Dr-1511

ORNL-5052

GEOLOGIC DISPOSAL EVALUATION PROGRAM

Semiannual Report

for

Period Ending March 31, 1975

W. C. McClain

T. F. Lomenick

R. S. Lowrie

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

BLANK PAGE

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$7.60; Microfiche \$2.25

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ORNL-5052
UC-70 - Waste Management

Contract No. W-7405-eng-26

CHEMICAL TECHNOLOGY DIVISION

GEOLOGIC DISPOSAL EVALUATION PROGRAM SEMIANNUAL REPORT
FOR PERIOD ENDING MARCH 31, 1975

W. C. McClain, Program Director
T. F. Lomenick, Geologic-Hydrologic Studies
R. S. Lowrie, Engineering Studies

JULY 1975

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

MASTER

CONTENTS

	Page
Summary	vii
1. Introduction.	1
2. Geology and Hydrology	4
2.1 Bedded Salt - Southeast New Mexico Area.	4
2.1.1 Potash Resources Evaluation	7
2.1.2 Mineralogical and Chemical Analyses	7
2.1.3 Gas Cavities in Bedded Salt	9
2.1.4 Area Seismicity	9
2.1.5 Central Basin Platform Seismicity	12
2.1.6 Oil and Gas Resources Evaluation.	13
2.2 Gulf Coast Salt Domes Studies.	13
2.2.1 Radioactive Waste Management by Burial in Salt Domes	13
2.2.2 Investigation of the Utility of Gulf Coast Salt Domes for Storage and/or Disposal of Radioactive Wastes.	14
2.2.3 Hydrologic Base Map of the North Louisiana Salt Dome Basin	15
2.3 Studies of Salt Anticlines	15
2.3.1 Salt Valley Anticline, Paradox Basin, Utah.	15
2.3.2 German Cooperative Agreement.	16
2.4 Argillaceous Rock Studies.	16
2.4.1 Storage Caverns for Liquid Petroleum Gas.	16
2.4.2 Rock Types and Geologic and Hydrologic Settings Favorable to Deep Placement of High-Level Radioactive Wastes	27
2.5 Evaluation of the Pierre Shale Formation	29

BLANK PAGE

	Page
2.6 Preliminary Study of the Green River Oil Shale Formation of Colorado, Utah, and Wyoming	29
2.7 Carbonate Rock Studies	31
2.7.1 Stability and Tightness of the Columbus Limestone and Surrounding Rocks in the Vicinity of Barberton, Ohio	31
2.7.2 Geohydrologic Appraisal of the Dry and Stable Excavations in Limestone of the Kansas City Area.	33
2.7.3 Chalk Deposits of the Southeastern United States	34
2.8 Volcanic Rock Studies.	34
2.8.1 Implications of Studies at the Hanford Plant on Establishing the Utility of Volcanic Rocks for the Disposal of Radioactive Wastes.	34
2.8.2 Excavations at the Nevada Test Site	35
2.9 Crystalline Rock Studies	35
2.9.1 Hypothetical Prototype Sites of Repositories for Radioactive Wastes: Certain Metamorphic Rocks and Mudstone.	35
2.9.2 A Study of Mines in Precambrian Rocks of the Lake Superior Region.	41
2.9.3 Canadian Cooperative Agreement.	42
2.10 Arenaceous Rock Studies.	42
2.10.1 Porous and Permeable Formations for Disposal of Liquid Wastes.	42
2.11 References for Section 2	43
3. Developmental Studies	44
3.1 Rock Property Measurements	45
3.1.1 Thermal Properties.	45
3.2 Thermal Analyses	50

	Page
3.3 Rock Mechanics	50
3.3.1 Finite-Element Analysis	51
3.3.2 Semiempirical Model	53
3.4 Stored Energy Studies.	55
3.4.1 Storage of Radiation Energy in Salt	55
3.4.2 Stored Energy in Solidified Radioactive Wastes.	60
3.5 Rock-Waste Interactions.	62
3.5.1 Literature Review - Effect of Radiation on Geologic Formations Other Than Halites	63
3.6 Borehole Plugging - Salt Dissolution Studies	63
3.6.1 Borehole Plugging with Natural-Earthen Material	64
3.6.2 Hydrothermal Plugs.	65
3.6.3 Molten-Salt Plugs	67
3.6.4 Salt Dissolution.	67
3.6.5 Review of Current Practices	68
3.7 References for Section 3	76
4. Engineering Assessment Studies.	80
4.1 Waste Emplacement Studies.	80
4.2 Studies of the Bedded Salt Pilot Plant	81
4.2.1 Conceptual Facility Design Description of a BSPP.	81
4.2.2 BSPP In-Situ Experimental Program	81
4.3 Alpha Repository Studies	81
4.3.1 Surface Facilities Engineering Study.	82
4.3.2 Mine Layout Engineering Study	83
Appendix A.	85
Appendix B.	115

SUMMARY

Introduction

The Geologic Disposal Evaluation Program (GDE), as now constituted, has two objectives: first, to evaluate the suitability of all potential geologic formations and rock types in the continental United States as permanent receptacles or repositories for any category of radioactive waste using any appropriate emplacement technique. Second, for those promising geologic formation-waste type-emplacement technique systems, to carry out the research and development activities which could eventually lead to the establishment of actual waste repositories using one or more of these systems. During the current report period, emphasis has been focused on (1) geologic and hydrologic studies of a number of rock types, to permit their fundamental suitability for use as waste receptacles to be evaluated; and on (2) developmental studies, in particular those concerned with rock mechanics, rock properties, and radiation effects on rocks and borehole plugging.

Major changes occurred in the GDE engineering programs. The Bedded Salt In-Situ Experimental Program to support the high-level waste repository design effort at the New Mexico site was terminated late in August 1974. With the assignment of primary responsibility for the design, construction, and operation of an alpha repository to Sandia Laboratories in February 1975, all ORNL engineering efforts directed toward the design of an alpha repository at the New Mexico site were (or will be by the end of FY-1975) terminated. Engineering efforts are now directed solely toward evaluating and assessing promising waste disposal systems developed by the GDE Program.

Geology and Hydrology

The objective of the geologic and hydrologic studies is to investigate the general characteristics, features, and occurrence of a number of rock types so that their fundamental suitability for use as radwaste receptacles can be evaluated. The principal characteristics to be examined for this purpose are those which relate to stability (both short-term mechanical stability for the operations and long-term stability for preservation of waste containment) and tightness (i.e., isolation from

BLANK PAGE

the circulating waters of the biosphere). This will be done largely through study of mines and other underground openings that have been constructed in the various rock types throughout the country. The geologic formations or rock types under investigation include: (1) rock salt (interior salt domes of the Gulf Coast area; Salt Valley anticline and other structures in the northwest portion of the Paradox Basin; and deep bedded salt deposits of the Williston, Supai, and Salina Basins); (2) argillaceous rocks (shales and especially the Pierre Shale formation); (3) carbonate rocks (limestones in northern Ohio and Kansas City areas, and the Selma Chalk in Alabama and Mississippi); (4) volcanic rock (basalts and tuffs); (5) crystalline rocks (granitic intrusives and high metamorphics); and (6) porous and permeable formations for disposal of fluids.

Bedded salt, salt domes, and salt anticlines. The stratigraphy of the southeastern New Mexico repository site developed from cores taken from exploratory boreholes AEC 7 and 8 indicates that marginal commercial potash ore zones occur in the McNutt potash zone of the Salado Formation that overlies the three candidate salt horizons which are at depths of 1900, 2100, and 2700 ft. A single unit seismograph operating at the site since January 1, 1974, sensed one significant seismic event which is being studied in an effort to determine whether it might have been a small earthquake or a rock fall in a nearby potash mine. Based on geologic and engineering studies, it was concluded that no economically significant oil and gas fields are likely to be discovered in or around the site. Several studies are under way to determine tectonic stability, hydrologic stability, and the location of salt domes suitable for waste storage facilities. Preliminary analysis of the data indicates that several domes appear to be suitable. A preliminary geologic investigation of the salt anticlines in Paradox Valley, Utah, indicated that the deposits at the northernmost portion of the Salt Valley Anticline have the greatest potential for a waste repository site.

Argillaceous rock studies. A survey study was completed which explains and illustrates the critical geologic and hydrologic characteristics of several rock types, such as shale and mudstones, that would be instrumental in their containment of radioactive wastes. Since the

most affirmative evidence of hydrological tightness and mechanical stability of rock exists in subsurface excavation, a survey of the more than 80 caverns that have been constructed for LPS storage was conducted. Those regions of the United States which appeared most favorable for a waste storage cavern were delineated. Studies to evaluate the suitability of the Pierre shale formation and the Green River oil shale formations for a waste repository were also begun.

Carbonate rock. Studies to evaluate the suitability for a waste repository of the essentially dry limestone formations near Barborton, Ohio, and Kansas City were begun.

Volcanic rock. Studies are under way to provide information about the geologic and hydrologic factors affecting the utility of basaltic rocks and tuff for waste disposal. Specifically, information about the rock underlying the Hanford Plant Site and Nevada Test Site is being evaluated.

Crystalline rock. A study to evaluate the information available from geologic studies at the Savannah River Reservation and to extrapolate it to other areas in the eastern coastal plains with the same type rocks has begun. A similar study was initiated of the rock in the Minnesota, Michigan, Wisconsin, and neighboring Canadian areas to establish the geologic and hydrologic conditions that cause mines in this area to be dry or wet.

Arenaceous rock. Studies are under way to evaluate small and "enclosed" basins containing rock formations of adequate porosity and permeability to receive liquid waste.

Developmental Studies

Various studies are in progress to provide the experimental and developmental information that is necessary to support both the geologic and hydrologic studies and the engineering assessment studies - in particular, to evaluate the impact of the waste disposal operations per se, as well as other works of man on the long-term containment provided by any geologic formation. These studies include the development of borehole plugging techniques, mine stability and rock mechanics analysis, rock property measurements, and rock-waste interactions.

Rock property measurements. The coefficient of thermal expansion (CTE) for pure NaCl crystals and natural rock salt from Lyons mine has been measured. The CTE of the pure crystal agreed well with the reported literature values and fits the expression

$$\text{CTE} = \alpha \times 10^{-6} \text{ }^{\circ}\text{C}^{-1} = 41.03 - 2.984 \times 10^3/t^2 + 1.015 \times 10^{-2} t + 3.352 \times 10^{-5} t^2 .$$

Natural rock salt CTE measurements differed greatly in that the sample expanded rapidly and irreversibly on first heating to 140°C; this was probably due to the expansion of the brine inclusions exceeding the plastic limit of the salt lattice, thereby causing plastic strain or deformation. Thus, the results obtained on heating the sample are only valid for this particular time-temperature history. The results obtained on cooling, however, show that the true CTE of natural rock salt is essentially that of pure NaCl after the induced stress is relieved.

A device, the "plane probe," for rapidly measuring the thermal conductivity and thermal diffusivity of rock samples has been developed and tested, and is now operational. The results will be used in the thermal analyses studies which are being made to determine the effect that heat released from radwaste will have on various waste disposal systems of interest to the GDE Program.

Rock mechanics. The rock mechanics analysis effort is divided into two parts: a finite-element analysis technique using both thermoelastic-plastic and thermo-viscoelastic laws to model the stability of mine excavations, and a complementary semiempirical model to simulate a full-sized repository. Both models are being validated using appropriate actual mine stability data.

Stored energy studies. The stored energy studies on salt and solidified wastes were essentially completed. It was concluded that the storage of radiation energy in salt will not present any barrier to the safe operation of a salt mine repository. Data obtained with solidified wastes in a cooperative program with Pacific Northwest Laboratory are still being analyzed. A review of the general aspects of radiation damage and energy storage in solids, and pertinent physical and chemical

properties of rocks (in particular, silicate minerals and limestone), do not indicate any significant amounts of stored energy, or any significant radiation-induced chemical effects at gamma dose and fast neutron fluences ($<10^{17}$, >3.4 keV) which will prevail in the rock immediately adjacent to buried waste. This program is being redirected into a broad study of rock-waste interactions to obtain information, such as the migration of radionuclides from waste through the geologic formation, the effects of radiation on physical and chemical properties of rock, chemical interactions between waste and rock, the effects of high temperatures including melting (on both waste and rock), and methods for effectively isolating waste packages from the rock and circulating ground water.

Borehole plugging - salt dissolution studies. Because boreholes have been or will be drilled at all prospective waste repository sites, it is necessary, particularly for a salt mine repository, not only to study the dissolution of soluble rock historically and theoretically, but also to develop materials and techniques for emplacing and testing borehole plugs. Studies are under way to determine the history of salt dissolution around boreholes in the Hutchinson salt formation in Kansas; to develop and validate a mathematical model of salt dissolution around a borehole in a salt bed which would predict the size and shape of the cavity that would develop if fresh water enters the top of the formation with brine removal at the bottom; and to develop and validate a mathematical model of convective-diffusive flow in a static-water column in an open borehole.

There are also several ongoing programs to develop methods for mechanically forming a borehole plug with natural materials, such as shales, to chemically emplace a borehole plug by hydrothermal transport (usually by aqueous solutions at temperatures and pressures different from the ambient), and, for rock salt, to grow a molten salt plug "in situ." Civil engineering grouting techniques and commercial borehole plugging programs were also reviewed, and a survey of the literature pertaining to naturally occurring borehole plugs was carried out.

Most of these studies will be completed early in FY-1976. The information obtained will be evaluated and used in developing a program

to field test in situ promising plugging materials and emplacement techniques.

Engineering Assessment Studies

Engineering studies and analyses are needed to assess the technological feasibility of the many potential waste disposal systems so that promising concepts can be identified and developed into viable waste disposal systems. These engineering assessment studies are carried out under five broadly defined programs: (1) analyses of techniques for emplacing gaseous, liquid, or solid wastes in a geologic formation; (2) waste characterization; (3) waste disposal system evaluation; (4) development of promising waste disposal systems; and (5) repository design. Emplacement techniques currently being analyzed include the rock-melt capsule concept, the deep rock disposal concept for high level waste, and a generalized study of the emplacement of heat-generating encapsulated waste in a mined cavity.

Studies of the Bedded-Salt Pilot Plant. To document the Bedded-Salt Pilot Plant (BSPP) design effort, a Conceptual Facility Design Description report was assembled and given limited distribution in May 1974. This report is a file compilation of the work done under the technical supervision of ORNL by Kaiser Engineers, Inc.; the work was terminated in November 1972. Some updated information and design alternatives were added.

The BSPP in-situ experimental program was terminated in August 1973. A report documenting the planned experiments, the preliminary equipment design, the mine layouts, and the initial contacts with potash mine operators in the southeastern New Mexico potash field was placed in ORNL Central Files.

Alpha repository studies. In July 1974, the GDE program was directed to develop "in house" concepts and mine arrangements for the disposal of alpha waste and spent fuel hulls in a suitable geologic formation. Further guidance in August 1974, specified that the conceptual designs developed for the Lyons, Kansas repository and the BSPP should be reviewed, evaluated, and, based on current alpha repository design criteria, used to develop a concept for the surface facilities by "fitting"

them to the New Mexico site. This study was completed, and 15 drawings showing the location of the facilities on the site, as well as their conceptual design features, were prepared.

Stratigraphic data for the New Mexico site indicate that potential salt horizons exist at 1900, 2100, and ~2700 ft below the surface. Engineering studies for preliminary analyses of: (1) the stability of a mine layout in each of the three horizons; (2) the methods and equipment required for drilling spent-fuel hull canister emplacement holes; and (3) the various methods for excavating storage rooms, etc., and for transporting excavated salt to the hoisting facility are in progress, and will be completed by the end of FY-1975.

Early in February 1975, Sandia Laboratories was given the overall direction for the design, construction, and operation of the alpha repository, and ORNL was directed to provide Sandia with all pertinent information. Any further alpha repository design effort at ORNL will be at the request of Sandia Laboratories.

GEOLOGIC DISPOSAL EVALUATION PROGRAM**SEMIANNUAL REPORT FOR****PERIOD ENDING MARCH 31, 1975****1. INTRODUCTION**

The Radioactive Waste Repository Project at the Oak Ridge National Laboratory has for some time been engaged in a program directed toward establishing a Federal Repository for radioactive wastes, primarily solidified high-level waste, in a bedded salt formation. Early in 1974, the project was restructured and, to more nearly reflect its broadened scope, was renamed the Geologic Disposal Evaluation (GDE) Program. The objectives of the program are twofold: (1) to evaluate the suitability of all potential geologic formations and rock types as permanent disposal receptacles or repositories for any category of radioactive waste using any appropriate emplacement technique; and, (2) to carry out in an orderly, stepwise manner, those research and development activities which could eventually lead to the establishment of actual waste disposal repositories using one or more of the promising geologic formation-waste type-emplacement technique concepts.

The structure of the overall program is shown in Fig. 1.1. It is essentially a sequence of steps or phases evolving from the general to the specific. In the first phase (Preliminary Investigations), the general properties and fundamental characteristics of various rock types will be investigated without reference to either the waste type or emplacement technique. At the same time, the feasibility of various emplacement concepts will be evaluated without reference to the rock type. In both cases, the evaluations and assessments will be based upon generalized acceptance criteria. Additional information related to the characteristics of the various waste types will also be developed, as needed, during this phase. The three components will then be brought together to identify the most promising combinations of rock type, region of occurrence, emplacement concept(s), and waste type(s).

BLANK PAGE

PHASE I
PRELIMINARY
INVESTIGATIONS

PHASE II
DISPOSAL SYSTEM
DEVELOPMENT

Fig. 1.1. Schematic diagram of overall program architecture

BLANK PAGE

ORNL DWG 75-5333

PHASE II
DISPOSAL SYSTEM
CONFIRMATION

---

program and general approach.

The second phase (Disposal System Development) will then implement those plans for each promising combination and would consist of: reconnaissance geological surveys serving to narrow consideration from a general region to a few specific potential sites; refinement of the concept by selection among the various alternative possibilities; and initiation of experimental work, probably (but not necessarily) limited to laboratory efforts at this stage. Again, the information developed from the various investigations would be integrated, and the specific site-specific concept combination or system would be reevaluated in light of the detailed information available. It is probable that many of the rock type-emplacement concept combinations which showed early promise would be eliminated in this evaluation, leaving only a few combinations which appear sufficiently attractive to justify further development.

The third phase (Disposal System Confirmation) would consist of: specific, in-depth site confirmation studies; a series of in-situ experiments, the last one of which presumably could be an actual repository; and the required supporting engineering designs, design analysis, safety analysis, etc.

The program effort is divided into three major investigative tasks. The geologic and hydrologic investigations are concerned with the general characteristics, features, and occurrence of a number of rock types so that their suitability for waste receptacles can be evaluated. The developmental studies provide the information necessary to support both the geologic and hydrologic studies and the engineering assessment studies. The engineering assessment studies are concerned with evaluating the many potential waste disposal systems and carrying out the necessary research and development effort so that promising concepts can be evolved into viable waste systems.

This report, whose format follows the three major investigative tasks, is the first in a series of semiannual progress reports which will be issued to document the progress made in the GDE Program. Most of the subject matter discussed is either geologic or developmental in nature, as would be expected, since the engineering assessment depends on the data generated in these two areas. In addition, since this report also covers

the transition period between the Radioactive Waste Repository Project (RWRP) and the GDE Program, information on several RWRP programs is included.

2. GEOLOGY AND HYDROLOGY

The objective of the geologic and hydrologic studies is to investigate the general characteristics, features, and occurrence of a number of rock types so that their fundamental suitability for use as waste receptacles can be evaluated. The principal characteristics to be examined are those which relate to stability (both short-term mechanical stability for operations and long-term stability for preservation of waste containment) and tightness or isolation from circulating waters of the biosphere.

2.1 Bedded Salt - Southeast New Mexico Area (G. D. Brunton)

After the United States Atomic Energy Commission (USAEC) decided that the Cary Salt Mine, Lyons, Kansas, was probably not a feasible site for a permanent nuclear-waste repository, an extensive investigation^{1,2} narrowed the list of other potential sites to the bedded-salt deposits of the Los Medaños area in Eddy and Lea Counties, New Mexico. A portion of this area, designated as the repository site in Fig. 2.1, was selected as the site for a nuclear waste repository. Although the nature of the proposed project has since been changed (see Sect. 4), investigation of the site geology was continued as part of the GDE Program. Two exploration boreholes were drilled at the site during April and May of 1974. The first hole, AEC No. 7, at the northeast corner of the site, was cored from a depth of 1000 ft (approximately the top of the Salado salt formation) to a total depth of 3918 ft. The second hole, AEC No. 8, at the southwest corner of the site, was cored from the surface to a total depth of 3028 ft. Information from the cores and the geophysical logs [a set of gamma ray-neutron, sonic, electric (self-potential and resistivity), short-arm caliper, and density logs were run in both boreholes] was used to develop the stratigraphic sections for each borehole, shown in Fig. 2.2.

Fig. 2.1. Index map of repository site in southeastern New Mexico.

D.R. L. 75 41 54

Fig. 2.2. Stratigraphic borehole sections of AEC test holes 7 and 8.

2.1.1 Potash resources evaluation

The McNutt member of the Salado salt formation contains sufficient quantities of potash ore to support an extensive potash mining industry in southeastern New Mexico. Obviously, the presence of commercial potash ore under the site or in the buffer zone surrounding the site could seriously compromise its usefulness as a waste repository. As part of a potash resource evaluation program,* core samples of the McNutt potash zone from boreholes AEC No. 7 and AEC No. 8 are being analyzed for their potassium content.

