeling transport of radionuclides.

Other observations, such as examination of the Culebra in core and in the air intake shaft, have provided insight into the nature of the porosity and fracturing. The physical variations observed in the Culebra have led to tracer studies where the different Culebra zones are isolated by packers to see which horizons contribute most to the transport and to what extent these horizons are isolated from each other.

Some chemical aspects of the Culebra saline brines south of the site are difficult to explain given the current flow model and the assumptions of steady state and confined aquifer conditions. An early interpretation, utilizing stable isotope and carbon-14 data coupled with geologic interpretations of past climate and recharge, led to an hypothesis that present conditions are not steady state but are recovering from recharge during a prior pluvial period. Current studies, using three-dimensional modeling capability, are examining the confined aquifer premise, allowing some small but perceptible level of vertical recharge to the Culebra. This concept of the hydrologic system can also explain the observed geochemistry. While it is not necessary to understand the origin of the chemical disparity to do transport modeling, a logical explanation lends confidence to our total understanding of the Culebra hydrologic system.

In addition to the field studies, extensive tests have been run to establish retardation parameters for actinides of interest. Many of these tests have been batch tests for \(K_d\) determination. Some have looked at the dolomite matrix while others have examined the clay which lines many of the Culebra fractures. A more realistic laboratory evaluation uses long cores taken horizontally in the
Culebra by coring from the Air Intake Shaft. These cores, some with intact fractures, were used in flow-through tests using Culebra brine and actual isotopes. These studies provide not only a measure of chemical retardation but the extent of matrix diffusion or physical retardation. Even this best laboratory effort is at a small scale compared to the actual transport one wishes to simulate. Presently the Project does not plan on an imminent implementation of an in-situ field test with sorbing tracers. Such a test could require several years and, if conducted, should be viewed as an experiment to confirm that the conceptual transport model is not violated by observations and to establish beyond doubt that retardation does in fact occur at the field scale.

An extensive hydraulic and non-sorbing tracer test is now underway at the H-19 well complex. This test employs seven (7) wells to investigate such transport issues as dispersivity, fracture spacing and matrix diffusion. Flow in different stratigraphic layers of the Culebra will also be examined.

Fluid Flow in the Salado Formation

Salt has always been considered a favorable host rock for a geologic repository because of its propensity to creep and recrystallize under stress load. This characteristic, plus the lack of observed dissolution within the Salado, led to the assumption that water flow through the Salado would not play a significant role in repository integrity. Because of the potential for gas generation from the wastes, drill stem tests (DSTs) in the Salado were conducted from the ground surface in the late 1970s to establish whether formation permeability would confine the gas. At that time the precise stratigraphic location of the repository had not been established and the DSTs could only evaluate large intervals of the Salado. These tests indicated very low, but non-negligible permeabilities, which were sufficient to dissipate gas before build-up to high pressures. As a result of this finding, gas generation studies were terminated. Access to the underground in 1983 allowed additional observations and tests to address the issue of fluid flow in the Salado units in the immediate stratigraphic interval of the WIPP excavation. A limited number of early in-situ permeability and flow measurements in the salt indicated a disturbed rock zone of increased permeability extending a couple of meters outside the excavation and a “free field” permeability much lower (<10^-20 M^2) than determined from the surface DSTs. Another observation was the seepage of brine to the surface of the excavations. This seepage was observed to vary lithologically, spatially, and to apparently decrease with time. Both observations led to extensive testing—to establish flow parameters of the Salado to explain and model the brine seepage and to implement gas generation experiments to better predict the potential for large volumes of gas. This was now necessary since the indicated low permeability would not allow for adequate escape of the generated gases. The added regulatory requirement (RCRA) to consider the transport of hazardous gases imposed still further incentive to understand both liquid and gas transport in the Salado.

Extensive testing of the Salado has provided considerable permeability data. The “pure” halite intervals exhibit permeabilities at or below the limit of our ability to measure—(10^-23 M^2). The argillaceous salt exhibits low but measurable permeabilities, one to three orders of magnitude greater than pure salt. Brine seepage has been studied by collecting accumulated brine volumes from many “sealed” boreholes. While the effects of the DRZ on these observations are impossible
to rule out, the observations seem consistent with the conclusion that brine seepage occurs from argillaceous halite--not pure salt--and that interbeds and their associated clay seams are also a primary source for and transport of brine.

Despite the study devoted to this area, there is still dispute over the fundamental mechanism controlling long-term brine seepage. One view is that in the undisturbed free field, the little permeability that exists is not interconnected and therefore continued flow into the manmade porosity is not possible and brine seepage will decrease and eventually stop as the brine in the DRZ is depleted. The other view is that, although the permeabilities of the interbeds and argillaceous halite are very small, d’Arcy flow will govern brine seepage from these units, and brine will ultimately fill all porosity until internal room pressure balances the free field pore pressure. Because the operating mechanisms for either process are so slow, and the interference of the DRZ so difficult to segregate, the existing data can be explained by either model within the range of reasonable parameter selection.