The accepted cutoff level for commercial ore is either at least 4 ft of 10% sylvite or 4 ft of 4% langbeinite ore. Several of the ore zones listed in Table 2.1 approach this level (e.g., the fifth ore zone in AEC No. 7, the fourth ore zone in AEC No. 8, and the tenth ore zone in both boreholes). These preliminary results indicate that a more extensive program of potash sampling will be necessary over the whole site to determine the extent and distribution of the potash zones.

2.1.2 Mineralogical and chemical analyses

Core samples of the Salado salt section from bore holes AEC No. 7 and AEC No. 8, southeastern New Mexico, are being analyzed petrographically for mineral content by Prof. O. C. Kopp, University of Tennessee, and for complete chemical content by Prof. R. E. Beane, New Mexico Institute of Mining and Technology. The samples were chosen in such a way as to avoid obvious nonsalt formations (e.g., shale, polyhalite, sylvite, etc.). Both investigators are analyzing for water content and phase changes by differential thermal analysis--thermal gravimetric analysis (DTA-TGA) techniques. The petrographic analyses provide qualitative estimates of the mineral content and mineralogical paragenesis of the samples. The results of the chemical analyses from identical core samples will be reconstituted as a theoretical mineral composition for comparison with the petrographic analysis. The preliminary results of the

---

*This program is under the supervision of Mr. C. L. Jones, Special Project Branch, USGS, Denver, Colorado, who also furnished the data in Table 2.1.

Table 2.1. Potash summary for AEC drill holes in New Mexico
(preliminary data)

Rock unit ore zone	AEC No. 8			AEC No. 7		
	Depth (ft)	Thickness (ft)	Grade (wt %)	Depth (ft)	Thickness (ft)	Grade (wt %)
11th	1,521.8-1,523.1	No analysis-weakly mineralized		1,561.0-1,563.0	2.0	2.0% K ₂ O as sylvite and carnallite
10th	1,589.7-1,594.7	5.0	13.6% K ₂ O as sylvite 6.7% carnallite 20.1% kieserite 5.9% insoluble ^a	1,634.5-1,637.9	3.4	12.4% K ₂ O as sylvite 13.2% carnallite 0.6% kieserite 6.7% insoluble ^a
	1,590.5-1,594.5	4.0	14.7% K ₂ O as sylvite 5.8% carnallite 17.1% kieserite 7.1% insoluble ^a	1,633.9-1,637.9	4.0	10.5% K ₂ O as sylvite 12.5% carnallite 0.6% kieserite 5.7% insoluble ^a
9th	1,604.3-1,607.7	3.4	3.4% K ₂ O as sylvite 20.1% carnallite 0.9% kieserite 1.2% insoluble ^a	1,650.0-1,651.9	1.9	8.1% K ₂ O as sylvite 17.3% carnallite 0.4% kieserite 2.9% insoluble ^a
8th	1,630.4-1,634.4	4.0	6.4% K ₂ O as sylvite 3.1% carnallite 3.2% insoluble ^a	1,682.3-1,683.4	1.1	10.4% K ₂ O as sylvite and carnallite
7th	1,666.5-1,671.0	Not mineralized		1,714.3-1,719.1	4.6	2.3% K ₂ O as sylvite and carnallite
6th	1,681.9-1,683.3	Not mineralized		1,732.4-1,734.9	2.5	1.2% K ₂ O as sylvite and carnallite
5th	1,688.7-1,697.0	Not mineralized		1,736.5-1,741.9	5.4	12.8% K ₂ O as sylvite 8.7% kainite 10.8% kieserite 0.9% insoluble ^a
				1,736.5-1,740.5	4.0	16.4% K ₂ O as sylvite 5.3% kainite 9.4% kieserite 0.5% insoluble ^a
4th	1,753.4-1,757.4	4.0	11.0% K ₂ O as langbeinite 2.2% leonite 2.6% kainite 2.3% insoluble ^a	1,797.7-1,807.5	No analysis-weakly mineralized (0.8 ft with sparse pseudomorphs of kainite after langbeinite)	
3rd	1,764.1-1,777.6	No analysis-weakly mineralized (1.0 ft with crystals of langbeinite showing various stages of alteration to kainite and leonite)		1,814.9-1,819.4	4.6	5.8% K ₂ O as langbeinite 5.5% kainite 5.1% leonite 2.4% bloedite 2.1% insoluble ^a
2nd	1,781.9-1,786.5	No analysis-weakly mineralized (0.7 ft with 90% leonite)		1,832.8-1,836.1	Not mineralized	
1st	1,796.0-1,810.5	Not mineralized		1,846.1-1,863.0	Not mineralized	

^aWater insoluble matter.

weight loss determinations indicate that the moisture content of most of the salt is less than 0.4 wt %, especially in the salt samples from depths below 2750 ft. The preliminary chemical analyses listed in Table 2.2 indicate that the salt core samples do not contain any carbonate minerals and that the salt is of high purity (e.g., pure salt is 39.33% sodium and 60.66% chlorine).

2.1.3 Gas cavities in bedded salt

The existence of gas cavities in the Salado salt formation was first mentioned by Brokaw et al.³ Although some of these cavities have been breached in the process of potash extraction, gas pressure is always relieved slowly by the mining operation before the cavity is discovered. Problems with high-pressure gas pockets can occur during drilling operations. After AEC borehole No. 7 was completed, and during the demobilization of the drilling rig, a blowout occurred that blew drilling mud to an estimated height of 80 ft above the well head.⁴ After the well had been shut in for two days, the gas pressure was 127 psi. Analyses showed nitrogen to be the principal constituent of the gas (Table 2.3). The gas pressure continued to hold steady at about 115 psi with the valve closed until the well was vented prior to capping about a month later. A temperature log was run in the well on the day after the initial blowout, and three possible sources of gas, as indicated by temperature decreases, were found at depths of 1610 ft, 1886 to 1898 ft, and 2155 to 2320 ft. The 1610-ft source correlates with a potash zone that is known to have cavities. The size and distribution of gas cavities in the Salado formation are still to be determined, but the experience from the potash mining operations indicates that the existence of these cavities does not endanger mining operations.

2.1.4 Area seismicity

The region around the New Mexico repository site and the Permian Basin, in general, is and has been tectonically stable for millions of years. While the area has been subjected to uplift and downwarping on a regional scale since Permian time, no major faulting has occurred at the site. The tectonic activity associated with the basin and range structure

Table 2.2. Chemical analyses of salt core samples^a

Sample No. ^b	Constituent (wt %)									
	SO ₃	Na	K	K ₂ O	MgO	CaO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	Total
7-1343.0	0.99	38.60	0.35	--	0.15	0.66	0.01	0.00	0.00	100.52
7-1468.5	2.88	34.44	0.37	0.07	1.85	0.19	2.15	0.24	0.07	95.87
7-1534.0	1.67	36.10	0.52	--	0.22	0.64	0.01	0.00	0.00	97.06
7-1698.0	0.58	36.47	0.06	0.07	1.20	0.34	2.07	0.25	0.61	100.00
7-1755.0	0.65	38.12	0.23	--	0.13	0.08	0.02	0.00	0.00	98.77
7-1957.5	1.72	38.38	0.36	0.01	0.41	2.18	0.37	0.04	0.11	102.58
7-1969.0	0.32	38.76	0.08	--	0.22	0.08	0.15	0.02	0.04	100.27
7-1973.0	0.26	38.45	0.07	--	0.20	0.06	0.13	0.00	0.02	100.96
7-1983.0	1.11	36.00	0.61	--	0.40	0.46	0.01	0.00	0.00	97.79
7-1993.5	2.96	38.25	1.68	--	0.79	2.30	0.00	0.00	0.00	99.79
7-2703.0	1.46	38.36	0.02	0.01	0.26	0.79	0.25	0.06	0.05	100.16
7-2736.0	0.42	39.75	0.01	--	0.06	0.51	0.01	0.00	0.00	100.64
8-1900.0	3.20	38.14	0.98	--	0.47	0.39	0.00	0.00	0.00	100.78
8-1905.0	0.20	38.67	0.13	0.03	0.93	0.45	0.91	0.14	0.25	99.62
8-1916.2	0.92	38.48	0.21	--	0.13	0.44	0.00	0.00	0.00	97.89
8-1938.0	2.91	35.63	0.68	--	0.84	1.02	0.00	0.00	0.00	100.53
8-2068.0	2.49	37.41	0.08	0.01	0.31	0.89	0.38	0.05	0.07	97.68
8-2130.0	2.31	37.79	0.42	--	0.25	0.75	0.03	0.00	0.00	99.10
8-2460.0	1.14	38.75	0.03	0.01	0.20	0.62	0.19	0.03	0.06	98.03
8-2809.0	2.02	38.56	0.01	0.01	0.04	1.09	0.04	0.00	0.01	101.48

^aAnalyses performed by Prof. R. E. Beane, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

^bSample No. indicates hole and depth (in ft).

Table 2.3. Results of gas analyses made after blowout of AEC test hole No. 7, April 20, 1974

Sample collection record			Constituent in gas (wt %)					
Date collected	Date analyzed	Analysis by	Carbon dioxide	Oxygen	Methane	Carbon monoxide	Ethane	Nitrogen
4-20-74 1:30 AM	4-25-74	Bureau of Mines	0.00	0.00	2.14	0.000	0.05	97.81
4-20-74 1:30 AM	4-25-74	Bureau of Mines	0.30	0.00	2.12	0.000	0.05	97.53
4-22-74 3:30 PM	4-25-74	Bureau of Mines	0.01	0.81	2.05	0.000	0.05	97.08
4-22-74 3:30 PM	4-25-74	Bureau of Mines	0.00	0.00	2.18	0.000	0.05	97.77
4-23-74	5-2-74	United Chemical Corporation	0.324	0.00	0.00	0.000	0.031	99.645
5-17-74	5-28-74	United Chemical Corporation	0.54	0.00	Trace	0.000	0.042	99.904

in New Mexico occurs west of the Pecos River. The USGS rates the seismic risk at the site as 1 (minor) on the scale of 0 (none) to 3 (major). However, the site is in an isolated region that has no permanent seismograph installation to monitor local events that might have a direct effect on a waste repository.

Professor Allen R. Sanford, New Mexico Institute of Mining and Technology, has had a single unit seismograph operating at the repository site since Jan. 1, 1974. The source of most of the seismic events recorded has been identified as blasting in the nearby potash mines or, possibly, water flooding operations in the Texas oil fields on the Central Basin platform to the southeast of the site. A strong magnitude (3.7) shock was recorded at the site on Nov. 28, 1974, at 03:35:20 GMT. The shock occurred within 30 km northwest of the site, possibly at the National Potash Company mine (Fig. 2.1), which had a major rockfall at the time of this earthquake. Unconfirmed information suggests that the cause of the earthquake was the sudden subsidence of an entire block of rock above a large mined-out area. The relationship between the earthquake and the mine subsidence has not been decisively determined, but further studies of the event are being made. The operation of the single unit at the site is expected to continue.

2.1.5 Central Basin Platform seismicity

Although microearthquakes from the Central Basin Platform of eastern New Mexico and west Texas have been recorded for a number of years, the Central Basin Platform does not have a past history of major seismic events; geologically and tectonically, it appears to have been a stable feature for millions of years, at least since late Permian time. The microseisms appear to be associated with recent water flooding operations for secondary petroleum recovery methods in the Permian oil fields of Ward and Winkler Counties, Texas. To resolve the question as to whether these water flooding operations are the source of the microseisms, the Seismicity and Risk Analysis Branch of the USGS, Denver, Colorado, is preparing to set up a 12-station FM telemetry array (Fig. 2.1) around the oil fields on the platform. This array is to be in operation by July 1, 1975.

2.1.6 Oil and gas resources evaluation

Significant quantities of oil and gas are found in southeastern New Mexico; consequently, it is possible that an economically significant oil or gas field might underlie the site, seriously compromising its usefulness as a nuclear waste repository. This possibility is being assessed by Netherland, Sewell and Associates,⁶ consulting geologists. Based on geological and engineering studies as of May 1974, they have concluded that no economically significant oil and gas fields are likely to be discovered in or around the site. They are currently updating this evaluation of the oil and gas resources, primarily to take advantage of the information being generated by the increased oil and gas exploration activity.

The Bureau of Land Management, Gas and Oil Division, is monitoring the local oil and gas exploration activity, primarily to keep an up-to-date file on boreholes that might eventually have to be plugged to preserve the integrity of the site.

2.2 Gulf Coast Salt Domes Studies (T. F. Lomenick)

2.2.1 Radioactive waste management by burial in salt domes

The Engineering Mechanics Research Laboratory at the University of Texas, Austin, has concluded a review study⁷ of salt domes that addresses questions related to (1) the locations of candidate domes for waste repository use, (2) tectonic stability, (3) hydrologic integrity, (4) dome geometry, and (5) residual stresses. The conclusions are summarized below:

No direct, positive evidence is available to show that movement is not occurring in any salt dome. However, it is shown through geologic reasoning that the likelihood of movement of domes in the interior basins is extremely remote; if movement is occurring, it is taking place at such a slow rate that no problems are presented. It is also believed that the likelihood of future movement caused by geologic activity within the repository time span of a million years is very remote.

The possibility that dissolution might become a threat to containment was found to be slight, particularly if the repository is surrounded by

tight shale formations and is below the base of fresh water or actively circulating ground water. Other mechanisms which protect against dissolution, as well as evidence of dissolution or nondissolution in the past, are discussed. Possible flooding of repositories in domes was not found to be a serious threat.

Temperature rise data from Project Salt Vault⁸ (a demonstration test of disposal in salt conducted in an abandoned mine at Lyons, Kansas) were used to estimate temperature rises which might occur in domes, and some simplified calculations were made to determine the temperature rise that would occur under certain hypothetical conditions. These data indicated that heating, of the extent to be expected, poses no threat to dome stability.

The available data indicate quite definitely that creep or plastic flow around a cavity mined in salt will cause the cavity to close, but the rate of closure is so slow that no serious problems occur during the operating lifetime of a repository.

Dome and bedded salt were compared from the standpoint of their suitability for radioactive waste repository sites. Neither was found to be superior to the other in an overall sense. In fact, depending upon the ultimate repository design, dome salt may be the preferred geologic formation. In a survey of all known domes, 29 were identified as potentially acceptable candidates for a waste repository; at least five of these met most of the criteria for the ideal dome. Objections to the use of domes as waste repositories based on their future tectonic stability and hydrologic integrity can probably be resolved with little difficulty.

2.2.2 Investigation of the utility of Gulf Coast salt domes for the storage and/or disposal of radioactive wastes

The Institute for Environmental Studies, at Louisiana State University, has undertaken studies* to determine (1) the tectonic stability

---

*Work being done for ORNL under Subcontract-4112; Dr. J. D. Martinez is the principal investigator.

of salt domes, (2) the hydrologic stability of domal structures, and (3) precise sizes and shapes of certain key domes. Highlights of their work to date include the preparation of a geologic map of the North Louisiana Salt Dome Basin, which includes structural sections and isopachous maps of key beds that relate to dome growth in the area. From computer-produced salinity calculations and other data, geohydrologic cross sections have been completed for Cedar Creek, Castor Creek, Winnfield, Coochie Brake, Rayburns, Prices, Kings, and Minden domes. Although the analysis is not yet complete, it has been tentatively determined that Kings, Rayburns, and Minden are hydrologically stable. This determination is based on limited data which indicate isolation of the domes from aquifers by relatively impermeable sediments and, consequently, an absence of saline water plumes in adjacent aquifers. Cedar Creek and Winnfield appear to be unstable. The hydrologic stability or instability of the Castor Creek, Coochie Brake, and Prices domes is not readily apparent from the cross sections; further analysis is required. Work is proceeding on the final interpretations for Vacherie, Bistineau, and Prothro domes.

2.2.3 Hydrologic base map of the North Louisiana Salt Dome Basin

To aid in interpreting data from specialized studies of the hydraulic stability of domes, and to provide base-line information, a study of the regional ground water regime of the North Louisiana Salt Dome Basin is being initiated. The work will be carried out by the Louisiana District, Water Resources Division, U.S. Geological Survey, since most of the data needed for such a study already exist in their files.

2.3 Studies of Salt Anticlines (T. F. Lomenick)

2.3.1 Salt Valley Anticline, Paradox Basin, Utah

From generalized studies of all of the anticlines in Paradox Valley, it was concluded that the salt deposits at the northernmost portion of the Salt Valley Anticline have the greatest potential for waste repository use. The Special Projects Branch, U.S. Geological Survey, Denver, Colorado, is currently conducting investigations of this area. To date,

a geologic map covering 24 square miles of the area of interest has been compiled at 1:24,000 from existing published and unpublished data. In addition, geologic sketch maps of selected small hills within the collapsed center of the anticline are being constructed at 1:2400 from field sketches and from new color aerial photography. These hills are composed of contorted beds of the Pennsylvanian Paradox Formation cap rock or of folded and faulted Jurassic and Cretaceous strata that have collapsed along the crest of the anticline. Finally, cataloging and filing of the subsurface data pertaining to Salt Valley and adjacent areas have been initiated.

2.3.2 German cooperative agreement

A cooperative agreement covering the management and disposal of radioactive wastes has recently been executed between the Federal Republic of Germany and the United States. Although no formal implementation of this agreement has taken place thus far, several informal discussions have been held. Cooperation and technical exchange in this area are particularly attractive because of the seven years of operating experience with disposal of actual wastes in the Asse II salt mine in Germany, located in the Asse salt anticline.

2.4 Argillaceous Rock Studies (T. F. Lomenick)

2.4.1 Storage caverns for liquid petroleum gas

Undoubtedly, the most affirmative evidence of the stability and tightness of rocks exists in subsurface excavations. It is thus apparent that a definition of the critical and, perhaps, subtle characteristics of the rocks that affect stability and tightness in the vicinity of underground excavations, such as liquid petroleum gas (LPG) storage caverns, would be instrumental in establishing the utility of various types of rock for radioactive waste disposal.

During the past two decades, more than 80 caverns have been constructed in rocks such as shale, limestone, granite, and chalk for the storage of petroleum products. These caverns, whose capacities range up to 800,000 barrels, are located 300 to 3000 ft below the land surface. Some have required extensive grouting to provide containment, while others have

been observed to be completely tight. In addition, roof bolting and other means have been employed to enhance cavity stability in some cavities; in others, the roofs and pillars have remained intact with little or no artificial support.

Cobbs Engineering, Tulsa, Oklahoma, is presently conducting a study* of existing petroleum product storage caverns in the United States to determine the hydrologic tightness and the mechanical stability of these excavations. To date, they have reviewed the feasibility investigations, construction history, and operating experience of 75 mined storage caverns at 49 sites to relate their tightness or impermeability and stability to physiographic subdivisions, stratigraphic factors, characteristics of overlying and underlying beds, regional and local structure, and regional and local hydrology.

For study purposes, a site is defined as a property of only one ownership and only one geologic horizon. In a few cases, caverns have been constructed in two geologic horizons beneath a single property; for this report, this is considered as two separate sites.

Small water inflows into the storage caverns do not create problems of great magnitude for the storage of petroleum products that are immiscible with water. The inflow of any water is undesirable; however, within limits, it constitutes only a nuisance insofar as the operation of the storage cavern is concerned. This is not the case with all potential materials that might be considered for storage in mined caverns; therefore, much of the effort has been directed toward determining the conditions that would lead to a cavern in which there was no water inflow. A summary of these results is given in the following paragraphs.

Hydrologic and structural characteristics of caverns constructed in principal rock types. In the discussion below, the rock types utilized for storage caverns have been grouped into three broad classifications: crystalline rocks, carbonate rocks, and shales. In a few instances,

---

*Work being performed for ORNL under Purchase Order 78X-64509V by James H. Cobbs Engineering, 5200 S. Yale, Tulsa, Okla. 74153.

caverns have been constructed in a host rock which contained siltstone; however, since the shaly portion and clay mineral content predominated, they will be considered as shale. Many caverns have also been constructed in a shaly carbonate zone, a calcareous shale zone, or a zone of inter-bedded carbonates and shales. In these cases, the predominant mineral will provide the definition for the zone.

Crystalline rocks. - Ten caverns have been constructed at seven sites in Precambrian Crystalline rocks. Nine of these caverns at six sites are in the Piedmont Region of the eastern United States, and the remaining cavern is located on the Canadian Shield of northern Minnesota. The crystalline rocks at all of these sites have been subjected to severe metamorphism after their deposition and, in all but two cases, have exhibited serious jointing and fracture patterns, at least to the depth of the cavern. In two instances, the caverns were mined in an intrusive body within the basic metamorphic crystallines. There was an absence of jointing in the cases where mining was in the intrusive body, and these caverns had only very slight water inflow, if any, which occurred at the contacts between the intrusive body and the metamorphosed rock.

It might be speculated that the jointing which crystalline rocks exhibit will disappear with depth; however, this has not been demonstrated and must remain only a speculation since the deepest cavern has penetrated to less than 400 ft of crystalline rock.

These preliminary data indicate that generally metamorphosed or extrusive crystalline rocks will probably display permeability in the form of jointing or weathering patterns in the rock. Intrusive crystalline rocks which have not been subsequently metamorphosed or eroded probably offer a good potential for exhibiting very low permeability. The speculation regarding the intrusive rocks is, in part, borne out by caverns which have been mined in the Piedmont Region.

Structurally, the crystalline rocks offer excellent potential for mined caverns, because their strength is normally quite high and large openings can be made with little roof support required.

Carbonate rocks. - Structurally, carbonate rocks are similar to the crystalline rocks because their strength is normally high and large openings can be constructed with minimum roof support. The carbonate rocks, however, do present problems of water inflow during and after construction, as exhibited by the fact 4 of the 22 carbonate rock caverns were wet to some degree. Two of these caverns failed by virtue of water inflow or failure to pass a pressure test because of the jointing or fracturing channels.

The carbonate caverns that exhibited permeability through jointing or solution channels have been shown to have one common characteristic; that is, the formation in which the cavern was mined was unconformably overlain by the next highest formation. From this and general knowledge of the behavior of carbonate rocks when subjected to water erosion, it can be tentatively concluded that a water-free cavern would be unlikely unless there is a thick conformable sequence with a conformably deposited rock, such as shale, above the carbonate section.

A significant hazard often encountered in carbonate rock caverns is that solution channels or jointing patterns will not necessarily be intersected by boreholes which are drilled in the course of a feasibility investigation. In evaluating the potential for a site where carbonate rocks are the principal candidates as host zones, a great deal of reliance should be placed upon the geologic history and depositional environment during the geologic period(s) of the potential host rocks. If, at some period, the potential host rocks were subject to erosion or weathering, the probability will be high that solution channels, possibly undetectable by core drilling, will exist within the carbonate section. If permeability is detected during core drilling within the sequence, and there is no subsequent break in deposition to a shale, the entire carbonate sequence becomes suspect.

Although carbonate rocks exhibit many negative features when considered as potential host zones for mined caverns, they should not be rejected out of hand. Many excellent storage caverns have been constructed in carbonate rocks where, either by appropriate investigation or fortunate choice of the site, no weathering or deep erosion occurred during the history immediately following the deposition of these host rocks.

Shales. - Over one-half of all the storage caverns mined in the United States have been mined in shale. Shales have had the smallest incidence of water in the mined cavern of any rock type. Two caverns mined in shale have been failures, but these failures might have been predicted. One was a structural failure because of inadequate strength within the shale for openings of the size being made. The second was caused by severe fracturing of the shale due to its brittle nature and the major folding that occurred subsequent to its deposition. Other cases of water inflow into shale caverns have been the result of encountering a water-bearing and permeable zone either immediately above or immediately below the cavern mining interval. These water-bearing zones were open to the cavern either through drilling for roof bolts or mining sumps for product removal pumps.

As a class, the shales exhibit the lowest permeability of any rock on a gross basis. Selected specimens of the crystalline rocks exhibit an even lower permeability; on the other hand, when jointing patterns are considered for a gross permeability consideration, the crystalline rocks have normally exhibited permeabilities exceeding those of the shales. Exceptions to this statement occur when the shale was severely jointed as a result of uplift and brittleness of the shale.

Shales do not exhibit the high strength of the other rocks and oftentimes are subject to severe slacking from the absorption of water; however, with adequate ventilation to control humidity during construction and appropriate opening design accompanied with adequate roof support, the shales have been almost ideal host rocks for mined caverns. When calcareous material is present in the shale, such as in a limy shale or dolomitic shale, the strength of the rock increases in direct proportion to the carbonate content and the rock becomes even more effective as a cavern host material.

Hydrological and structural characteristics of caverns constructed in the major physiographic divisions of the United States. Table 2.4 is a tabulation, arranged by physiographic provinces, of the mined storage caverns that have been constructed in the United States. Figure 2.3 shows the locations of the cavern sites on a physiographic map.

ORN . DWG 75-5353

Fig. 2.3. Physiographic province location of cavern sites.

Coastal plain. - Five caverns have been constructed at a single site in the Atlantic Coastal Plain, in a Triassic red shale which had possibly been subjected to some metamorphism and had shown a large amount of uplift. These caverns were extremely wet due to water inflow through the jointing or fracturing system, and there was some evidence of exchange of product between caverns through this jointing or fracturing pattern.

In general, it can be concluded that the Atlantic Coastal Plain is not particularly favorable for the construction of mined storage caverns; the thick, unconsolidated, young materials, which are deposited unconformably on older crystalline rock, do not, for the most part, present candidate zones of sufficient structural strength or impermeability.

One cavern has been constructed in the eastern portion of the Gulf Coastal Plain, in the state of Alabama. This cavern was mined in the Cretaceous-age Selma Chalk which was found in outcrop at the surface and extended to a depth of 1200 ft. This chalk made a nearly ideal host zone for the cavern constructed at a depth of 330 ft. The chalk did not have the high compressive strength that other carbonate rocks exhibit, but it did have sufficient strength for the mining requirements; in addition, its permeability was near zero. The chalk or, possibly, shale sections developed within the East Coastal Plain are probably excellent candidates for mined storage facilities.

Piedmont province. - Nine storage caverns have been constructed at six sites in the Piedmont Region. All of these caverns have been constructed in Precambrian Crystalline rocks which have exhibited some degree of jointing and gross permeability. Two of the caverns were only slightly wet because of the absence of a well-developed jointing system. These caverns were mined essentially in an intrusive body within the metamorphosed crystalline mass.

At first glance the crystalline rocks of the Piedmont Region would seem to offer good potential for mined storage caverns; however, the severe distortion that these rocks have experienced throughout geologic time has led to major jointing and weathering patterns which extend to depths below any caverns that have been constructed. Although these

jointing and weathering patterns may disappear with depth, this can only be a speculation; thus, this province could not be recommended except as a last resort.

Appalachian Plateau. - Two caverns have been constructed in western Pennsylvania, within the Appalachian Plateau. The Pennsylvanian-age cyclothem type of deposition in many areas would preclude finding a potential host zone of sufficient thickness for a mined storage cavern. Some of the intense folding which has occurred in the Appalachian Plateau could give suspicion of extensive jointing or fracturing within otherwise acceptable host rocks.

Central lowland. - Seventeen storage caverns have been constructed on the crest and flanks of the Cincinnati Arch. The depositional conditions in this area, particularly through Ordovician and Devonian time periods, have led to the development of thick sections of uniform shales and carbonates with little, if any, break in deposition; such a condition promotes the proliferation of host zones of adequate strength and low permeability. Another factor that has made this region ideally suited for mined storage caverns has been the continuity of formations over extended distances of hundreds of square miles.

Eleven storage caverns have been constructed on the crest or flanks of the Kankakee Arch. Two of these caverns were failures because they were mined in a carbonate section which had been subjected to erosion and weathering after its deposition and prior to the deposition of younger beds. One other cavern had a reduced life because it was constructed on the axis of the arch where, due to appreciable thinning of the section, there was insufficient distance between the cavern and an aquifer above the cavern. This led to an eventual breakthrough of water into the cavern and its abandonment. This cavern was one of the first six caverns constructed in the United States, and the design or location would probably be altered in the light of today's knowledge. In general, the margins of the Kankakee Arch would seem to present good candidate formations for mined storage caverns, particularly in formations of Ordovician and Silurian age.

Twelve caverns have been constructed in the Illinois Basin; eight of these are in the south and west margins of the basins, and the remaining four are central to the basin. The caverns have been primarily

mined in Mississippian carbonates, although some have been mined in Pennsylvanian shales. All but one of the caverns constructed in the Illinois Basin have been dry and successful. The long, relatively stable, and quiet depositional history through Mississippian and Pennsylvanian times have made the Illinois Basin an excellent region for cavern construction. Thick, impermeable carbonate and shale sections exist over virtually all of the basin, characterized by good continuity of beds and good structural characteristics.

Five storage caverns have been constructed in Iowa within the Forest City Basin. Two of these caverns were constructed in Mississippian Shale, and the remaining three in Ordovician Shale. In particular, the eastern margins of the Forest City Basin, where Mississippian and older rocks can be found at relatively shallow depths, offer excellent potential for storage caverns. The Ordovician Maquoketa Series offers superior prospects for storage caverns because the calcareous shale exhibits excellent strength and no permeability.

Three storage caverns have been constructed in Pennsylvanian shales on the Central Oklahoma Platform; one cavern was constructed in a Permian shale. Although all of these caverns were successful, one was abandoned after ten years of operation because of water inflow and structural failure within the cavern. This geologic province offers potential for mined storage caverns, primarily in Pennsylvanian Shale sections; however, considerable site evaluation is required to determine the continuity of the shale and to confirm the existence of adequate shale thickness to preclude the possibility of encountering water outside the limits of the storage caverns. The one cavern that failed after ten years of service first encountered water from a thin, lenticular sand section which was penetrated when drilling for a roof bolt. The subsequent water inflow led to serious construction problems and ultimate abandonment of the cavern. Because of the problems associated with developing adequate assurance of sufficiently thick shale sections, the Central Oklahoma Platform is not a first-order candidate for mined storage caverns.

Great Plains Province. - Three caverns were constructed on the Nemaha Ridge at its northern end in Nebraska. Two of these caverns were

constructed in Pennsylvanian Shale; the third was constructed in Mississippian Limestone. One of the caverns constructed in shale suffered a structural failure during construction. The limestone from which the third cavern was constructed was wet due to weathering that occurred after its deposition and before Pennsylvanian deposition took place. In general, the northern regions of the Nemaha Ridge or Uplift do not appear to be a particularly good area for cavern construction.

One cavern has been constructed in the eastern rim of the Central Nebraska Basin in a Pennsylvanian Shale. This cavern and its host rock have been very nearly ideal; thus, at least insofar as the Pennsylvanian sediments in the basin are concerned, this area offers excellent potential for cavern construction. On the other hand, suitable host rocks might be at uneconomic depths for cavern construction in the central depths of the basin, but this is only a matter of speculation.

Superior Upland. - One cavern was constructed in Precambrian Canadian Shield rocks in northern Minnesota. This cavern was extremely wet because of a highly developed jointing or fracturing system which was encountered in the host rock. In general, the Canadian Shield rocks do not appear to be attractive host material for mined storage caverns because of the high probability of deep jointing and water flows.

Ozark Plateaus. - Two storage caverns have been constructed on the western flank of the Ozark Uplift. These two caverns were constructed relatively close together in Mississippian-age shale. Problems are encountered in finding suitable storage cavern sites on the Ozark Uplift because the sedimentary sequence is predominantly carbonate that has been subjected to severe distortion and weathering as a consequence of the uplift. Several feasibility investigations have been performed in the carbonate sections of the uplift; without exception, they have exhibited severe solution channels and extremely high permeabilities and water flows.

Wyoming Basin. - One cavern was constructed in Cretaceous Shale in the Rawlins Uplift. This shale was strong, but brittle, and had been subjected to flexure to the failure point during uplift. The failure of the shale manifested itself in the development of a jointing pattern which permitted very large water inflows into the cavern and the subsequent

inability of the cavern to pass the acceptance air-pressure test. In general, the Rocky Mountain Uplift region of the United States would present poor prospects for mined storage caverns because of the development of extensive jointing or fracturing within the potential host rocks as a result of their uplift and deformation.

Conclusions. Figure 2.4 illustrates the regions of the United States that are tentatively considered most favorable for mined storage caverns, with the provision that there be virtually no water inflow into the individual caverns after construction. The area outlined does not preclude other areas as being satisfactory; nevertheless, it is considered the most nearly ideal based on the information obtained from those caverns which have already been constructed.

The rocks most suitable for use as mined storage caverns are apparently those that were deposited during a geological environment which was of extended uniform deposition with a minimum of subsequent deformation and erosional history. Rocks deposited under these conditions seem to have the most ideal formations for cavern construction, at least in the case of the 75 caverns that have been constructed to date.

The most ideal rock types appear to be sedimentary rocks, with first preference being given to shale and second preference to carbonate rocks. However, the foregoing must be qualified because carbonate rocks are superior to shales in certain circumstances. Crystalline rocks, based upon the experience to date, have usually been too jointed and fractured to be considered ideal for water-free, mined storage caverns. This is especially true for the metamorphosed crystalline rocks. It appears that intrusive igneous rocks which have not been subjected to serious metamorphism or weathering might offer a good potential for mined caverns, but experience in these rocks is lacking.

2.4.2 Rock types and geologic and hydrologic settings favorable to deep placement of high-level radioactive wastes

Mr. Arthur M. Piper, consulting geologist, has completed a study which explains and illustrates the critical geologic and hydrologic characteristics of several rock types that would be instrumental in

Fig. 2.4. Favored area for mined cavern construction.

their containment of radioactive wastes. His report on this study is presented in Appendix A. The author, who is one of the foremost authorities in the world on ground-water movement, is quite cognizant of the problems of permanent disposal of radioactive wastes in rocks. He has also served in a review and advisory capacity with the National Academy of Sciences on many occasions. The fundamentals and principles described in his report provide the broad bases for our approach and objectives in the GDE Program.

2.5 Evaluation of the Pierre Shale Formation (T. F. Lomenick)

A large part of the Northern Plains region of the United States is underlain by thick and relatively impermeable shales. As a first step in evaluating the utility of these rocks for waste disposal, the Special Projects Branch, U. S. Geological Survey, Denver, Colorado, is making a study to determine the regional geologic and hydrologic characteristics of these shales that are commonly referred to as the Pierre Shale Formation. In addition, Prof. John Abel, Colorado School of Mines, Boulder, Colorado, has contracted to assemble, review, interpret, and document all available information concerning the structural and support characteristics of the formation.

2.6 Preliminary Study of the Green River Oil Shale Formation of Colorado, Utah, and Wyoming (T. F. Lomenick)

Netherland, Sewell and Associates, consulting petroleum engineers and geologists, has initiated a study* of the oil shales of the Green River Oil Shale Formation of Colorado, Utah, and Wyoming to determine (1) the suitability of the oil shale formations for possible waste disposal, (2) the economics of the oil shale formations as a source of oil and gas production, and (3) the feasibility and the economics of using the oil shale formations for possible waste disposal facilities.

---

*Work being performed for ORNL under Purchase Order 78X-70345V by Netherland, Sewell and Associates, Inc., 2000 Republic National Bank Bldg., Dallas, Tex. 75201.

In studying the suitability of the oil shale formations for possible waste disposal, investigations are being made of:

- (1) The "stability" of the storage cavities that the "room and pillar" type of mining in the oil shale formations might make available for possible waste disposal; included in this investigation is a consideration of the dryness and tightness of the seals of possible storage cavities.
- (2) The depth, areal extent, and thicknesses, as well as the lithology of the oil shale formations.
- (3) The presence and/or isolation from circulating ground water which might render the shale formations unsuitable for waste disposal.
- (4) Those adjoining formations either above or below the shales which may contain circulating ground waters and which, therefore, would be affected by possible waste disposal in the adjoining shale formations.
- (5) The various formation structures, dips, folds, faults, fractures, etc., that might tie into the consideration of circulating ground water.
- (6) The possible thermal effect on "stability" features, such as the compressive strength of the oil shale formations, and the manner in which this would relate to the "room and pillar" stability of roofs, pillars, etc., of the shale formations.

In studying the economics of the oil shale formations as a source of oil and gas production, investigations include:

- (1) The present extent of oil and gas production as well as the potential for possible future oil and gas production of the Green River Formation, not including the oil shales as a source of oil and gas production.
- (2) The oil shale formations with regard to their potential for the recovery of oil and gas - the areas in the oil shale formations of the greatest organic concentrations as well as the areas of lesser organic concentrations.
- (3) The general economics of recovering oil from the oil shale formations by different methods of extraction in the areas of greater and lesser organic concentrations.

- (4) The value of the oil shale formations for waste disposal compared with the value of the oil shale formations for the recovery of oil, as discussed above.

In studying the feasibility and the economics of using the oil shale formations for waste disposal facilities, investigations are being made of using:

- (1) The cavities remaining after "room and pillar" mining of the oil shales for the extraction of oil and/or other minerals.
- (2) Those areas of lesser organic concentrations which may be marginal when considered as source material for oil extraction.
- (3) Those areas of very low organic concentrations which would be unsuitable from an economic standpoint for the extraction of oil.

2.7 Carbonate Rock Studies (T. F. Lomenick)

2.7.1 Stability and tightness of the Columbus Limestone and surrounding rocks in the vicinity of Barberton, Ohio

Completely dry and stable openings are known to exist in the Columbus Limestone formation at Barberton, Ohio. Prof. D. W. Byerly, University of Tennessee, is currently analyzing all pertinent and available geologic and hydrologic data, locally as well as regionally, to determine and define the conditions that promote dryness in these rocks.* With these findings it is envisioned that it will be possible to identify specific study areas which would subsequently be evaluated for waste repository use.

The first phase of this work, which concerns the study of an existing mine at Barberton, is summarized below.

Barberton, Ohio, is located approximately six miles southwest of Akron, Ohio, and about 40 miles south of Cleveland, Ohio. The mine lies below a tract of land (Lot 64-T.IN.-R.12W.) embracing between 600 and 700 acres. Geologically, the mine is situated near the westernmost outcrop belt of the Pennsylvanian rocks of the Appalachian Basin and along a wedge of Devonian and younger strata which lap off the Findlay Arch.

---

*Work being performed for ORNL under Subcontract 4251 by Prof. D. W. Byerly, consultant.

The surface stratigraphy consists of Pennsylvanian conglomeratic sandstones and Pleistocene drift. The subsurface stratigraphic section which was revealed through pre-mine exploratory drilling extends from the above-mentioned units to the Salina formation of Silurian age. The mine is developed in the Columbus (Onondaga) limestone of Devonian age.

Lithologically, the Columbus is a gray-to-bluish-gray, partly crystalline limestone that is medium- to thick-bedded. Numerous horizons of chert, mostly in the form of nodules, occur in the mine section. There are also distinct shaly partings (often associated with stylolites) within the section. Prominent shale partings have been used in developing the roofs at the 17-, 28-, and 46-ft levels in the mine. X-ray examinations of these shales have been made, but the results have not been compiled as yet.

A microscopic study of the rock was made by Lee C. Armstrong of the E. J. Longyear Company, Minneapolis, Minnesota, in the early 1940s. His analysis is as follows:⁹ the rock is nonporous, medium-gray limestone with a few, very wavy streaks of dark-colored material. Mineralogically, he reports the following composition: calcite, 92%; dolomite, 3%; quartz, 2.5%; kaolin, 1%; pyrite, 0.3%; and asphalt, 1.2%.

The mine is serviced by two shafts 550 ft apart, one to a depth of 2320 ft and the other to a depth of 2258 ft. The mine is being developed by the "room and pillar" method. Entries are 32 ft wide by 17 ft high, and rooms are 32 ft wide and up to 46 ft high. Over 55 miles of tunnels have been developed, creating an estimated volume of 325×10^6 ft³. About 40% of this mined volume is at the 17-ft level, about 15% at the 28-ft level, and about 45% at the 46-ft level.

The temperature in unventilated areas (i.e., areas that are temporarily closed off) is approximately 85°F, while it is about 5°F lower in areas being worked (where there is forced-air ventilation). The mine is dry; no evidence of percolating water has been observed anywhere. The only water present is that which has been piped down for use in drilling and dust control.

Heavy cribbing, as well as concrete or "gunite," has been used around the entries leading from the main shaft to prevent excessive scaling of the walls. "Gunite" coatings on walls have also been used in other portions of the mine to prevent scaling.

Some methane was encountered during the shaft sinking, but it dissipated readily. Occasional blowouts occurred during roof-drilling through shale partings, which often caused excessive roof breakdown. This problem was remedied by drilling relief holes in the roof as the drifts were being driven. The mine is not considered "gassy."

Excessive wall sloughing occurred in drifts where adjacent drifts were taken to the 46 ft-level. Walls where this occurred are now stabilized with "gunite." Only minor cracking has been observed on the "gunite" surface. This wall sloughing, undoubtedly a result of strain in the rocks, has apparently been alleviated by leaving a 17- or 28-ft drift between 46-ft drifts.

The roofs at the 17-ft level are very stable. The roofs at the 28- and 46-ft level have experienced only minor breakdowns, located primarily at points where roof-drilling has penetrated too high. Stabilization at these sites has been accomplished by roof-bolting. The roof at the 46-ft level appears to be the least stable, based upon the amount of breakdown observed.

2.7.2 Geohydrologic appraisal of the dry and stable excavations in Limestone of the Kansas City area

A team of geologic consultants under the direction of Prof. E. D. Goebel at the University of Missouri, Kansas City, has initiated a study* directed toward defining, describing, and illustrating the topographic, geologic, and hydrologic features of the Bethany Falls Limestone and/or other formations within the Kansas City area that account for the dry and stable subsurface excavations in these rocks. Initially, the study will focus on the area of existing workings, which now totals about 140,000,000 ft² at 13 sites; later, however, it will be extended to cover rocks within a few tens of miles where the same geohydrologic conditions would prevail even in the deeper subsurface.

---

*Work being performed for ORNL under Subcontract 4299 with Dr. E. D. Goebel, consulting geologist.

2.7.3 Chalk deposits of the southeastern United States

Prof. Serge Gonzales, of the University of Georgia, has initiated a study* aimed at determining and defining the critical geohydrologic features of the Selma group of rocks in Tennessee, Mississippi, and Alabama responsible for the mechanically stable and apparently dry excavations that have been made at depths of a few hundred feet. These data would be instrumental in establishing the utility of the Selma and other chalk deposits in the United States for the storage and/or disposal of radioactive waste.