A major effort to resolve this issue was to bore a 350-foot drift and seal the entrance with an effective airlock. Pore pressure data outside the walls and brine collection inside the room were obtained. Resistivity measurements monitored the redistribution of brine in the DRZ around the room. Despite efforts to overcome the shortcomings of earlier, smaller-scale studies, the results of this test are inconclusive for the same reasons as stated above. Consequently, for purposes of performance assessment, the quantity of brine is established by assuming d’Arcy flow limited only by the hydrologic parameters appropriate to the situation.

Another aspect of the fluid flow in the Salado is the transport by fluids outward from the waste rooms driven by gas pressures in the rooms which potentially exceed the pore pressure in the formation. This is complicated by the need to consider the creation of fractures or separations at bedding planes if pressures exceed lithostatic pressure. The orientations of these openings are expected to be horizontal due to the presence of clay partings at the base of anhydrite interbeds and the presence of pre-existing fractures within the anhydrite. Both of these features may provide a minimum stress path for fracture propagation due to the lack of tensile strength across these features.

The geometry of propagation within these horizontal units is more difficult to establish. It is unlikely that a single fracture would propagate to the distance of the site boundary. Efforts of the petroleum industry to create horizontally extensive fractures has shown how unlikely this is. There may, however, be a tendency for a fracture network to develop in a generally preferred direction--perhaps influenced by such factors as regional dip. This is accommodated in the modeling by assuming a range of “flaring angles” which are more restrictive in geometry than uniform radial propagation. It is not practical to implement an experiment which would be of sufficient scale to effectively examine this issue. The natural heterogeneity of the interbeds make extrapolation of small scale results of dubious value.

WASTE ROOM INTERACTIONS\textsuperscript{(10,11,12)}
The starting point for all the WIPP performance assessment calculations is the waste disposal room and it is essential to have a good understanding of the possible range of physical and chemical conditions that control the source term and behaviors that can occur in the event of human intrusion. The physical process of room closure, fluid flow and chemical interactions are all closely coupled and can significantly affect one another.

The physical condition of the room due to creep closure can be reliably predicted as a function of time if the nature of the room contents (backfill, waste) is known. If the room is backfilled, the room closure will approach its final state of closure before internal gas pressures can build enough to provide much opposition to closure. The studies performed on consolidation of backfills such as salt or clay/salt mixtures show that they will compact to high densities and low permeabilities within 100-200 years. Therefore the nature of the waste form itself, which will vary over time with degradation, is the major uncertainty in determining the physical (and hydrologic) parameters of importance within the waste room. Experiments which assume various physical waste properties have examined the compacted properties such as strength and porosity, and indirectly, permeability. This range of parameter data is used by performance assessment to input such values as the amount of spilled and entrained waste into flow up a human intrusion borehole.\(^{(10)}\)

The degree of porosity remaining after compaction by room closure determines the maximum amount of brine that can enter the room and cause metal corrosion and gas generation, and also establishes the amount of liquid available to solubilize the actinides.

The chemistry within a waste room will be a determining factor in the solubility of actinides in brine. Consequently, extensive laboratory tests have been conducted to establish solubility for the possible oxidation states of critical actinides at different values of brine pH. In the last few years, the question of colloid formation and their role in contributing to source term and transport have been examined. Studies indicate most colloids will not be stable in the brines present for the WIPP. Solubility, rather than colloid concentrations, is expected to be the major factor for establishing the waste room source term.\(^{(11)}\)

The source term predictions will be based on models developed using information from laboratory studies, but both solubility and colloids will be the subject of tests using real transuranic waste. These tests are of liter and drum size scale and are still underway at Los Alamos National Laboratory (LANL). The results will be used to lend confidence to the predicted range of values and, where necessary, will be factored into the model parameters.

The information obtained from the solubility program provides the knowledge base to tailor waste room conditions to lower the solubility of critical actinides. For example, backfill with a cement component would assure basic conditions for which plutonium has been shown to be less soluble.

**GAS GENERATION**\(^{(12)}\)

As previously mentioned, gas generation studies were resumed when permeability studies indicated gas might not escape rapidly enough to prevent build-up of high pressure in the repository. This study received additional impetus when it became apparent that the WIPP would
have to comply with the no-migration variance aspect of RCRA. While volatile organic compounds are small in volume, they could be carried towards the unit (site) boundary by the much larger volume of gases derived from waste degradation.