In particular, the depth, thickness, and rock and mineral composition of the group throughout its extent in the Southeast will be traced. Structural characteristics of the group would also be determined on a local as well as a regional level since any solutioning or water movement within the rocks would probably be closely controlled by joint and/or fault patterns. The geomorphic development of the present landscape must be ascertained because this would provide the basis for estimates of future erosion and removal of the chalk. Too, the surface and ground-water regimes of the area need to be defined, especially for any water-bearing rocks that lie in close proximity to the chalk deposits. Underground excavations provide a direct means for determining permeabilities and stabilities of these potential host rocks. Thus, a thorough examination of all such openings and/or available data would be invaluable. On a regional scale, the tectonics and seismicity are to be plotted and the resource potential (petroleum, cement) of the chalk, as well as other rocks that lie directly above or below the chalk, is to be determined. Finally, rails, highways, population centers, etc., that are situated astride the deposits would be delineated.

2.8 Volcanic Rock Studies (T. F. Lomenick)

2.8.1 Implications of studies at the Hanford Plant on establishing the utility of volcanic rocks for the disposal of radioactive wastes

During the 1960s, rather extensive investigations were made at the site of the plant at Hanford, Washington, to evaluate the potential of

---

*Work being performed for ORNL under Subcontract 4310 with Dr. S. Gonzales, Department of Geology, University of Georgia, Athens, Ga. 30602.

underlying basaltic rocks for containing high-level radioactive wastes. Although the data generated by these studies particularly assess local conditions, they also provide unique information relative to the critical geologic and hydrologic factors affecting the general utility of basaltic rocks for waste disposal. A review* of these previous findings at Hanford has been initiated by Mr. Arthur M. Fiper, consulting hydrologist.

2.8.2 Excavations at the Nevada Test Site

A large number of excavations, including shafts, cavities for emplacements of nuclear devices, tunnels, and drill holes, have been made in a variety of rock types at the Nevada Test Site. In addition, unique geohydrologic tests have been conducted in many of the excavations that would provide data on the tightness and stability of rocks such as granite and tuff, especially at great depths. In collaboration with the Special Projects Group of the U.S. Geological Survey, Denver, Colorado, work is under way to review and interpret the geologic data on excavations at the test site as they pertain to the hydraulic permeability and mechanical stability of the various rock types encountered. Special significance is placed on efforts to determine the effects of folding and faulting on rock tightness and permeability because the rocks in this region have been subjected to a moderate amount of deformation in the geologic past.

2.9 Crystalline Rock Studies (T. F. Lomenick)

2.9.1 Hypothetical prototype sites of repositories for radioactive wastes: Certain metamorphic rocks and mudstone

This study summarizes the available information with regard to two rock types in a geologic and hydrologic setting which has been explored rather intensively and can be taken as a hypothetical prototype site for a waste repository. The particular setting is that of the Savannah River Plant (SRP), of the Energy Research and Development Administration. The

---

*Work being performed for ORNL under Subcontract 3745 with Mr. A. M. Fiper, consulting hydrologist.

two rock types are metamorphic (gneiss, schist, and quartzite) and mudstone. Neither of these crops out within the SRP reservation, so that their characteristics and distribution there are known only from boreholes and seismic traverses. Most of the information pertains to the metamorphic (basement) rocks.

The general question at issue in this study is: To what extent can the information generated at the SRP reservation be extrapolated to other areas containing the same rock types, as a means of appraising those other areas as potential repositories for radioactive wastes? The two rock types are distributed widely in the Piedmont and New England province of the eastern United States, as well as in the Superior Upland province of the Great Lakes region.

The SRP reservation covers about 315 square miles of the Atlantic Coastal Plain on the north bank of the Savannah River, South Carolina, about 75 to 100 miles from the sea. Its land surface is formed on coastal-plain sediments of middle or early Tertiary age, and in large part is from 300 to 350 ft above sea level. The sediments of Tertiary age are underlain in succession by:

- (1) The Ellenton and Tuscaloosa Formations, which are largely, if not wholly, of upper Cretaceous age; together, they are about 600-ft thick and contain one or more conspicuously permeable zones that constitute a region-wide, principal fresh-water aquifer.
- (2) A layer of clay ("saprolite") which extensively is as much as 100-ft thick (but might be discontinuous) and, at least locally, constitutes a barrier to the vertical movement of ground water.
- (3) Locally by sedimentary rocks of Triassic age which grade from coarse sandstone or conglomerate to mudstone, probably are cut by numerous faults of small displacement, and possibly are bounded in part by a fault of large displacement.
- (4) Extensively, if not universally, by metamorphic ("basement") rocks of Paleozoic or Precambrian age.

The surface of unconformity at the top of the metamorphic rocks is known to be of moderate relief, perhaps as much as 150 ft.

The rational goal of managing high-level radioactive wastes should be to exclude from the biosphere all toxins in concentrations greater than are "permissible" in public drinking water. For unfractionated waste, this goal implies assured containment for a few million years within a repository structure and a surrounding zone of rocks prededicated to that containment.

It must be presumed that waste-enclosing canisters may be breached within a century. There is also the potential hazard that any rock medium may yield ground water sufficient to dissolve soluble constituents of the waste, and to transport those dissolved constituents at rates and in directions determined by the hydraulic drive of the water.

In regard to a waste repository in metamorphic rocks, only a non-transmissive variety of that rock type* appears to be satisfactory. The desired goal is maximum residence time of leached waste toxins within a prededicated containment zone of practicable extent. Ordinarily, this would be synonymous with residence time of the native ground water, under the applicable hydrologic regimen. For any particular repository site, this residence time must be determined in terms of equivalent defense against the dispersal of toxins--specifically, in terms of diminished relative toxicity.

Despite an intensive, decade-long exploration via boreholes, it has not been shown that nontransmissive metamorphic rock, in a mass of sufficient size to contain a hypothetical repository vault and to provide a surrounding zone of containment, exists beneath the Savannah River Plant reservation. This deficiency in knowledge is due, in part, to the 1000-ft-thick mantle of sedimentary rocks, which precludes identification of a favorable lithologic zone at the land surface and its projection downward to the depth of exploration.

In an area whose metamorphic rocks crop out, exploration from the land surface might prove to be relatively simple and adequately definitive. At the SRP, however, a shaft and exploratory tunnels were proposed to verify the extent of rock of the quality desired.

---

*The apparent hydraulic conductivity is estimated to be about 0.001 gdp/ft²; the calculated mean porosity is about 0.004%.

Metamorphic rock of somewhat inferior quality might, in principle, be repaired by grouting or analogous means. Of course, the long-term stability of the grout material, especially in the environment of the containment zone, could limit the practicality of such measures.

Conceivably, the small natural hydraulic conductivity of nontransmissive metamorphic rock, via fractures, could be largely nullified by sealing the faces of a repository vault and, at appropriate times, back-filling its galleries and injecting a sealant. An effective life of 1000 years for such measures seems attainable from a practical viewpoint. Assuming that the waste toxins are contained within a vault for such a term, the residual relative toxicity of ^{137}Cs would be about 0.003, of ^{90}Sr about 1, and of actinides as much as 10,000. In other words, the relative toxicity of 10-year-old waste would have diminished by somewhat more than five orders of magnitude. Such a reduction in hazard potential would represent a substantial achievement.

The form of solidified waste offers a wide range of leachability. In metamorphic rocks, the remaining defenses against dispersal of toxins--dilution by ground water and adsorption onto mineral surfaces--are of limited effectiveness and best reserved to offset unforeseen dispersal. Thus, for placement in metamorphic rocks, unfractionated solidified waste should generally be in a form having a very low solubility, such that the quantity of toxins leached would be less than the total toxins by a factor of 10^{-3} or, preferably, 10^{-4} . It seems reasonable, then, to expect that absolute containment of waste during its first 1000 years in a repository, coupled with the practically insoluble nature of the waste medium, would virtually eliminate all hazard to the biosphere.

Thus far, this summary has dealt only with unfractionated waste. Assuming that chemical separation could isolate a waste fraction, of relatively small volume, which contained substantially all of those nuclides whose term of required containment exceeds 1000 years, the greater fraction might conceivably be placed in a metamorphic-rock repository in the form of desiccated salt cake. The minor fraction of persistent toxins would, of course, need to be transported to a special repository in a more secure medium. Seemingly, a broad field of potential compromise among forms of solidified waste and repository procedures would be opened.

Thus far, this summary has considered only radioactive waste toxins in containment zones which may not be absolutely separate from the biosphere. However, on the one hand, certain separation-process wastes contain nonradioactive NO_2 , NO_3^- , and Hg in relative toxicities of about 6×10^3 to 2×10^4 . On the other hand, in certain areas and depth zones, metamorphic-rock waters have a high salt content and, by ordinary indicators, are wholly separate from the biosphere. In such circumstances: (1) very extensive containment zones become practical, (2) the previously noted defenses against dispersal of waste toxins could be relaxed or waived, and (3) both radioactive and nonradioactive solidified wastes might be deposited with acceptable hazard.

The mudstone of the SRP reservation is a common lithologic type among sedimentary rocks of Triassic age which underlie the Tuscaloosa Formation in a 5- to 7-mile-wide belt in the southeastern part of the reservation. This rock type offers a potentially superior setting for a repository vault to receive solidified radioactive wastes. Aspects in which the rocks of Triassic age appear to be a superior host rock may be summarized as follows:

- (1) The three boreholes which penetrate them show the Triassic rocks to be of extremely small hydraulic conductivity. For example, one borehole penetrated the Triassic for 95 ft, from 1218 to 1313 ft below the land surface; the bottom 60 ft was not cased. In 1963 this borehole was pumped, with a drawdown of 120 ft, in an unsuccessful attempt to obtain a water sample for chemical analysis. Six years later the water level had not recovered fully. From the rate of recovery, the hydraulic conductivity of the 60ft section of uncased Triassic was tentatively determined to be about 6×10^{-6} gpd/ft². This value is fully two orders of magnitude smaller than has been ascribed to nontransmissive metamorphic rock, and three orders smaller than tentatively ascribed to the clay layer that overlies the metamorphic rocks extensively.
- (2) While a second borehole was being drilled, with 920 ft of uncased hole in the Triassic and with the water level drawn down 1935 ft, the rate of water inflow was 0.14 gpm. No borehole in the metamorphic rocks has shown less inflow.

- (3) The third borehole penetrated 3040 ft of Triassic rocks, from about 1170 ft to 4212 ft below the land surface. One zone 430 ft below the top of the Triassic yielded about 0.1 gpm of water containing about 12,000 gpm of dissolved solids. The 2600 ft of uncased hole below this zone did not yield detectable inflow.
- (4) Driller's logs and cores from the three boreholes do not show zones of closely spaced fractures analogous to those of transmissive zones in the metamorphic rocks.
- (5) The Triassic rocks include mudstones in an aggregate thickness of hundreds of feet; even their coarser strata commonly have a fine-grained matrix. Presumably, therefore, they can be expected to have large adsorptive and ion exchange capacities.

Hydraulic gradients within the Triassic rocks, and also between them and the metamorphic rocks, are virtually unknown, although horizontal gradients probably do not differ greatly from those in the central part of the SRP reservation (which have been described). Incomplete data on water levels in boreholes indicate incomplete recovery from the effects of drilling; they suggest a relatively large potential hydraulic gradient upward, between the rocks of Triassic age and the overlying Tuscaloosa formation.

An average hydraulic conductivity of extremely small magnitude in the rocks of Triassic age, suggested by the scant data summarized above, implies potential waste residence times severalfold longer than in the metamorphic rocks, other hydrologic factors being the same. A single report of the chemical character of the Triassic-rock water implies that a very extensive containment zone would be feasible. The sections of Triassic rocks hundreds of feet thick, largely mudstone, which yielded no detectable inflow of water to boreholes, represent the ideal situation for a repository vault--a host medium virtually devoid of water over a sufficiently extensive space. These several implications would, of course, need to be confirmed by meticulous exploration; tunnels permitting in-situ inspection and tests might prove to be necessary.

A strong caution derives from an area in North Carolina where rocks of Triassic age, similar to those of the Savannah River reservation,

crop out. There, most of the wells drilled into these rocks yield very little, or no, water; however, a few which intersect faults, joints, or abnormally coarse-grained strata are moderately productive. Analogous permeable zones doubtless exist, at least locally, in the rocks of Triassic age beneath the SRP reservation; obviously, their spacing, geometric pattern, and hydraulic conductivity would need to be determined in evaluating the Triassic mudstone as a candidate site for a repository vault. The determinations probably could not be made readily and accurately from boreholes alone.

In mudstone, grain sizes tend to be poorly assorted and bedding to be indistinct and thick; thus, the conductivity to water is usually small. Further, the rock commonly has sufficient flexibility to have withstood some deformation without fracturing extensively. These attributes make any thick and extensive mass of mudstone an attractive candidate site for a waste repository. Each such site, however, must be qualified by thorough exploration, particularly of its regional hydrologic setting.

2.9.2 A study of mines in Precambrian rocks of the Lake Superior Region

Prof. D. Yardley, University of Minnesota, a specialist in Canadian Shield rocks, has initiated a study* of 10 to 20 of the driest mines in the Minnesota-Michigan-Wisconsin and neighboring Canadian area. The primary aim of these investigations is to establish precisely the geologic and hydrologic conditions that cause these workings to be dry or wet. Depth, rock types, overburden, faulting, jointing, etc., are some of the more critical water-controlling parameters to be studied. Hopefully, this work will lead to a definition of the most promising areas and/or rock types of the shield area for waste disposal and, possibly, to further investigations.

---

*Work being performed for ORNL under Subcontract 4367; Dr. D. Yardley is the principal investigator.

2.9.3 Canadian cooperative agreement

Atomic Energy of Canada, Limited (Canadian counterpart of ERDA), has determined that geologic disposal of their spent fuel and/or fission product waste from the reprocessing of spent fuel will probably become a required part of the CANDU fuel cycle. Therefore, they are initiating a program to survey and evaluate the geologic formations and rock types available in Canada for this purpose. This program will be closely coordinated with our Geologic Disposal Evaluation Program through an existing cooperative agreement. Several discussions, including a large, formal meeting at Oak Ridge National Laboratory in late August of 1974, have already been held with the Canadian group to implement this coordination and cooperation.

At the present time, the scope of the Canadian program consists of: (1) a survey of the characteristics of the several bedded salt formations in Canada (principal effort by the Geological Survey of Canada), (2) preliminary investigation and evaluation of the properties of several granitic intrusives in the Precambrian Canadian Shield region, and (3) examination of deposits of serpentinite for features which may be particularly attractive for waste disposal.

2.10 Arenaceous Rock Studies (T. F. Lomenick)

2.10.1 Porous and permeable formations for disposal of liquid wastes

Several small and "enclosed" sedimentary basins throughout the country are being studied for their possible utility as host media for the disposal of liquid (aqueous) wastes. Any wastes emplaced within these structures would be assured of remaining within a small and precisely defined subsurface area. These studies will also include waste-rock interactions, flow regimes, injection systems, etc.

In general, only those areas of the country underlain by thick deposits of sedimentary rocks are considered as likely reservoirs for the storage of liquid waste solutions. As a rule, igneous and metamorphic or crystalline rocks in depth are not fractured sufficiently or characterized by adequate porosity and permeability to provide satisfactory injection horizons. The principal geologic requirements for deep-

well injection include rock units or formations that extend over relatively large areas, have adequate porosity and permeability to receive the waste solution, and are confined by impermeable barriers to prevent the escape of waste solutions by intermixing with fresh-water reserves.

Thick, porous, and permeable beds of sandstone and limestone in closed sedimentary basins are perhaps the most desirable horizons for deep-well disposal of fluids, since dense liquids will not migrate laterally out of the structures and the wastes are confined vertically when impermeable beds of shale, clay, and evaporites lie immediately above and below the porous zone. Waste fluids may also be stored in suitable sedimentary rock strata in nonbasin-type structures. Structural, as well as stratigraphic, barriers may serve to restrict the lateral flow of liquids in these environments; however, there is usually considerably more uncertainty associated with determining the effectiveness of the confinement under these conditions than for closed basins. Thus, because of the great thicknesses of sedimentary rocks in basins, the restricted circulation of the liquids, and the relatively large amount of geologic information about them that has been obtained through extensive investigations for petroleum, sedimentary basins appear to be more suitable for disposal of liquid wastes than any other geologic environment. However, this should not imply that other geographic areas would not be appropriate for deep-well disposal.

2.11 References for Section 2

1. A. L. Boch et al., Radioactive Waste Repository Project Annual Progress Report for Period Ending September 30, 1972, ORNL-4824.
2. C. L. Jones, M. E. Cooley, and G. O. Bachman, Salt Deposits of Los Medanos Area, Eddy and Lea Counties, New Mexico, USGS Open-file Report USGS-4339-7 (1973).
3. A. L. Brokaw et al., Geology and Hydrology of the Carlsbad Potash Area, USGS Open-file Report USGS-4339-1 (1972).

4. R. F. Walters, Walters Drilling Company, Wichita, Kansas, personal communication to W. C. McClain, ORNL, Aug. 12, 1974.
5. E. A. Merewether et al., Shale, Mudstone, and Claystone as Potential Host Rock for Underground Emplacement of Waste, USGS Open-file Report USGS-4339-5 (1973).
6. Netherland, Sewell and Associates, Evaluation of Hydrocarbon Potential, AEC Study Area, Southeast New Mexico, GDE Program Open-file Report (May 1974).
7. J. O. Ledbetter, W. R. Kaiser, and E. A. Ripperger, Radioactive Waste Management by Burial in Salt Domes, EMRL-1112 (Jan. 17, 1975).
8. R. L. Bradshaw and W. C. McClain (Eds.), Project Salt Vault: A Demonstration of the Disposal of High Activity Wastes in Underground Salt Mines, ORNL-4555 (April 1971).
9. G. A. Morrison, Am. Inst. Mining, Met. Engrs. Spec. Rept. Ser. 1622, 2 (1943).

3. DEVELOPMENTAL STUDIES

The programs comprising this task will provide the information necessary to support both the geologic and hydrologic studies and the engineering assessments of waste disposal concepts. These programs are experimental (rock property testing and borehole plugging techniques) as well as developmental (methodology associated with rock mechanics analyses) in nature.

3.1 Rock Property Measurements (T. G. Godfrey,* S. H. Jury**)

3.1.1 Thermal properties

Thermal expansion of salt. Measurements of the coefficient of thermal expansion (CTE) of pure, single crystal sodium chloride and of natural rock salt (from the floor of the Lyons mine) have been completed in the CODAS CTE Apparatus.¹ The CTE for the pure crystal was very reproducible from room temperature to about 400°C, but self-loaded creep affected the measurements at higher temperatures. The natural rock salt, however, showed an entirely different behavior, which was probably the result of strain induced by the entrapped brine.

The results for a single crystal of sodium chloride, shown in Fig. 3.1, are expressed as the instantaneous coefficient of thermal expansion determined over a 20 to 100°C ΔT , rather than the more conventional average CTE from room temperature to a specified temperature. Data were obtained for heating stepwise to 518°C, for cooling to room temperature, and for heating to 719°C. An apparatus failure forced a cooldown to 518°C. The procedure was repeated and data were again obtained from 518 to 719°C and then cooling to room temperature. The calculated results from the first heating, though shown in Fig. 3.1, were not used in the analysis because of a shift of the sample in the apparatus that caused a change in the zero point. The high precision of the measurements is shown by the agreement of the CTE below about 400°C for heating and cooling. Above 400°C, however, compressive creep caused by the ~35-g-push rod and the sample's own weight produced a difference of about 1% in CTE for heating and cooling. The final length measurement indicated that the total creep was 185 $\mu\text{in./in.}$

Our CTE results are in excellent agreement with those of Enck and Donnel,² especially at the higher temperatures where the CTE is increasing rapidly. Agreement with results obtained by Leadbetter and Newsham³ is not quite as good, though differences are only about 2%. The cited measurements are not shown in Fig. 3.1, because the differences are too small to be apparent.

---

*Metals and Ceramics Division, ORNL.

**Consultant, University of Tennessee, Knoxville.

ORNL DWG 75-5285

Fig. 3.1. Instantaneous coefficient of thermal expansion for a single crystal of pure sodium chloride.

The CTE results for single crystal sodium chloride were least-squares fitted to yield the expression:

$$\text{CTE} = \alpha \times 10^{-6} \text{ } ^\circ\text{C}^{-1} = 41.03 - 2.984 \times 10^3/t^2 \\ + 1.015 \times 10^{-2} t + 3.352 \times 10^{-5} t^2 ,$$

where t = temperature, $^\circ\text{C}$, with an average error of 0.7% and a maximum error of 1.8%.

Quite a different picture was presented by the natural rock salt, as shown in Fig. 3.2. For these measurements, the ΔT 's for which ΔL 's were determined averaged 20°C . The temperature range was limited to about 200°C because of possible decrepitation of the sample. During the first heating to 140°C , the sample expanded rapidly and irreversibly, as shown by the results obtained for cooling. Subsequent heating repeated the cooling results up to about 130°C , but the CTE increased rapidly above that point. Final cooling from 200°C showed a marked deviation from the heating results and coincided with the earlier cooling results as well as with the results from the single crystal. The final increase in length at room temperature was $116 \text{ } \mu\text{in./in.}$ (expansion). The obvious reason for this net expansion is the stress caused by the expansion of the brine inclusions that exceeded the elastic limit of the salt lattice, and thus caused plastic strain or deformation. (Lyons salt averaged 0.5 vol % H_2O .) This is clearly a time dependent creep, and the present results may be considered valid only for this particular time-temperature history. The results obtained on cooling, however, show that the true CTE of rock salt is essentially that of pure sodium chloride after the induced stress is relieved.

Development of the plane probe. Measuring thermal physical properties of core samples pertinent to the GDE Program tends to be both tedious and time consuming. Research and development efforts have resulted in the development of a transient plane probe method for rapid (about 12 min, including data analyses), simultaneous measurement of the thermal conductivity (k) and diffusivity (α) at ambient conditions of core samples.⁴ The plane probe is readily adaptable to higher or lower temperatures so long as these are compatible with the materials involved. The system

Fig. 3.2. Instantaneous coefficient of thermal expansion for natural rock salt (Lyons).

utilizes a PDP-8 computer to provide completely automatic calibration, operation, and data acquisition and analysis. An outstanding feature of the probe data analyses scheme is that it is exact, and no approximations are used. Any deviations in the results are due solely to experimental errors.

A number of experiments were performed using amber gum rubber, Pyroceram,* and unfired lavite test specimens. National Bureau of Standards (NBS) thermal data were available for the gum rubber and Pyroceram. The probe was found to operate reliably from the start of the experiments. Also, a rise of 2 to 4°F (1 to 2°C) in specimen temperature was found to be more than adequate to obtain very reliable results. Variables investigated included loading of one-half to 18 psi with and without silicone oil or grease at the heater-specimen interface. Based on various statistical analyses, the effect of the oil or grease and the several loadings was found to be insignificant. The agreement of the measured k value for gum rubber is within 1% of the reported NBS value. Since the Pyroceram results are dependent upon the previously determined gum rubber results, the 1% agreement in k and 3% agreement in α is a fair assessment of the overall accuracy of the method.

Machined, unfired, lavite samples of identical size were prepared to test four sample configurations with various thermocouple emplacements. In this instance there are no reference values for comparison. In each case, the thermocouple was parallel to the plane heater and the effect of applied load is small. However, the differences between the various configurations are significant and probably result from the assumption of the exact location of the thermocouple junction for the various cases.

Further development of the plane probe device. The prototype version of the plane probe device has been replaced by a permanent experimental apparatus consisting of three probe chambers capable of operation from 0 to about 180°C. This new apparatus has been interfaced with a new PDP-8 Computer Operated Data Acquisition System (CODAS III).

---

*A trademarked glass-ceramic manufactured by Corning Glass Works, Corning, New York.

Measurements of samples from the New Mexico site will begin when the apparatus has been calibrated by comparative measurements on gum rubber and Pyroceram standards.

3.2 Thermal Analyses (H. C. Claiborne)

Thermal analyses studies are made to determine what effects the release of heat from the various types of radioactive wastes will have on the numerous waste, rock formation, and emplacement technique concepts of interest to the GDE program.

An examination of the available information indicated that more data on thermophysical properties were needed (particularly in relation to the effect of porosity, water content, pressure, and temperature) before credible thermal analyses could be made on the candidate rocks for nuclear waste disposal. The accumulation of additional information and correlation of the available thermal data has been initiated.

Two-dimensional calculations were also begun to determine the thermal characteristics of an alpha waste repository (including canisters of spent fuel cladding) in bedded salt using the heat transfer code HEATING-4, an improved version of HEATING-3,⁵ that can include phase-change effects. Use of this code in the initial thermal studies of other geological formations is planned. Final design calculations for any candidate rock will require three-dimensional calculations using the previously developed SIP code.

3.3 Rock Mechanics (W. C. McClain)

The rock mechanics analysis effort is divided into two parts: the first is based upon finite-element analyses techniques using both thermoelastic-plastic and thermo-viscoelastic behavior, and includes the laboratory rock property testing necessary to provide the data for input constitutive relationships. The second is based upon the special model developed for interpretation of the Project Salt Vault deformation data and, consequently, is called the semiempirical model. These two approaches are complementary. The semiempirical model is designed to provide a simulation of a full-sized waste repository with properly

time-sequenced excavation and waste emplacement; it yields an overall picture of the resulting deformations as a function of time, both in the mine and throughout the surrounding rock mass, including the surface. Due to the large scope, many details of stratigraphy are omitted or "averaged out," and the fine structure of the deformations cannot be obtained. However, this model is directly tied to the real world, because the required input parameters are determined by trial and error correlation with actual mine deformation data.

On the other hand, the finite-element technique is capable of modeling the details of the mine stratigraphy and provides the fine structure of the deformations, especially near the excavations and heat sources where the most severe conditions occur. The model is built around idealized deformation laws of viscoelasticity or elastic-plasticity, whereas actual in-situ salt probably behaves as a combination of these two idealizations. Furthermore, the rock properties are determined by laboratory testing that raises questions concerning the similitude with in-situ behavior.

3.3.1 Finite-element analysis

Most of the effort on this program* has been directed toward the development of code capability,⁶ and was largely completed by the middle of this reporting period. Codes were available (both thermo-viscoelastic and thermoelastic-plastic) for two-dimensional problems, axially symmetric geometry, large deformation (geometrical nonlinearities), and simulation procedures for the mining sequence. Although a preliminary formulation of strain hardening with temperature-dependent yielding was completed, it was not included in the thermoelastic-plastic code because of the lack of applied experimental data. Initial consideration of confining-pressure dependency of yield in the strain-hardening formulation revealed substantial mathematical complexity and, consequently, was not included. Consideration was given to the formulation of a

---

*Work being performed under Subcontract-4269 by RE/SPEC Inc. of Rapid City, South Dakota.

generalized creep law for adaption to the thermo-viscoelastic code, utilizing a state function approach.

From the viewpoint of specific applications of the codes to analyses of the salt-mine repository concept, consideration was given to the thermoelastic, thermoelastic-plastic, and thermo-viscoelastic loading of the salt on the steel sleeve. These studies included evaluations of both the stress and the displacement states during periods of heat generation by the waste for as long as 10 years. These analyses also provided stress and displacement information relative to the behavior of a typical section of the room and pillar configuration.

In order to assess the accuracy of the finite element procedures for computing the transient temperature rise in the salt as a consequence of heat generation by the waste, an analysis of the room-and-pillar configuration for the Lyons, Kansas concept was undertaken. On the basis of the quantitative agreement between these results and those previously obtained by ORNL with finite difference procedures, the analysis of the transient temperature field for the New Mexico pilot-plant concept was continued. Subsequently, initial consideration was given to the effects of free convection and radiation in the annulus between the waste container and the wall of the sleeve.

The experimental portion of this program is behind schedule in comparison with the analytical portion as a result of problems with equipment fabrication and procurement, unavailability of core material from the New Mexico site, and unexpected problems with specimen preparation. However, much data have been obtained for commercial pressed "block salt," including creep deformation over a confining pressure range of atmospheric to 3000 psi, at room temperature. These experiments were conducted for time spans up to 297 hr at differential stress for the salt. Further experiments, with time durations up to 4 hr were performed at differential axial stress levels substantially exceeding the initial yield stress. Experiments of this type on natural rock-salt specimens will provide considerable information about the time-dependent behavior for stress states both below and above the yield stress.

Because of the reorientation of the GDE Program away from bedded salt and toward other rock types, effort on the finite-element rock

mechanics analysis was redirected toward completing and finalizing present capabilities, and toward the preparation of final completion reports documenting the capability. Several topics have been completed,⁷⁻¹⁰ including the several heat transfer codes that are used with and coupled to the finite-element codes, and the thermoelastic-plastic analysis of the sleeve-hole liner for assuring retrievability of canisters of high-level waste in pilot plant operations. The results of this analysis indicated that a sleeve which was grouted into a hole in the floor would be subjected to horizontal collapse stresses averaging about 3500 psi, with possible peak stresses reaching 5000 psi. These stresses are entirely a consequence of the heating when the waste is installed, but would require the sleeve to be very thick walled. On the other hand, the analysis also indicated that a relatively small air-gap (a few tenths of an inch) between the sleeve and the salt wall of the hole would be sufficient to prevent contact loading and would not constitute an appreciable thermal barrier.

In addition to the final completion documentation on outstanding topics, the principal effort in this program during the next year will be the validation of the thermoelastic-plastic and thermo-viscoelastic modeling capability for mine excavations, and in-place heat sources by comparison with the deformations and other results obtained from the Project Salt Vault experiment. This validation will include sufficient testing of specimens from the Lyons, Kansas salt-core stock to obtain the necessary physical property parameters.

3.3.2 Semiempirical model

The principal accomplishment on this portion of the rock mechanics analysis program during the reporting period was the completion of the preliminary checkout of the model for simulating the behavior of a full-sized high-level waste repository. This model required an expansion in both size and total length of time, as compared to the previously correlated Project Salt Vault experimental area model; consequently, an extensive series of internal checks was required. These checks included:

- (1) Confirmation that the simulated deformations are not dependent upon the length of time step used in the problem.

- (2) Evaluation of the differences in results when the mine area is divided into elements of different sizes.
- (3) Check of the model performance for mining horizons at different depths.
- (4) Examination of the model behavior for various characteristics of the heat sources.
- (5) Confirmation that the arbitrary parameters describing width-height ratio of the mine pillars, overall extraction ratio and creep-effective stress were being assimilated within the model in the proper way.
- (6) Examination of the effect of the fundamental parameters (creep properties, elastic constants, etc.), which served primarily to confirm that the program was operating properly.

A topical report is being prepared which describes this checkout procedure and the results in detail; in addition, it also discusses the theoretical basis for the semiempirical model and its development into a computer simulation technique.

Other effort during the reporting period has involved the translation of the previously correlated Project Salt Vault experimental area model into a more flexible mine design tool. This translation involves removal of all portions related to heat sources, modification of the data input formats to facilitate the running of a wide variety of mine geometries and optimization of the requirements for fast memory space. This translation will provide improved capabilities for two principal objectives: (1) analysis of alternative mine layouts for an alpha waste repository, in support of the current program to establish such a facility in southeastern New Mexico, and (2) facilitate the implementation of a possible technical cooperative agreement with the Province of Saskatchewan, Department of Natural Resources. This possible agreement is being explored at the present time and appears to offer several advantages to both sides. They are interested in the semiempirical model, because preliminary trials suggest that it may accurately simulate the behavior and deformational characteristics of the deep potash mines in the Province. Our interest stems from the fact that a large amount of actual underground measurements would become available for correlating various

analyses of the structural performance of deep salt. This issue is of particular importance in the current repository program because of the 2700 ft depth of one of the most desirable possible disposal horizons at the southeastern New Mexico site.

3.4 Stored Energy Studies (G. H. Jenks, C. D. Bopp)

3.4.1 Storage of radiation energy in salt

The results of previous work¹¹ with bedded salt from the Carey mine at Lyons, Kansas, and with Harshaw synthetic crystals showed that energy storage in salt in a waste repository would be negligible at salt temperatures exceeding 150°C. It was also indicated¹¹ that energy storage in Harshaw salt at 95°C reaches saturation in the range of 30 to 40 cal/g. However, since only a few experimental results were available for bedded salt at temperatures less than 150°C, and since no results were available for dome salt, experimental work was undertaken to obtain additional information on the effects of dose, temperature, and source of salt on the accumulation of stored energy in salt in this temperature range.

Reaction products and stored energy released from irradiated sodium chloride by dissolution and by heating.¹² It was found that the amount of heat evolved upon aqueous dissolution of irradiated sodium chloride samples were consistently about 50% lower than the stored energy released during heating of the samples. Since it seemed likely that these differences could be explained in terms of the reactions that take place during dissolution, a series of measurements to help identify such reactions were made. Parameters measured included heat release upon thermal bleaching and upon dissolution of irradiated samples, identity and quantity of gases evolved during aqueous dissolution, and concentrations of hypochlorite ion formed during dissolution.

Analyses of the experimental data for Harshaw salt, which was irradiated in a cobalt source at either 95 or 126°C, indicated that essentially all of the trapped electrons, Na^+e^- , react with H_2O during dissolution to form H_2 :

At the same time, essentially all of the trapped holes, $(\text{Cl}^-)^+$, react with H_2O to form HOCl and OCl^- :

The results also indicated that the stored energy per defect pair in the salt, $\text{Na}^+\text{e}^- + (\text{Cl}^-)^+$, is approximately equal to the heat of formation of crystalline sodium chloride from the elements (i.e., ~ 4.25 eV) and that the defects are in the form of agglomerates of trapped electrons (probably colloidal sodium) and trapped holes (probably colloidal chlorine).

Storage of gamma-ray energy in Harshaw salt at 126°C. Samples of Harshaw salt were gamma irradiated in a cobalt source ($\sim 10^7$ rads/hr) to a variety of doses ranging from 0.35×10^{10} to 3.5×10^{10} rads. Stored energy (E) vs dose (D) results of drop calorimeter and OCl^- measurements¹² were correlated using the rate expression,¹¹

$$dE/dD = K_1 - K_2 E , \quad (3)$$

with

$$K_1 = 1.4 \times 10^{-9} \text{ cal g}^{-1} \text{ rad}^{-1}$$

$$K_2 = 7.0 \times 10^{-11} \text{ rad}^{-1} .$$

Equation (3) indicates a saturation value of stored energy equal to (K_1/K_2) . For the above values of K_1 and K_2 , this term equals 20 cal/g. A detailed discussion of these data and correlations will be included in a topical report.¹³

Storage of gamma energy in bedded, dome, and Harshaw salt at 130°. Gamma-exposures of these salts were made at $\sim 130^\circ\text{C}$ using the HFIR-spent-fuel element facility.¹¹ The irradiated specimens were analyzed for H_2 evolution upon aqueous dissolution.* A few specimens were also analyzed by drop calorimetry. The experimental conditions during exposure, the experimental results, and correlation information are listed in Table

---

*Work performed by the Analytical Chemistry Division at ORNL using gas chromatography.

3.1. A plot of the results for the bedded salts and a calculated correlation curve are in Fig. 3.3; the general correlation equation listed in Fig. 3.3 is the integral of the rate expression given in Eq. (3).

Most of the calorimetric and H_2 -evolution data fit the general correlation relationship between stored energy and dose. The value of K_1 was independent of the type of salt, and it equaled that for both the 95 and 126°C Harshaw salt. The value of the annealing constant, K_2 , for the Harshaw salt exceeded that for the bedded salt by a factor of 1.40. The doses to the dome salt were below those at which K_2 could be evaluated.

The calorimetric results for the set of specimens from exposure 78 were out of line on the high side of the correlation curves by up to 80%, while the amounts of H_2 evolved during aqueous dissolution remained in line. The temperature control for this set of specimens was one in which the temperature cycled 5 to 7°C about one time each 100 sec. The specimens in exposure 78 were first irradiated to ~7000 Mrads, were then stored in air at 34° in a low-intensity gamma field (~100 rads/hr) for 17 days, and were finally irradiated for an additional ~8000 Mrads at 130° prior to the calorimetric and H_2 measurements. These specimens returned to in-line behavior during a still further irradiation exposure of ~7000 Mrads in which the constant electrical power control was used. A constant electrical power control¹¹ was used with the other exposures.

Summary of conclusions. The results of this work support our previous tentative conclusions¹¹ that storage of radiation energy in salt will not present any restriction to the safe operation of a salt mine repository. The most recent calculations of dose rate in rock salt surrounding buried waste were made by Claiborne¹⁴ for a 12-in.-ID canister, 8-ft high, containing 10-year aged PWR-U waste.¹⁵ Upon integrating his dose-rate values, we found that the gamma doses in rock salt at the outer surface at the midplane of the can would be 1.2×10^{10} rads, 1.3×10^{10} rads, and 1.9×10^{10} rads at 90, 1000, and 10^7 years after burial, when the can contained 3.2 kW of 10-year aged waste at burial. In the present work, the investigated doses ranged up to about 3×10^{10} rads, and the maximum stored energy was about 27 cal/g. This maximum stored energy is well within the range for which previously reported^{11,16} considerations showed that no apparent hazard to the safe

Table 3.1. Exposure conditions and results of stored energy measurements for HFIR-gamma exposures 7B, 9, and X at 130°C

Salt source	Type	Sample and exposure No. ^a	Dose ^b (10 ¹⁰ rads)	Stored energy from results of H ₂ measurements				Predicted stored energy ^g (cal/g)	Calorimetric measurement ^d	
				From prior exposure ^c		After this exposure ^d			Cal/g	Date
				Cal/g ^e	Date ^f	Cal/g ^e	Date			
New Mexico	Bedded	29-X	0.73	-	-	8.3 ± 0.2	2-25-75	8.5		
		30-X	0.73	-	-	7.9 ± 0.1	2-25-75	8.5		
		31-X	0.73	7.7 ± 0.4	2-25-75	15.2 ± 0.5	2-25-75	13.8		
		32-X	0.73	16.7 ± 0.9	2-25-75	19.7 ± 0.1	2-25-75	19.9		
		18-9	0.65	-	-	7.9 ± 0.03	12-12-74	7.7		
		18a-9	0.65	-	-	7.7 ± 0.4	2-25-75	7.7		
		20-9	0.65	12.7 ± 0.03	11-22-74	17.1 ± 0.2	12-12-74	16.8		
		20a-9	0.65	12.7 ± 0.03	11-22-74	16.7 ± 0.9	2-25-75	16.8		
		7-78	1.44	-	-	12.7 ± 0.03	12-12-74	14.2	27 ± 10%	12-5-74
		7a-78	1.44	-	-	12.3 ± 0.2	2-25-75	14.2		
		8-78	1.44	-	-	12.1	12-12-74	14.2		
		9-78	1.44	-	-	12.8	12-12-74	14.2		
Marshall	Synthetic crystal	26-X	0.73	-	-	7.9 ± 0.1	2-25-75	7.9		
		27-X	0.73	7.8 ± 0.5	2-25-75	13.5 ± 2.2	2-25-75	12.5		
		28-X	0.73	12.4 ± 0.3	2-25-75	14.3 ± 0.1	2-25-75	15.2		
		12-9	0.65	-	-	8.6 ± 0.1	12-12-74	7.3	9.4 ± 10%	1-20-75
		12a-9	0.65	-	-	7.8 ± 0.5	2-25-75	7.3		
		14-9	0.65	11.3 ± 0.1	11-22-74	14.7 ± 0.1	12-12-74	14.3	12.4 ± 5%	12-16-74
		14a-9	0.65	11.3 ± 0.1	11-22-74	12.4 ± 0.3	2-25-75	14.3		
		1-78	1.44	-	-	11.3 ± 0.1	11-22-74	12.5	16 ± 4%	12-17-74
		1a-78	1.44	-	-	10.5 ± 0.1	2-25-75	12.5		
		2-78	1.44	-	-	11.0	11-22-74	12.5		
		3-78	1.44	-	-	11.7	11-22-74	12.5		
Lyons	Bedded	16-9	0.65	-	-	8.1 ± 0.3	12-12-74	7.7		
		17-9	0.65	13.5 ± 0.2	11-22-74	17.7 ± 0.3	12-12-74	17.3	17 ± 12%	1-21-75
		4-78	1.44	-	-	13.5 ± 0.4	11-22-74	14.2	24 ± 10%	12-5-74
		5-78	1.44	-	-	13.5 ± 0.2	11-22-74	14.2		
		6-78	1.44	-	-	13.0 ± 0.3	11-22-74	14.2		
Grand Saline	Dome	22-9	0.65	-	-	7.7	12-12-74	7.7		
Winfield Mine	Dome	24-9	0.65	-	-	8.0 ± 0.4	12-12-74	7.7		
Weeks Island	Dome	25-9	0.65	-	-	9.2 ± 0.4	12-12-74	7.7		
Asse	Dome	23-9	0.65	-	-	8.0 ± 0.1	12-12-74	7.7		

^aThe "a" samples were analyzed for I_2 evolution on 2-25-75 along with specimens from exposure X. The "a" samples were from the same materials as those, with the "a," analyzed earlier. Exposure 7B was accomplished in two separate exposures: 7 and B.

^bAverage dose rates were 46, 48, 34, and 44 Mrads/hr for exposures 7, 8, 9, and X, respectively. Doses were 6600, 7900, 6500, and 7300 Mrads, respectively.

^cSome specimens were irradiated in more than one exposure.

^dValues show the spread between duplicate (or several) measurements.

^eCalculated from H₂ results using 4.25 eV $\frac{1}{2}$ H₂.

^fExposures 7, 8, 9, and X removed from gamma source on 10-18-74, 11-11-74, 12-10-74, and 2-14-75, respectively.

^gUsing correlation equation and constants given in Fig. 1 for all samples of bedded and dome salt. Those used with Marshall salt were the same, except that the value of K_2 was 1.40 times that of the bedded salt.

Fig. 3.3. Stored energy in New Mexico and Lyons bedded salt before and after gamma irradiation at 130°C in HFIR-gamma exposures 78, 9, and X.

operation of a repository would result from sudden, and adiabatic, release of the stored energy.

3.4.2 Stored energy in solidified radioactive wastes

The oxides (calcines or glasses) that contain the high level wastes in a repository will be exposed to a variety of nuclear radiations, including those formed by the alpha disintegration of transuranic elements. They will thus undergo some radiation damage and concomitant storage of radiation energy.¹⁷ Information on the amount of energy that will accumulate in solid waste of a given type during storage and on the release of energy during heating was needed as part of the effort to evaluate the overall suitability of given waste types. Experiments, in collaboration with Pacific Northwest Laboratory (PNL), were designed to provide such information for several waste types currently under evaluation at PNL.