Gases will be generated in the WIPP primarily by anaerobic corrosion of iron and aluminum and by microbial decomposition of organics, principally cellulose. Radiolysis has been determined not to be a major gas generation mechanism relative to the other two. Recent studies confirm the gas production rates and potential established in the late 1970s. Provided sufficient brine is present, there could be enough hydrogen from metal corrosion and CO₂ (primarily) from organics to generate enough gas to pressurize the repository, closed by creep, to pressures above lithostatic. Since pressure above lithostatic is not a realistic long-term pressure condition in halite, the repository would increase its volume and reduce its pressure by either expansion of rooms or creation of fractures as discussed in the prior section on rock mechanics. Studies also examined conditions which might lead to a decrease in gas production rates or volumes. Passivation of iron corrosion in the presence of high partial pressures of CO₂ was considered for a time to be likely, but continued testing has shown this not to be the case. Experiments continue to show, however, that liquid phase water is necessary for corrosion to proceed—water vapor alone is not conducive to significant anoxic corrosion rates. If sufficient brine is present for gas generation to proceed at its optimum rate, a few hundred years would be required for pressures to reach levels similar to lithostatic pressure. As gas pressure builds it will decrease, and eventually stop and reverse, the brine inflow into the room. Thus the brine-gas relationship is very interactive and potentially self limiting so that a saturated repository and lithostatic pressures may never be realized. There are factors which complicate this scenario and increase uncertainty such as the presence of a one-degree dip to the beds. This could allow brine to flow in at the bottom gas exits at the top. This is being examined in modeling calculations and will be incorporated in the final performance calculations.

Gas generation studies in the laboratory have been completed. At the Idaho National Engineering Laboratory (INEL), tests of gas generation which employ actual TRU wastes are still ongoing. These tests will serve to provide confidence in the laboratory test results and in the bounding values of gas generation the average stoichiometry model can be used to predict. Some gas generation data will also be produced by the source term tests at LANL although this is not the primary focus of these tests, and the test conditions could result in misleading rate data due to experimental conditions such as agitation.

This summary of scientific studies does not touch upon every experiment and test or upon every issue, but does indicate the major areas of investigation. With the exception of the real waste tests at LANL and INEL, all the currently-planned experimental data are now available. In some instances it has been impractical to provide total closure to an issue through experimentation. That is where other arguments such as bounding approaches or independent professional judgment are adopted to provide an acceptable, conservative input to performance assessment.

Finally, although this discussion has focused on the experimental tests and geotechnical studies, the area of performance assessment has been a major program development in and of itself. While performance assessment requires the input from the technical studies, it is the performance
assessment result and the associated sensitivity studies that can determine which experimental activities are required to improve confidence in compliance with EPA standards. Equally important, PA can be used to establish when enough testing has been completed in a given area, based upon compliance needs and uncertainty bounds indicated by the analyses.

Several studies have been carried out within the PA arena to allow the EPA probabilistic approach to compliance to be implemented. Codes which run rapidly, but reproduce the results of mechanistic calculations, allow the hundreds of necessary discrete calculations to be performed. Other issues, such as the probability of human intrusion, are critical in implementing the long-term performance modeling and have received considerable study within the PA group. The only practical approach to quantifying input parameters in this arena is through the application of expert judgment since no experiment can be devised to resolve the issues.

SUMMARY

Twenty-one years of geotechnical, chemical and physics studies have provided a comprehensive database to support a confident assessment of the WIPP’s long-term performance. Some studies have fully resolved issues—others have established bounds on a range of uncertainty. The limits of our knowledge in these areas have been defined, and these limits can be used in developing a conservative approach to compliance. The program will continue to assess the results of continuing experiments and other sources of new information to assure the performance assessment inputs and assumptions are consistent with knowledge obtained from longer duration tests.

REFERENCES


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Fig. 1: Location of the WIPP Site and Relation to Geologic Features Considered in Site Selection
Fig. 2: Generalized Geologic Cross-Section North-South through the WIPP Site
Tests:

A. 18 W/m² Mockup
B. DHLW Overtest
C. Intermediate Scale Rock Mechanics and Permeability Tests
D. Mining Development
G. Geomechanical Evaluation
H. Heated Pillar
J. Simulated CH TRU Tests (Wet) and Materials Interface Interactions Test (MIIT)
L. Plugging and Sealing
M. Small Scale Seal Performance Tests
T. Simulated CH and RH Tests
Q. Circular Brine Room Tests
V. Air Intake Shaft Performance Tests
WPP. Waste Package Performance, Simulated DHLW (B, A1)

Notes:
1. All Dimensions in Meters
2. Not to Scale

Fig. 3: Plan View of the In-Situ Experiments in WIPP
Fig. 4: Sealing System Proposed for WIPP Shafts
Fig. 5: Distribution of Rustler Halite and Culebra Transmissivity Around the WIPP Site