Samples of synthetic wastes of five different compositions and of alumina and fused silica (four of each) were exposed to fast neutrons in the ORR, while the sample temperature was maintained near 100°C. The irradiated samples were subsequently analyzed for stored energy using the Roux-type drop calorimeter.* Two different sets of radiation exposures (6 and 12 weeks) and calorimetric measurements of samples from these exposures were completed.

The results of measurements of enthalpy change upon heating the specimens are listed in Table 3.2. The temperature to which a specimen was heated in the calorimeter is also shown. The maximum temperature with a given specimen type, other than the borosilicate glasses, was as high as appeared feasible with that type. Factors that limited the maximum temperature included swelling of the platinum in which the sample was encapsulated, large thermal effects with control specimens, and calorimeter limitations. The softening temperatures for the borosilicate glasses are 500 and 540°C for SEN-4 and -5, respectively.¹⁸ Accordingly, it could be assumed that rapid annealing of all stored energy would take place at about 510°C.

---

*One sample of each irradiated material was sent to PNL where analyses for stored energy release below 600°C are being made by F. P. Roberts and coworkers using a differential scanning calorimeter.

Table 3.2. Specimen compositions and results of measurements of enthalpy change upon heating of irradiated and unirradiated specimens^a

Sample No.	Composition ^b	Change in enthalpy upon heating ^c					
		Irradiated				Unirradiated ^e	
		6 week		12 week		°C	Cal/g
		°C	Cal/g	°C	Cal/g		
SEN-1	Al ₂ O ₃ spheres coated with type 2 Pu-4b calcine (34.7%)	512	6	670	12		
		743	10. ^e 15	748	11, 16 ^f	840	-3 ± 1
		968	2	714	15		
SEN-2	Type 1 Pu-4b calcine (100%)	897	13. ^e 21	887	14.5, 17.5	850 ^g	13 ± 2
		975	10				
SEN-3	Al ₂ O ₃ spheres 100%	978	8, 12	982	16.5, 20.5	978	<1
				748	19 ^h		
				809	0		
SEN-4	Borosilicate glass-70-wt : frit 111-15, 30-wt : Pu-4b waste oxide	333	7	489	18.5	510	4 ± 0.1
		510	16, 22	506	23.5		
				533	18 ^h		
SEN-5	Borosilicate glass-75-wt : frit 73-149, 25-wt : Pu-4b waste oxide	510	20, 20	489	17	510	2 ± 0.1
		482	16 ⁱ	506	21		
		334	7	538	18		
		375	1				
SEN-7 ^j	Hot press, 50-wt : quartz, 50-wt : Pu-4b waste oxide	738	13	714	28	940	-4 ± 1 ^j
		838	24, 32	809	34		
				714	30 ^f		
				668	30		
SEN-9	Crushed fused quartz, 100%	977	35, 37, 52 ^k	809	36	977	<1
				968	31, 34		

^aSpecimens were irradiated in the ORR for 6 and 12 weeks. The fluences of fast neutrons (0.18 MeV) were 2.9×10^{20} and 7.0×10^{20} cm⁻².

^bK. J. Schneider and J. E. Mendel, "Reference Research and Development Activities Waste Program," in Quar. Prog. Rept. Research and Development Activities Waste Fixation Program July through November 1972, BNWL-1899 (December 1972), pp. 9-16.

J. E. Mendel, "Commercial Radioactive Waste Compositions Used in the Waste Fixation Program," in Quar. Prog. Rept. Research and Development Activities Waste Fixation Program April-June 1974, BNWL-1841 (July 1974), pp. 28-29.

F. P. Roberts, J. E. Mendel, and J. E. Gose, "Stored Energy Measurements," in Quar. Prog. Rept. Research and Development Activities Waste Fixation Program July-September 1974, BNWL-1871 (November 1974), pp. 25-30.

^cThe calorimeter temperature is shown. The initial temperature was 125°C.

^dThe values show the deviation from the average of duplicate samples.

^eThis specimen subsequently heated to higher temperature with release of additional heat as shown in following line.

^fThis specimen was first heated at lower temperatures (or temperature) with release of part of this heat as shown in following lines (or line).

^gAverage and deviation for four samples in the temperature range 850 to 1000°C.

^hThis temperature is probably above the transition temperature.

ⁱG. J. McCarthy, "Quartz Isolation of Radioactive Wastes," J. of Materials Sci. 8, 1358-59 (1973).

^jMeasurements at calorimeter temperatures above and below 838°C gave this value within about 10%.

^kThis high value is probably in error for some unknown reason.

No significant differences were found between the specific heat values of samples of irradiated and unirradiated materials after heating (annealing) except for the borosilicate glass, SEN-4. After being heated to 510°C, the average specific heat values of this material in the temperature range of 125 to 500°C were 0.238, 0.218, and 0.208 cal/g, respectively, for the unirradiated, 6-week irradiated, and 12-week irradiated samples. The specific heat values in the temperature range 75 to 195°C exhibited no differences between irradiated and unirradiated samples, except for the other borosilicate glass, SEN-5. The average specific heat values for the unirradiated and 12-week irradiated samples were 0.182 and 0.166 cal/g, respectively, in this temperature range.

It was estimated that the collision energy dissipation by recoiling atoms of fission product elements in SEN-1, -4, -5, and -7 during the 6 and 12-week irradiations was equivalent to that which would be produced by alpha decay in solid wastes from LWR-UO₂ equilibrium cycle fuel in minimum times of 9 and 40 years, respectively, assuming fuel reprocessing 150 days after discharge from the reactor.^{17,19}

Complete details of this work and discussions of the results will be reported in a joint PNL-ORNL topical report.²⁰

3.5 Rock-Waste Interactions (G. H. Jenks)

Evaluating the feasibility of any waste disposal system will include a review of available information to insure that possible rock-waste interactions will not compromise the integrity of the repository during its operating lifetime (up to 10⁶ years). Information is being compiled from studies being made, such as:

- (1) Migration of radionuclides from the waste through the formation.
- (2) Effects of radiation on physical and chemical properties of the rock.
- (3) Chemical interactions between waste and rock.
- (4) Effects of high temperature, including melting of waste and adjacent rock, on both waste and rock.
- (5) Methods for effectively isolating waste packages from rock and circulating ground water.

3.5.1 Literature review - effect of radiation on geologic formations other than halite

A literature²¹ search was made to compile data concerning the effect of radiation on geologic formations other than halite. No reported direct experimental measurements of energy storage in either silicate minerals or limestone under gamma irradiation were found, and there were essentially no reported measurements of chemical stability of these materials under gamma irradiation. However, a review of the general aspects of radiation damage and energy storage in solids, and of pertinent physical and chemical properties of these rocks, indicated no apparent reasons to expect any significant amounts of stored radiation energy in any of the important rock-forming minerals at the maximum gamma dose and fast neutron fluences ($<10^{17}$, >3.4 keV) which will prevail in rock immediately adjacent to buried waste. Additionally, there are no apparent reasons to expect any significant radiation induced chemical effects in any of the minerals, but the information is so sparse that the possibility of significant effects due to radiation cannot be completely ruled out. Consequently, certain radiation experiments will be performed to verify the absence of significant effects as time and rock samples become available.

3.6 Borehole Plugging - Salt Dissolution Studies (G. D. Brunton)

All of the possible geologic sites for the disposal of radioactive waste have a common denominator: they must be free of circulating water that could disperse the radionuclides. Salt mine disposal, bedded, anticlinal or domal, presents the additional problem that circulating unsaturated water dissolves the salt and could breach the disposal site. Because boreholes have been or will be drilled in all prospective waste disposal sites, techniques and materials must be developed to reseat boreholes with the assurance that the seals or plugs will maintain their integrity for time periods comparable to the lives of the rock formations surrounding them. In addition, the rates and configuration of dissolution must be predictable in soluble rock formations.

3.6.1 Borehole plugging with natural-earth material

Personnel of the Civil Engineering Department, Massachusetts Institute of Technology (MIT),* are studying methods for the emplacement of boreholes composed of naturally occurring rock materials, specifically, borehole samples and/or outcrop samples of Minnescah shale, Kansas, of Conasauga shale, East Tennessee, and of Dewey Lake Redbeds, New Mexico. Laboratory tests were made with these materials to determine the optimum water content, particle size distribution, and compressive force necessary to give the maximum bulk density, maximum plug strength, and minimum permeability. The ultimate physical properties attained were a function of the relative amounts of sand, clay, and water; usually, 8 to 14% water gave the maximum values for the bulk density and plug strength. In most cases, the permeability was as low or lower than the permeability measured in the original core samples; for example, a compacted Conasauga outcrop sample had a permeability of 1.7 μ darcys and a compacted Dewey Lake outcrop sample had a permeability of 4.4 μ -darcys.

Tests are being carried out using the same materials to determine the best techniques for subsurface compaction of plugs, to determine the amount of cohesion between plug and wall rock (with and without drill mud present), and to investigate the effect of plug emplacement on lateral stresses around the borehole. Static compressive compaction, dynamic tamping, and air gun compaction are three of the downhole emplacement techniques being considered.

Extrusion of plugs compacted into holes drilled in compacted samples suggests that drilling mud on the wall of the hole may not be a serious problem. A pressure of 7400 psi was required to puncture a hole into a compacted sample using a 1.0-in.-diam piston. The extruded soil belled out at the bottom to 1.4-in.-diam, which was the hole diameter in the retaining plate. Plugs were compacted into 1.1-in.-diam holes drilled in compacted samples where the drilling was done with and without mud (6% Na montmorillonite) in the hole. For the mudded holes, no effort

---

*Work performed for ORNL by MIT under Subcontract-3960, Dr. R. T. Martin, principal investigator.

was made to clean off mud clinging to the hole wall. Plug extrusion was with the 1.0-in.-diam piston. For samples extruded immediately after compaction, the nonmudded hole required 4600 psi, and the mudded hole required 2900 psi. For samples that were allowed to stand sealed against moisture content change for 17 days, the nonmudded and mudded holes required 6500 psi and 4800 psi, respectively, to extrude. In every instance, the extruded plug had the same shape as the plug that was punctured from a compacted sample where no hole had been drilled; that is, the extruded plug failed through the compacted soil, not along the drilled hole interface.

The result of these studies will be a report that will list the alternative techniques that can be used to emplace a borehole plug of natural earthen material, assess the scope of the research and development effort leading to an in-situ field test for each technique, and discuss the techniques to be used in testing the physical properties of the in-situ test borehole plugs.

3.6.2 Hydrothermal plugs

The Materials Research Laboratory at Pennsylvania State University, University Park,* is investigating the feasibility of the chemical emplacement of borehole plugs by hydrothermal (usually by aqueous solutions, at temperatures and pressures different from ambient) transport. The following hydrothermal systems will be covered in the feasibility report: (1) $\text{SiO}_2\text{-H}_2\text{O}$, (2) clay-water, (3) hydrothermal cements, (4) carbonates, and (5) sulfur-water. Table 3.3 lists a preliminary comparison of these five systems with respect to reaction feasibility, kinetic feasibility, plug stability, and engineering constraints. The high temperatures (500°C) and pressures (2000 bars) required for the $\text{SiO}_2\text{-H}_2\text{O}$ system, for example, appear to eliminate it as a feasible plugging technique.

---

*Work performed for ORNL under Subcontract-4091, Drs. D. M. Roy and W. B. White, principal investigators.

Table 3.3. Comparison of hydrothermal systems

Hydrothermal systems	Reaction feasibility	Kinetic feasibility	Plug stability	Engineering constraints
Hydrothermal	$\text{CaO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$	Exothermic	Nonreactive	Slurry in single pipe
Cement	Tobermorite is final product.	Self setting 24 hr	Expands when set Impervious	100-200°C Drive pressure only
Quartz	Direct precipitation from solution. As SiO_2 cement.	Tends to be sluggish	Stable Impervious Low thermal expansion	Dilute solution - requires much fluid transport 500°C; 2000 bars Precipitation by cooling and loss of pressure
CaCO_3	Direct carbonation	Rapid	Attack by ground water Stable in contact with carbonate rock Expands when set	Double pipe system with reaction in the hole
Clay-water	Coprecipitation	Sluggish	Stable Consolidation	Double pipe system with reaction in the hole 200°C
Sulfur	Freeze from liquid Steam transport	Rapid	Possible wall rock reaction Shrinkage May be porous	200°C

3.6.3 Molten-salt plugs

Los Alamos Scientific Laboratory* (LASL) investigated the feasibility of melting salt in a borehole to form a salt plug. The results of their laboratory experiments are given in a LASL report included as Appendix B. An engineering assessment of this technique to determine the scope of a research and development effort to design, build, and field test an in-situ molten-salt plug has been undertaken by Westinghouse Electric Corporation.

3.6.4 Salt dissolution

In the event that a nuclear-waste repository is constructed in a salt formation, it will be necessary to confidently predict the effects of the flow of water into or through the salt if: (1) an open hole connecting aquifers is drilled through the salt, or (2) an incredible event breaches the salt permitting water flow. Several investigations are under way to provide this information.

Dr. R. F. Walters, drilling consultant, is investigating examples of salt dissolution in the Hutchinson salt formation around boreholes in Kansas.** These studies include examples of dissolution in salt beds in the subsurface in Russell, Lincoln, Ellsworth, Barton, and Rice Counties in central Kansas, salt dissolution in the Gorham oil field in Russell County, and salt dissolution in oil and gas test holes in the Silica-Chase oil field in Barton and Rice Counties. He will determine the history of salt dissolution around old oil and gas wells with respect to water flooding operations, disposal of salt brine, and the effect of leaving old holes open and unplugged for long periods of time.

Dr. R. H. Snow, Illinois Institute of Technology Research Institute, Chicago,*** is developing a mathematical model of salt dissolution around a borehole in a salt bed. The model will be used to predict the size and

---

*Work performed for ORNL by C. A. Bankston and L. B. Lundberg of LASL under purchase order 78X-41866V.

**Work being performed for ORNL by Dr. R. F. Walters, Wichita, Kansas 67202, under Subcontract-3457.

***Work being performed for ORNL under Subcontract-4005, Dr. R. H. Snow, principal investigator.

shape of cavities that would develop if fresh water enters at the top of the formation and brine is removed at the bottom. The experimental data from the Detroit Salt Mine Cavity Experiment will be used to validate this model which uses a new approach to the treatment of the turbulent boundary layer flow that occurs at the interface of the water and the salt. To date, the differences between calculated and experimental values are less than 10%, indicating that the model is sophisticated enough to predict cavity growth and shape. After validation, the model will be used to calculate the growth of cavities under the conditions of a few gallons water flow per year for time periods covering many years, and simulating natural borehole conditions.

Drs. R. M. Knapp and A. L. Podio, Petroleum Engineering Department, University of Texas, Austin,* have three projects devoted to the study of salt dissolution around boreholes: (1) the development of a mathematical model of convective-diffusive flow in a static water column in open wellbores, (2) an experimental study of convective-diffusive fluid flow in wellbores, and (3) the numerical simulation of brine invasion into a fresh-water aquifer. The mathematical problems associated with the numerical solution of the differential equations required for projects 1 and 3 are under investigation and a three-story high, 4-in.-diam experimental wellbore is being constructed for project 2. The experimental wellbore will contain static saturated salt water connecting a salt source at the top and a fresh water sink at the bottom. It will be instrumented to determine the temperature, the rates of flow, and the composition of the salt water axially along the wellbore. The data from these measurements will be used to validate the mathematical models.

3.6.5 Review of current practices

The best current practical experience in borehole plugging is not in oil and gas wells, where plugging is perfunctory at best, but in the somewhat remotely related civil engineering project involving such things as curtain-wall grouting for dams, squeeze grouting for tunnels

---

*Work performed for URNL under Subcontract-4082, Dr. R. M. Knapp and Dr. A. L. Podio, principal investigators.

and shafts, and most important, in sealing underground gas storage reservoirs. In addition, if suitable examples of the formation of natural plugs by igneous intrusion, low grade metamorphism, or any other process could be discovered, they would give insight into the longevity of natural plugging materials; by inference, insight would also be given to the longevity of similar artificial cements and grouting material under geologic conditions for geologic time periods.

Naturally occurring borehole plugs - a review of dikes and stocks.

One aspect of the borehole plugging program is concerned with identifying situations where natural materials have effectively plugged geologic formations for long time periods ($>10^6$ years).^{22,23} As the first step in this identification process, a bibliography was prepared of the geologic literature which cited 254 references to small intrusive bodies into geologic formations.* The bibliography was not exhaustive, particularly with respect to igneous dikes and sills, because the articles cited as references were selected on the basis of title references to small dikes or stocks of igneous rock intrusive into sedimentary rock, or dikes and stocks of fluidized clastic material injected into fractures in preexisting rocks. In the preparation of this bibliography, no effort was made to read abstracts or articles to find additional references that might have been overlooked if the titles failed to include references to subject matter of interest.

Reprints of approximately 40 articles listed in the bibliography were obtained. The articles were selected on the basis of the subject matter in their titles. The objectives of the search were to cover all of the types of dikes mentioned in the bibliography, and to obtain a representative cross section of the literature with at least two examples of each type of dike or plug. Additional articles were selected from the references cited in the first articles if they appeared to contain additional useful information.

---

*The work was done by Mr. N. S. Brackett, consultant, University of Tennessee, Knoxville.

Some types of information that might be contained in the articles and which would be of importance to the borehole plugging program are:

- (1) Age of emplacement of the plug,
- (2) Original permeability of the plug,
- (3) Geology and hydrology of the formations penetrated by the plug, particularly information with respect to aquifers penetrated by the plug,
- (4) Mechanisms of cementation or alteration of the plug, if any,
- (5) Changes that might have occurred in the original formations as a result of the emplacement of the plug or water flow through it.

The history of the plug and its mineralogy would have to be known from the surface and throughout a considerable portion of its vertical extent to meet the above criteria. No examples from the literature were found that gave all of the above information, and only one or two gave part of it. Except for examples from two salt mines and from a few coal mines, all of the igneous and clastic dikes that are described in the literature are surface exposures occasionally exposed vertically by erosion for several tens of feet. In some of the examples, water flow at some time in the history of the plug is implied by the fact that either the interstices have been filled with cementing minerals or metastable minerals have been hydrolyzed to their more stable weathered products. No permeability data are given for any of the dikes, and there is no mention of water flow through them or when it occurred.

Minerals that are the end products of the weathering cycle and that are the components of the common clastic sedimentary rocks are also the most common constituents of clastic dikes and stocks. Examples of sandstone dikes are given in refs. 24-30. Newsom³⁰ also reviews examples of other kinds of dike material, such as gilsonite and asphalt, but all of the preceding citations have one thing in common - they are descriptions of the occurrence of dikes from their surface exposures and contain no physical data. Examples of articles concerning clay dikes,³¹ limestone dikes,³² coal dikes,³³ and salt dikes³⁴ also have the same failing; no physical measurements or subsurface examinations are given or discussed by the writers that would be useful to describe the dikes effectiveness

in preventing vertical hydrologic circulations. The conclusions that can be drawn from these examples are that the end products of the normal weathering cycle (i.e., quartz sand, clay minerals, calcite or limestone, and iron oxides) can fill fractures and voids in preexisting rock formations, and these weathered minerals will last as long as the enclosing rock. There are no data given in these examples from the literature that permit an evaluation of clastic dikes with respect to permeability, age, or other physical properties needed for nuclear waste repository borehole plugs.

Most of the dikes and stocks described in the literature are of igneous origin. Of the 163 examples cited in the bibliography, only two provide data that make them of particular interest to the borehole plugging program. Both of these examples are of igneous dikes that penetrate salt beds; they are of importance because the presence of the salt is an indirect measure of the volumes of water that might have flowed along the dike. As will be noted in the subsequent descriptions of the occurrences, no permeability determinations were made directly on the dike rock, although the rock is porous, weathered, and hardly ideal as a plug. The existence of the salt, however, testifies to the fact that there has been no appreciable dissolution along the dikes since they were emplaced.

The first example of an igneous dike injected into a salt bed occurs in the Salado formation in the Permian basin of southeastern New Mexico, east of Carlsbad.^{25,36} A nearly vertical lamprophyre dike is present in mine workings of two potash mines about 10 miles apart. The dike is presumed to be the same in both mines and in an oil well along the same northeast-southwest strike. The possibility that the occurrences represent parts of en-echelon dikes cannot be excluded, because there is a series of lamprophyre dikes that extends northeastward almost 80 miles from the Gypsum Hills in southern Eddy County near the New Mexico-Texas state line to the Vacuum oil field south of Buckeye in central Lea County, New Mexico. The northeast trend of these dikes parallels the trend of crevasses and joints in the carbonate rock of the Capitan and Tansill formations near Carlsbad Caverns. These fractures are filled with early Cretaceous sandstone and conglomerate.

The lamprophyre dike (or dikes) has a similar appearance, composition, structure, and other properties wherever it occurs. The dike is usually only a few inches to a foot thick, but thickens to approximately 15-ft wide at its widest observed point in the Kerr-McGee mine. The dike rock is described as a medium-gray to grayish-black fine-grained porphyritic lamprophyre. The dike has a chilled border and a rather poorly developed flow structure. The rock contains corroded andesine phenocrysts, and pseudomorphs of siderite and antigorite after pyroxene. Amygdules, as much as 2 mm in diameter and filled with halite, siderite, calcite, and natrolite are scattered throughout the rock. The groundmass of the dike consists of orthoclase with accessory amounts of biotite, some of which is partially altered to vermiculite. The minor constituents are ilmenite, apatite, anatase, and pyrite. There are near vertical and subhorizontal fissures in the rock that are usually filled with halite, but which locally may contain polyhalite, anhydrite, and minor amounts of pyrite, dolomite, quartz, and crystalline hydrocarbons. The rock salt of the salt bed is recrystallized as much as 3/4-in. thick along the dike contact and, in places, contains methane and other gases under pressure. In the mines, the lamprophyre dike disappears horizontally and vertically into a polyhalite vein that contains minor amounts of dolomite, pyrite, and crystalline hydrocarbon. Drill cuttings of the dike rock from the Texas Company No. 1 Moore well, located about 3½ miles northeast of the Kerr-McGee potash mine have been dated as mid-Tertiary (30 ± 1.5 million years).

There is no apparent evidence that the dike penetrates the Salado salt formation into overlying aquifers. It would be of interest to find out if and where this penetration occurs, because the dike must penetrate underlying aquifers in the Capitan limestone. A pressure head difference exists between the Capitan aquifer and those aquifers overlying the Salado salt formation that would drive water along any passages provided by the dike. The present evidence indicates that the salt bed provided its own seal against water trying to penetrate along the dike; certainly, little or no dissolution has occurred since its intrusion some 30 million years ago.

The second example of an igneous dike penetrating a salt bed is described by Broughton.³⁷ The peridotite dike intrudes the Syracuse salt formation of the Upper Silurian Salina group near Ithaca, New York. The dike is exposed at the ground surface and in a salt mine 1928 ft below the surface. The average strike and dip of the dike are N 11-14 W and 75-79 W, respectively, and the dike parallels one of the sets of regional jointing.

The kimberlite or peridotite is described as a greenish-gray rock with prominent olivine phenocrysts that have been altered completely to serpentine. A fresh-looking brown mica is also present as phenocrysts. The groundmass consists of a felt-like aggregate of calcite, serpentine, and chlorite. There is no microscopic evidence of any reaction between the igneous rock and the halite. In specimens of the underground dike, halite has filled cavities and cracks. Calcite has also filled the centers of olivine phenocrysts "in quantities too large to have been supplied by alteration of original melilite."³⁷ Broughton believes that the source of the calcite is the limestones penetrated by the dike below the salt. Pyrite appears to have been deposited last, following the salt-dike contacts, enclosing olivine phenocrysts and limestone inclusions, and filling voids.

In the subsurface, the dike is broken and brecciated, with recrystallized salt around the breccia fragments and in all of the fractures. The molten rock in contact with the salt appears to have frozen, providing selvage walls that were subsequently filled with additional magma and molten salt. The molten salt flowed into the core when the frozen selvage walls were brecciated by new inflow of peridotite magma. It is difficult to see how Broughton³⁷ visualized the support for the selvage walls in the molten salt, but he described what he considered the sequence of events associated with the dike intrusion as follows: "(1) intrusion of a very fluid kimberlite magma in a tension joint or series of parallel joints, (2) as the magma moved upward, it carried with it fragments of limestone, but had insufficient heat even to calcine them, (3) as it intruded the rock salt bed, it formed an intricately frozen contact and probably lost heat rapidly through the country rock salt, although the frozen selvage may have acted as a flue lining, (4) extension of the

dike resulted in its being torn away internally from the frozen contacts. As it brecciated, it was intruded by the salt magma. The moving salt supported the dike fragments and intruded the dike mass, (5) the salt recrystallized under control of the dike fragment contacts." Broughton infers that the salt was molten because it is recrystallized with a comb-like pattern along its contacts with dike fragments.

Broughton recognizes that either there must have been enough water in the magma or it was introduced later to form the serpentine, but he does not offer any explanation for its source. He sees no evidence for salt dissolution subsequent to the intrusion. The dike is exposed at the surface in the Devonian Tully limestone, but he does not present any additional data for its ultimate vertical extent or age.

Although a survey of the geologic literature on dikes and stocks has not provided any examples of natural plugs that have the properties that make them comparable to borehole plugs, several conclusions can be inferred. Metastable minerals, such as olivine, pyroxene, biotite, andesine and other high temperature minerals, weather and hydrolyze to more stable forms, such as clay minerals (serpentine), quartz, calcite, and iron oxides. These stable minerals are the end products of what is considered to be the normal weathering cycle, and they are also the stable constituents of the examples of clastic dikes that have been cited. The clean quartz grains that compose some of the clastic dikes have been subsequently cemented together by calcite presumably deposited from circulating water. In the cases where clay and silt size particles make up a substantial fraction of the dike material, the rock probably has a very low permeability. If necessary, the permeability could be determined from field specimens for comparison purposes. The mineral combinations that will have the longevity needed for borehole plugs are probably mixtures of the common constituents of the clastic dikes; mixtures of quartz sand and clay, or clay minerals alone, would form the most stable impermeable plugs. Additional field work on examples of clastic and igneous dikes will be undertaken wherever additional physical measurements will contribute to the better characterization of borehole plugs (e.g., age determinations and permeability measurements on some of the older clastic dikes).

Civil engineering grouting methods. As part of the borehole plugging program plan, Profs. H. H. Einstein and M. J. Barvenik,* have compiled and published a two volume review.³⁸ Volume 1 consists of 10 chapters in which are discussed grouting techniques for dams, reservoirs, foundations, anchors, tiebacks, piles, tunnels, shafts, pipes, and structural applications. Volume 2 is a bibliography of approximately 800 references from which the material in Vol. 1 was collected.

Helium gas storage. Dr. R. F. Walters, drilling consultant,** has submitted the following review of borehole plugging at a helium gas storage field.

"As regards borehole plugging, there is little to be learned from the U.S. Bureau of Mines (USBM) Helium Storage Operation in the Cliffside Field near Amarillo, Texas. The USBM operation was studied because helium, the most fugitive of substances, is being stored underground on a large scale basis as crude helium (70% helium - 29% nitrogen) with the stored helium bubble continuously monitored.

Two abandoned native gas wells drilled with cable tools in the 1920's, formerly used as gas producing helium supply wells, were plugged in 1961. These holes were abandoned in 1935 and 1942 and hole plugging was done in a totally unplanned manner following a series of mishaps (such as unrecovered stuck drill pipe) in attempted workover repair operations. These abandoned gas wells, one located at the apex of the subsurface gas storage area, are poorly, and perhaps inadequately, plugged. The only other plugged holes are two dry holes drilled in the 1960's near the gas-water contact which were plugged in the conventional oilfield manner using Portland cement.

Recent (1960's on) well completions for crude helium input and/or observation wells are rotary drilled and cored with excellent geophysical logs with adequate cemented casing strings, and with controlled well completions made by perforating through casing set near total depth. This is in sharp contrast to the early (1920's to 1941) cable tool drilled wells with casing strings set and pulled in haphazard manner with no cementing of casing, and with no control of the gas section due to open hole completions.

The present review is based on the literature cited; on two visits to the USBM facility by Peter J. Stubbs, consultant; on access to and

---

*Work performed for ORNL at Massachusetts Institute of Technology under Subcontract-3960, Dr. R. T. Martin, principal investigator.

**Work performed for ORNL by Dr. R. F. Walters, Wichita, Kansas 67202, under Subcontract-3457.

study of the USBM well files preserving daily progress reports concerning drilling, well completion, well repair, and well plugging. A master file of the basic well data copied and studied was compiled.

The USBM Helium Storage Project was found to be a prototype of underground storage on a large scale of a product requiring absolute containment. The problems involved beyond borehole plugging, and the solutions devised, may be directly applicable to the underground geological containment of radioactive wastes."

3.7 References for Section 3

1. T. G. Kollie, D. L. McElroy, J. T. Hutton, and W. M. Ewing, "A Computer-Operated Fused Quartz Differential Dilatometer," in Thermal Expansion - 1973 (Lake of the Ozarks), R. E. Taylor and G. L. Denman (eds.), AIP Conf. Proc. 17, series ed. H. C. Wolfe, AIP, N. Y., 1974.
2. F. D. Enck and J. G. Dommel, J. Appl. Phys. 36(3), 839 (1965).
3. A. J. Leadbetter and D. M. T. Newsham, J. Phys. Chem. (Solid St. Physics) 2(2), 210 (1969).
4. T. G. Godfrey and S. H. Jury, A Transient Method for Rapidly Measuring Thermal Conductivity and Diffusivity of Salt Mine Core Samples (The Plane Probe), ORNL-TM-4956 (in preparation).
5. W. D. Turner and M. Simon-Tov, HEATING-3, An IBM 360 Heat Conduction Program, ORNL-TM-3208 (February 1971).
6. P. F. Gnirk et al., Analysis and Evaluation of the Rock Mechanics Aspects of the Proposed Salt-Pine Repository Concept-III, RSI-0012 (Sept. 28, 1974).
7. G. D. Callahan et al., Heat Transfer Analysis of the Waste-Canister Sleeve/Salt Configuration, RSI-0023 (Mar. 31, 1975).

8. William G. Pariseau, Thermoelastic-Plastic Analysis of Waste-Container Sleeve: II. Influence of Large Displacements of Sleeve Loading, RSI-0017 (Mar. 21, 1975).
9. William G. Pariseau, Thermoelastic-Plastic Analysis of Waste-Container Sleeve: III. Influence of Salt Strength on Sleeve Loading, RSI-0018 (Mar. 21, 1975).
10. William G. Pariseau, Thermoelastic-Plastic Analysis of Waste-Container Sleeve: IV. Air Gap Influence on Hole Closure, RSI-0019 (Mar. 21, 1975).
11. G. H. Jenks and C. D. Bopp, Storage and Release of Radiation Energy in Salt in Radioactive-Waste Repositories, ORNL-TM-4449 (January 1974).
12. G. H. Jenks, E. Sonder, C. D. Bopp, J. R. Walton, and S. Lindenbaum, "Reaction Products and Stored Energy Released from Irradiated NaCl by Dissolution and by Heating," J. Phys. Chem. 79, 871 (1975).
13. G. H. Jenks and C. D. Bopp, Experimental Studies of Energy Storage in NaCl, ORNL-5058 (in preparation).
14. H. C. Claiborne, personal communication, July 1974.
15. J. O. Blomeke, C. W. Kee, and J. P. Nichols, Projections of Radioactive Wastes to be Generated by the U.S. Nuclear Power Industry, ORNL-TM-3965 (February 1974).
16. J. O. Blomeke et al., An Analysis of Energy Storage and Its Effects in the Proposed National Radioactive Waste Repository, ORNL-TM-3404 (June 1971).
17. G. H. Jenks and C. D. Bopp, Energy Storage in High Level Radioactive Waste and Simulation and Measurement of Stored Energy with Synthetic Wastes, ORNL-TM-3781 (January 1973).

18. J. E. Mendel, BNL, private communication, April 1974.
19. D. F. Newman, "Radiation Damage in Borosilicate Glass," in Quar. Prog. Rept. Research and Development Activities Waste Fixation Program, December 1972 through March 1973, BNL-1741 (April 1973) pp. 31-33.
20. F. P. Roberts, C. D. Bopp, G. H. Jenks, and J. E. Mendel, Stored Energy Release in Simulated High-Level Wastes, joint PNL-ORNL report in preparation.
21. G. H. Jenks, Review and Analyses of Available Information in Gamma-Radiation Effects in Geologic Formations, Other Than Halite, of Interest in Waste Disposal and Suggestions for Additional Experimentation, ORNL-TM-4827 (in preparation).
22. Committee on Waste Disposal, Division of Earth Sciences, The Disposal of Radioactive Wastes on Land, National Academy of Sciences - National Research Council Publ. 519 (April 1957).
23. R. S. Bradshaw and W. C. McClain, Project Salt Vault: A Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines, ORNL-TM-4555 (April 1971).
24. J. M. McMillan, Jr., "Clastic Dike in Fort Hays Chalk, Kansas," Bull. Am. Assoc. Petrol. Geologists 15(7), 842-47 (July 1931).
25. B. H. Parker, "Clastic Plugs and Dikes of the Cimarron Valley Area of Union County, New Mexico," J. Geol. 41(1), 38-51 (1933).
26. N. B. Smyers and G. L. Peterson, "Sandstone Dikes and Sills in the Moreno Shale, Panoche Hills, California," Bull. Geol. Soc. Am. 82(11), 3201-07 (1971).
27. R. L. Lupper, "Clastic Dikes of the Columbia Basin Region, Washington and Idaho," Bull. Geol. Soc. Am., 55, 1431-62 (1944).

28. T. B. Lawler, "On the Occurrence of Sandstone Dikes and Chalcedony Veins in the White River Oligocene," *Am. J. Sci.* 5, 160-72 (1923).
29. J. R. L. Allen, "Sandstone-Plugged Pipes in the Lower Old Red Sandstone of Shropshire, England," *J. Sediment. Petro.* 31, 325-35 (1961).
30. J. F. Newson, "Clastic Dikes," *Bull. Geol. Soc. Am.* 14, 227-68 (1903).
31. P. H. Price, "Clay Dikes in Redstone Coal, West Virginia and Pennsylvania," *Bull. Am. Assoc. Petrol.* 17, 1527-33 (1933).
32. D. W. Lewis, "Polyphase Limestone Dikes in the Oamaru Region, New Zealand," *J. Sediment. Petro.* 43, 1031-45 (1973).
33. M. H. Podrýsocki and R. R. Dutcher, "Coal Dikes that Intrude Lamprophyre Sills, Purgatoire River Valley, Colorado," *Econ. Geol.* 66, 267-80 (1971).
34. G. W. Frank, "Salt Intrusion in Northeastern Ohio," *Ohio J. Sci.* 63, (1963).
35. C. L. Jones and B. M. Macken, "Observations on Igneous Intrusions in Late Permian Evaporites, Southeastern New Mexico," *Bull. Geol. Soc. Am.* 70, 1625-26 (1959).
36. C. L. Jones, M. E. Cooley and G. O. Bachman, Salt Deposits of Los Medaños Area, Eddy and Lea Counties, New Mexico, USGS Open File Report USGS-4339-7 (1973).
37. J. G. Broughton, "Observations on the Intrusion of Rock Salt by Peridotite (N.Y.)," *Trans. Am. Geophys. Union* 31, 229-33 (1950).
38. H. H. Einstein and M. J. Barvenik, Grouting Applications in Civil Engineering, Soils Publication No. 334, Department of Civil Engineering, Massachusetts Institute of Technology (January 1975).

4. ENGINEERING ASSESSMENT STUDIES

Engineering studies and analyses are needed to assess the technological feasibility of the many potential waste disposal systems so that promising concepts can be identified and developed into viable waste disposal systems. These engineering assessment studies are carried out under five broadly defined programs: analyses of techniques for emplacing gaseous, liquid, or solid wastes in a geologic formation; characterization of wastes; evaluation of waste disposal systems; development of promising waste disposal systems; and repository design.

4.1 Waste Emplacement Studies (R. S. Lowrie, F. C. Zapp)

There are a large number of waste emplacement techniques, some of which are fairly well defined (e.g., packaged radwaste in a mined cavity), while others are only proposals (e.g., the rock-melting concepts) which must be analyzed before any waste disposal systems can be evaluated. The initial engineering analyses would ensure that (1) a complete waste emplacement concept existed, (2) the major subsystems comprising the concept were identified and defined, (3) the major problem areas in each subsystem requiring a research and development effort were identified and defined, (4) the scope of the effort for each of these problem areas was delineated, and (5) the probability of a successful conclusion to the research and development effort was assessed. Fortunately, these initial analyses, while dependent on the type of radwaste involved, do not depend on knowledge of a specific site and geologic formation and thus can be conducted in parallel with the geologic studies. Emplacement techniques currently being analyzed include the rock-melt capsule concept, the deep rock disposal concept for high-level waste, and a generalized study of the emplacement of heat-generating encapsulated waste in a mined cavity.

4.2 Studies of the Bedded Salt Pilot Plant

Prior to its reorganization, the Radioactive Waste Repository Project had as its specific objectives the design and construction of the Bedded Salt Pilot Plant (BSPP) for high-level waste in southeastern New Mexico. The design effort was terminated in November 1972 and the in-situ experimental effort was terminated in August 1974.

4.2.1 Conceptual Facility Design Description of a BSPP (B. F. Bottenfield)

To document the BSPP design effort, a Conceptual Facility Design Description Report was assembled and given limited distribution. The report is a compilation of the ORNL-supervised work which was done by Kaiser Engineers, Incorporated, in early 1972 and was terminated in November 1972. Some updated information and design alternatives have been added.

4.2.2 BSPP in-situ experimental program (C. G. Lawson, R. S. Lowrie)

Prior to the construction of the BSPP, the in-situ experimental program was to provide: (1) information about the method for emplacing waste canisters in salt, and about physical and chemical interactions between the salt environment and the canister to ensure both the integrity of the canister and its contents and the retrievability of the waste at any time during the pilot plant operations; and (2) information to ensure the stability of the underground workings and, in turn, the accessibility of the waste throughout the operating lifetime of the pilot plant. It was felt that these data could best be obtained by conducting the experiments in an existing potash mine in the Carlsbad, New Mexico potash field. The in-situ experimental program was terminated in August 1974, and a report documenting the experiments that were planned, the preliminary design of the equipment, the mine layout, and the initial contacts with potash mine operators in the southeastern New Mexico potash field was placed in the ORNL Central Files.

4.3 Alpha Repository Studies (R. S. Lowrie)

In July 1974, the GDE Program was directed to develop "in-house" concepts and mine arrangements for the disposal of alpha waste and spent

fuel hulls in promising geologic formations. On August 23, 1974, this directive was modified to give first priority to an alpha repository in bedded salt at the site near Carlsbad, New Mexico.

Early in February 1975, the overall direction of the design, construction, and operation of an alpha pilot plant at New Mexico was transferred to Sandia Laboratories, and ORNL was directed to provide Sandia with all pertinent information. This task was accomplished in a series of meetings held during March and April of 1975. Any further alpha repository design effort at ORNL will be carried out at the request of Sandia Laboratories.

4.3.1 Surface facilities engineering study (G. W. Renfro, R. M. Holmes, W. D. Manrod, R. S. Lowrie)

The directive dated August 23, 1974, specified that the conceptual designs developed for the repository at Lyons, Kansas, and the BSPP should be reviewed and evaluated. Based on current alpha repository design criteria, a concept should be developed for the surface facilities by "fitting" the existing designs to the New Mexico site. This would require:

- (1) Evaluation of the topography of the site in New Mexico to determine routes for the access road, railroad, power lines, etc., and the location of fences, support buildings, and a possible site for the excavated salt dump.
- (2) Preparation of a preliminary layout of the receiving facilities needed for low-level bulk alpha waste received by rail or truck, based primarily on the alpha-waste portion of Lyons Conceptual Design, and for spent fuel cladding canisters received via rail, based on BSPP high-level waste concepts.
- (3) Determination of the number, location, and type of shafts and shaft equipment needed to safely operate the repository, including a review and modification (if necessary) of the salt handling facilities at the top and bottom of the shaft and the hoisting and ancillary equipment and facilities needed to transfer both types of waste to the underground transportation system.

- (4) Identification of major design problems in existing conceptual designs, or where drastic redesign will be needed, and the scope of effort required in these areas.

This study was completed, and 15 drawings showing the location of the facilities on the site as well as their conceptual design features were prepared. A report that describes the conceptual design and identifies major design problems is currently being prepared.

4.3.2 Mine layout engineering study (R. S. Lowrie)

Stratigraphic data for the site in New Mexico (see Sect. 2.1) indicated that potential salt horizons for the mine existed at 1900, 2100, and approximately 2700 ft. Since pertinent design information about the underground facilities for an alpha repository at these depths did not exist, a contract was negotiated with RE/SPEC Inc., to carry out the following engineering studies:*

- (1) A preliminary analysis of the stability of alternative mine layouts in each of the three candidate salt horizons.
- (2) An analysis and evaluation of the methods and equipment required for drilling emplacement holes for spent fuel hull canisters.
- (3) An analysis and evaluation of various methods for excavating storage rooms, etc., and for transporting excavated salt to the hoisting facility.

This effort is now under way and will be completed by the end of FY-75.

---

*Work being performed for ORNL under Subcontract-4269 by RE/SPEC Inc., Rapid City, S. D. 57701.

APPENDIX A

**ROCK TYPES, ALSO GEOLOGIC AND HYDROLOGIC SETTINGS,
FAVORABLE TO
DEEP PLACEMENT OF HIGH-LEVEL RADIOACTIVE WASTES***

Arthur M. Piper**

October 1974

---

*Work performed under ORNL Subcontract 3715.

**Consultant, Carmel, California 39321.

ROCK TYPES, ALSO GEOLOGIC AND HYDROLOGIC SETTINGS, FAVORABLE TO DEEP PLACEMENT OF HIGH-LEVEL RADIOACTIVE WASTES

Arthur M. Piper

INTRODUCTION

Scope

This report seeks to resolve, in general terms, two natural factors that are crucial to managing so-called high-level radioactive wastes over the long term, in particular, the large quantity of such wastes in prospect from nuclear-fired electric generating plants. The two factors are: (1) the characteristics and relevant properties of all those rock types in which it might be feasible to emplace the wastes below the biosphere, and (2) the criteria for a geologic-hydrologic setting such that constituents of emplaced waste would not migrate beyond some particular geographic and stratigraphic zone prededicated as a repository, so long as the waste remained radiologically hazardous.

Character of the wastes

The wastes of concern are the prospective effluents from rejuvenating spent nuclear fuel, initially that from current-generation light-water reactors, but ultimately that from reactors of breeder or other future-generation types. The procedures of waste management must be sufficiently flexible to accommodate effluents of diverse chemical and radiological character, from various processes for rejuvenating the nuclear fuel.

As presently generated, the waste effluents carry a full array of fission products: a small but appreciable quantity of actinides (transuranics), chiefly uranium and plutonium; and products from the fuel-rod cladding, solvents, and other reagents. By conventional definition, the high-level wastes are those having a fission-product concentration of 100 $\mu\text{Ci/ml}$ or more; maximum concentration is commonly on the order of 5 Ci/ml. Radiogenic heat from typical waste is initially about 1,250 W per metric ton of fuel, 1,000 W after 10 years of decay, and 10 W after 200 years.

This heat derives principally from the decay of the two most abundant nuclides, strontium and cesium.

Among the many constituents in new high-level waste of typical composition and concentration, two fission-product nuclides, ^{90}Sr and ^{137}Cs , initially are by far the most radioactive. After about 1,000 years those two key nuclides, and all other nuclides having half lives of less than 1,000 years, will have decayed to or below their so-called maximum permissible concentrations for public drinking water. However, this behavior of the two does not indicate, as has been presumed commonly, that all 1,000-year-old waste would be innocuous. A more instructive indicator is the so-called relative toxicity--that is, the ratio of actual concentration of the particular constituent to its maximum permissible concentration--at any time, with due allowance for radioactive decay. On this basis, ^{90}Sr and ^{137}Cs are initially about 150,000- and 3,000-fold more toxic than any other waste constituent, but after about 550 years of decay one of the actinides, ^{239}Pu , would have become the most toxic single constituent. Even after 250,000 years of decay, relative toxicities would remain about 100 or more for the one actinide just mentioned (^{239}Pu), for certain of the longest-lived fission products (chiefly ^{79}Se , ^{93}Zr , ^{99}Tc , ^{129}I , and ^{135}Cs), and for three common nonradioactive constituents (Hg , NO_3 , and NO_2). The characteristics just outlined assume a present-day waste of typical composition and concentration, homogeneous distribution of constituents, and a full array of fission products.¹

Requirements for responsible management of the wastes

Obviously, the toxic constituents of high-level radioactive waste must not reach the biosphere in concentrations that pose an unacceptable biologic hazard. To this end, two options exist in principle: (1) diluting the waste to a permissible concentration, which generally is not feasible; or (2) containing the waste, either in its initial liquid form or after it has been desiccated and possibly converted to a solid of limited solubility. Also in principle, the waste might be separated chemically into fractions having different ranges of toxicity, each fraction then to be treated according to its characteristics. Such are the basic requirements for responsible management of the wastes.

Assuming that acceptable biologic hazard is equivalent to concentration less than the maximum permissible in public drinking water, for any and all radioactive constituents, the required time of exclusion from the biosphere becomes long indeed--some hundreds of thousands of years for the most toxic constituents. This greatest required term of exclusion exceeds the term of all civil history, greatly exceeds the assured life of any container manufactured from common materials by common techniques, and probably would involve geologic change, such as a rejuvenated glacial environment in the northern half of the United States, with a pluvial environment to the south.

Evolution of waste-management philosophy in the United States

High-level waste from the nuclear industry in the United States has been held initially as liquid and sludge in tanks near the points of its origin. Some leaks have occurred, and experience has shown the median life of a tank to be about 25 to 30 years. To retain the waste indefinitely would involve periodic replacement of tanks. With the ever larger volume of waste in prospect from rejuvenating spent fuel of the commercial nuclear-power industry, the projected demands for steel and concrete to construct tanks, and for space in which to construct them, can become serious. Thus, containing waste in tanks as liquid and sludge is regarded generally as only a temporary and expedient measure.

Some departures from this expedient practice have evolved. In particular, much old waste has been evaporated to salt cake held in tanks retired from liquid storage. Processes are being explored for solidifying the terminal liquor from the evaporators. Also, ^{90}Sr and ^{137}Cs have been separated from some waste as salt cake, to be encapsulated and then held in a water basin. Following such fractionation, the residual liquid does not self boil and requires neither cooling coils in its tanks nor intensive surveillance of its temperature. A smaller quantity of dehydrated waste has been pelletized and held in steel bins.

In regard to high-level waste from the electric-power industry, current policy is that it shall be held at the fuel-rejuvenation plant as liquid for not more than five years, and before ten years have passed it shall be solidified, charged into canisters, and transferred to a Federal repository.

Neither a particular chemical composition nor a particular type of solid are prescribed by the relevant regulations.

General schemes for final, unretrievable disposal of liquid radioactive wastes originated nearly 20 years ago. Under one scheme, the wastes would have been injected, as liquid, into saline-water aquifers deep in major sedimentary basins. This scheme has serious shortcomings, chiefly that: (1) The bulk volume of waste in early prospect is large and, presumably, yearly volume will increase exponentially for decades, at least. (2) In large part, the candidate receiving basins would be distant from points of waste origin; transporting the large volumes of prospective waste, as liquid, would be unacceptably hazardous. (3) The capacity of receiving basins to retain the prospective volumes of waste within preselected areas and stratigraphic zones is difficult or impossible to demonstrate clearly. Although virtually discredited as a general means for final disposal, in principal, this first scheme remains viable for relatively small volumes of waste generated at places which may be underlain by demonstrable receiving basins of adequate capacity.

In a first variant of the liquid-injection scheme, high-level wastes presently accumulated at the Savannah River plant of the Atomic Energy Commission, largely as salt cake and sludge, would be redissolved and re-suspended, and would be charged into vaults excavated in metamorphic bedrock deep beneath the plant site. Following intensive on-site investigation, a panel of the National Academy of Sciences-National Research Council¹ concluded that the scheme had sufficient merit to warrant a pilot excavation. However, subsequent evolution of waste-management proposals has suggested an alternative to vaults of sufficient volume to accept the waste as liquid. Accordingly, authorization for the pilot excavation has not been sought.

In a second and specialized variant of the liquid-injection scheme, waste of intermediate concentration (from 5×10^{-5} to $100 \mu\text{Ci/ml}$) has been mixed with cement to form a slurry for injection into shale by the process of hydrofracture. This variant is virtually limited to sites very close to waste-producing plants which might happen to be underlain by a suitable body of shale. It would not ordinarily apply to unfractionated high-level wastes, owing to their rate of heat generation.

A second early proposal for final disposal concluded that a bedded-salt deposit probably was the most satisfactory medium in which to place wastes deep beneath the land surface. The scheme was approved conditionally by another panel of the National Academy of Sciences-National Research Council.² At a first candidate site, tests in an abandoned salt mine in central Kansas, by simulation, demonstrated that radiogenic heat from solidified waste in metallic canisters could be dispersed readily into the salt medium. However, the particular site was disqualified for a pilot repository, owing to disclosure of certain long abandoned deep borings for oil and gas. A second candidate site, in southeastern New Mexico, is being evaluated. For this scheme, the proposed form of waste was a granular calcine.

Presently, emphasis has shifted from final disposal of the wastes to interim storage in a man-made facility (or facilities) on, or at some shallow depth below, the land surface. In particular regard to such interim storage, the trend in concept is toward: (1) a waste form of maximum chemical and physical stability, also of minimum leachability, possibly a glass or a ceramic, (2) waste canisters enclosed in overpacks (casks) of the greatest practicable integrity, to minimize the possibility for dispersal of waste constituents; (3) a means of shielding against radiation that would require little or no maintenance or surveillance; and (4) a number of dispersed facilities, to minimize aggregate mileage of transportation from fuel-rejuvenation plants. Anticipated practicable life for such a storage facility appears to be a few decades, certainly not more than a century. Obviously, the canisters of waste would need to be readily retrievable at any time. Also obviously, although the need of a means for final effective disposal would be postponed, that need would by no means be voided.

To follow the interim storage just outlined, it seems most practicable to emplace the canisters of solidified waste (and possibly their overpacks as well) below the biosphere in galleries excavated in a thick body of massive rock in which ground-water movement is minimal. Canisters would be so spaced that radiogenic heat could dissipate into the surrounding rock mass. Waste would be immobile so long as the enclosing canisters remained intact. A canister having failed (as all canisters eventually

would), waste then could be dissolved by surrounding ground water according to leachability of the particular waste form (calcine vs glass vs ceramic), and could then be dispersed according to hydraulic drive of the ground water. Direction of drive and rate of movement would need be predetermined and shown to be such that, during the desired term of exclusion from the biosphere, no waste constituents presumably would escape beyond a geographic and stratigraphic zone dedicated as a waste repository in perpetuity.

Such is the background for the objectives of this report: to discriminate those rock types and geologic-hydrologic settings in which a repository for high-level radioactive wastes, deep beneath the biosphere, might be expected to remain functionally intact for at least a thousand years, and possibly a few hundreds of thousands of years. Assuming that a variety of rock types are satisfactory in their general characteristics, repositories then might be dispersed widely and so be sited near fuel-rejuvenation plants.

ROCK TYPES

General features

In very general terms, a rock medium favorable to deep placement of high-level radioactive wastes should, primarily:

- (1) Be unweathered and distinctly homogeneous (isotropic) in both micro- and macro-textures, over a space sufficient to contain not only the galleries or other features of a repository, but also adequate buffer zones between those galleries and any surface of conspicuous discontinuity, such as a stratigraphic boundary or a fracture having a selvage of crushed rock. As a suggested practical minimum, dimensions of such space probably should be at least 100 ft vertically and 1,000 ft horizontally; desirable dimensions would be 500 ft and 1 mile, respectively.
- (2) Have no more than nominal intergranular pore space and pore-water content, particularly interconnected pore space imparting hydraulic conductivity. Ideally, interconnected pore space would be zero, but, in the absolute sense, no such condition exists naturally through a mass of rock sufficiently

large to accommodate a waste repository. Also, joints and other near-planar discontinuities must be tight and, according to the classification by Deere and Miller,³ be spaced at least widely, but preferably very widely. Specifically, their median width should not greatly exceed 0.1 mm and their minimum spacing should not be less than 1 m.

- (3) Be nonslaking--for example, contain no anhydrous minerals which might bulk in the presence of moist air. Ordinarily, slaking would occur only in certain types of shale or tuff.

Other rock characteristics might influence the design or affect the operation of a waste repository, but ordinarily would not be definitive; such characteristics involve the following considerations:

- (1) Density of the medium is an approximate index of its capability as a radiation shield. Among the several rock media, density ranges moderately, but not sufficiently to affect repository design greatly.
- (2) Strength needs to be sufficient so that repository galleries excavated according to conventional designs and techniques would remain open as long as it might be necessary to ventilate, or have access to, the waste canisters. The term of such accessibility presumably would be no more than a few decades or a century. Rock of medium strength--say with uniaxial compressive strength of 750 kg/cm^2 --should suffice. Very high strength could involve costly excavation without an offsetting advantage.
- (3) Elasticity, brittleness, or plasticity of the rock medium would have some influence on methods of excavation and dimensions of galleries and rooms, but little or none on effectiveness of a repository.
- (4) Thermal conductivity of the rock medium would determine its ability to dissipate radiogenic heat, and so determine the maximum quantity of waste permissible in a single canister and the minimum spacing of canisters in a gallery. Among the several rock types, the coefficient of thermal conductivity ranges moderately and diminishes as ambient temperature increases; the range is not sufficient to require drastic variations in repository design.

- (5) A very soluble medium, such as bedded salt or other evaporite, is not precluded if the repository zone is thoroughly isolated from circulating water. This matter will be discussed at greater length under the topic of hydrologic criteria.
- (6) Potential chemical reactivity between mineral constituents of the medium and of the waste cannot be ignored because, inevitably, over the very long term that wastes must be excluded from the biosphere, canisters will fail and waste will make contact with medium. Sufficient water probably will be present to serve as a solvent and vehicle. The normal rock temperature at the repository depth, with or without additional radiogenic heat, might accelerate reactions that proceed slowly at ambient land-surface temperatures. One likely reaction, adsorption of waste constituents onto particular minerals of the medium, would retard mobility of those constituents. Other reactions tending to disintegrate the medium, or to accelerate mobility of waste constituents, are conceivable over the long term. The likelihood of such reactions can be assessed only in regard to a waste of known chemical composition and a specific repository medium.
- (7) Magnitude and orientation of residual stress in the rock medium would be of concern only in the case of a waste fraction of intermediate concentration, emplaced by hydrofracture. Ordinarily in this case the medium would be shale, and the desirable orientation of fractures would be horizontal. This involves the principle of Fairhurst that fractures induced by fluid pressure propagate in the plane which is perpendicular to the direction of least residual compressive stress in the medium.⁴ Ordinarily then, the desirable direction of least stress would be vertical. Incidentally, magnitude and orientation of a residual stress field can be determined only by in-situ tests.⁴

Favorable rock types: their physical constants
and engineering characteristics

Seven petrologic types seem most likely to offer masses of rock that will satisfy the three primary requirements for a waste repository. Table 1 shows average chemical compositions; Tables 2 and 3 give relevant physical constants and engineering coefficients. The seven types, in general order of diminishing promise, are:

- (1) Salt, bedded or (possibly) domal;
- (2) Shale or mudstone, nonfissile;
- (3) Granite and other holocrystalline rocks;
- (4) Certain metamorphic rocks: chiefly gneiss, quartzite, and schist if indistinctly foliated;
- (5) Limestone, noncavernous;
- (6) Tuff, dense or welded;
- (7) Chalk.

In general, bedded salt is the most consistently promising medium of the seven in that it (1) is the most nearly homogeneous, (2) has sufficient strength, yet can be excavated easily, (3) is notably plastic so that its voids, if any, tend to close under the load of overlying strata, and (4) conducts heat the most freely. Being so readily soluble, any large, unthinned mass of salt indicates that circulation of ground water at its stratigraphic horizon has been, and is, virtually nil.

Shale and mudstone range greatly in petrologic character, also in physical and engineering properties. Among all the rock types, they are notably elastic-plastic, weak in compressive strength and, chalk excepted, have about the least thermal conductivity. Only their thickest bedded, strongest, least porous, and nonfissile varieties promise suitability for a waste repository. There are in the United States, however, numerous extensive deposits which are suitable. In these, hydrologic conditions are likely to be notably favorable; also, excavation of galleries for a repository generally would be easy.

Granite and other holocrystalline igneous rocks, gneiss, and quartzite are relatively homogeneous in macrotexture, only nominal in intergranular porosity, and comparatively brittle. Some schist approaches

Table 1. Chemical composition of average rock types

Constituent	Igneous	Shale	Sandstone	Limestone	Sediment
SiO_2	59.14	58.10	78.33	5.19	57.45
TiO_2	1.05	0.65	0.25	0.06	0.57
Al_2O_3	15.34	15.40	4.77	0.81	13.39
Fe_2O_3	3.08	4.02	1.07	0.54	3.47
FeO	3.80	2.45	0.30		2.08
MgO	3.49	2.44	1.16	7.89	2.65
CaO	5.08	3.11	5.50	42.57	5.89
Na_2O	3.84	1.30	0.45	0.05	1.13
K_2O	3.13	3.24	1.31	0.33	2.86
H_2O	1.15	5.00	1.63	0.77	3.23
P_2O_5	0.30	0.17	0.08	0.04	0.13
CO_2	0.10	2.63	5.03	41.54	5.38
SO_3		0.64	0.07	0.05	0.54
BaO	0.06	0.05	0.05		
C		0.80			0.66
	99.56	100.00	100.00	99.84	99.83

¹Sedimentary rocks, 1948: Harper Bros.

Table 2. Physical constants for rocks^a

Rock type	No. of Samples	Porosity (%)	Bulk density, dry		No. of Samples	Thermal conductivity, k^b	
			Average (g/cm ³)	Range (g/cm ³)		°C	W/cm ⁻¹ deg ⁻¹ x 10 ⁻³
Granite	155		2.667	2.516-2.809	1	100 1500	23.8 15.9
					15	Range Average	0-300 27.0
Other holocrystalline rocks	136		2.872	2.630-3.120	1 (Diabase)	0 100 200	23.5 22.4 22.5
					12	Range Average	0-400 21.6
Granite gneiss							28-18
Parallel to foliation					1	0 100	31.0 27.5
Perpendicular to foliation					1	0 100	21.6 20.1
Limestone and marble	58	0.0-42.8					
Limestone					24	Range Average	0-377 19.0
Parallel to bedding					1	0 100 200	34.5 29.5 27.4
Perpendicular to bedding					1	0 100	25.5 22.6
Marble					19	Range Average	0-360 19.5
Parallel to bedding					1	0 200	30.8 21.7
Perpendicular to bedding					1	0 200	30.1 21.1
Dolomite					1	0 100 200	49.8 38.9 33.3
Chalk					1		9.2
Sandstone	104	0-51.2		1.60-2.68			41.8-8.0
Quartzite					13	Range Average	0-200 49.7
Parallel to bedding					1	0 200	56.9 31.7
Perpendicular to bedding					1	0 200	54.8 36.2
Shale	41	0.0-44.8		1.54-3.17	5	Range Average	-25 15.9
Tuff							16-7
Rock salt			2.1			17	72.0

^aAdapted from Geol. Soc. America, Handbook of physical constants: Special Paper 36.^bAt 1 atm.

Table 3. Elasticity and compressibility of rocks

Rock	Young's modulus (E_t , kg/cm ² $\times 10^5$)	Uniaxial compressive strength σ_a (ult), kg/cm ² $\times 10^3$	Ratio E_t/σ_a (ult)
Granite and other holocrystalline rocks (80 specimens, 16 loca- tions)			
Fresh	4.2- 8.5	1.0-2.7	325-500
Coarse grained, altered	1.4- 3.6	0.6-1.1	200-425
Diabase (26 specimens, 8 loca- tions)	7.0-11.0	2.2-3.5	275-350
Basalt, andesite, and diorite (70 specimens, 20 locations)	1.3-14.0	0.3-3.8	200-500
Limestone and dolomite (77 specimens, 22 locations)	2.6-10.0	0.5-2.9	250-600
Marble	4.7- 8.0	0.6-0.8	600-750
Quartzite	6.0- 9.5	1.3-4.2	225-500
Sandstone	116 specimens }	- 5.0	50-420
Shale		- 3.6	25-300
Gneiss	3.2- 8.0	0.9-2.1	200-600
Schist			
Foliation dips $>45^\circ$	0.6- 7.8	0.1-1.4	275-850
Foliation dips $<45^\circ$	0.5- 5.0	0.2-2.1	100-400

^aAdapted from ref. 3.^bThe ranges of numerical values shown are taken from graphs, and include 75% of the data points.

them in general rock quality, but if foliation is distinct, this particular rock type is likely to be seriously anisotropic. The most likely insufficiency of these rocks is too-close spacing of joints. In them, excavation would be somewhat slow and costly. Thermal conductivity is generally moderate except in quartzite, in which it is notably large and approaches the conductivity of salt (see Table 3).

Limestone (and dolomite) that is satisfactory as the medium of a repository would be of the thicker bedded and finer-grained varieties, generally of inorganic chemical origin. Further and critically, it must be virtually devoid of channels and intergranular voids formed by dissolution; this particular characteristic is most likely where the limestone stratum is, and over geologic time has been, isolated by overlying and underlying strata of impervious shale. Limestone having the characteristics just summarized would be of high to very high strength and notably elastic. Excavation should be of only moderate difficulty. Thermal conductivity would be about equal to, or slightly less than, that of the holocrystalline igneous rocks.

As the medium for a waste repository, most deposits of tuff would not be favorable in one or more characteristics. However, some deposits appear potentially suitable in that they are thick bedded or massive, fine textured, and have little interconnected pore space. Generally, these are of the welded variety. They promise sufficient strength, and excavation is almost as easy as in shale. However, thermal conductivity of tuff may be expected to be much less than that of salt, considerably less than that of the holocrystalline igneous rocks and the metamorphic rocks, and about equal to that of shale.

Chalk, best known from its extensive deposits in England and France, appears superficially favorable for a waste repository in that commonly it is massive, very fine grained, and homogeneous. In it, excavation would be easy. However, its thermal conductivity is least among conductivities of all the rock types here described--specifically, less than one-tenth that of salt and generally about from one-fourth to one-half that of the other conductivities. Being calcareous, chalk is susceptible to dissolution by circulating ground water, and so commonly might fail to satisfy hydrologic criteria for a repository (such criteria will be outlined).

Verification of rock quality

Ordinary methods of stratigraphic and structural geologic mapping can identify a candidate repository site in terms of the desired volume of a seemingly favorable rock type. However, to assure that rock quality is appropriate in detail will require intensive and innovative tests in situ and in the laboratory. Only general and tentative standards can be derived in this report.

A few cored boreholes may suffice to verify a candidate site tentatively, or to reject a grossly inadequate site, on the basis of a so-called rock-quality designator (by convention, RQD). This designator is the percentage of core recovered in relation to footage drilled, and is modified to exclude core pieces less than 10-cm long unless their ends are fresh irregular fractures obviously due to breakage in the core barrel, and unless they can be fitted together tightly to make up core segments of at least the minimum 10-cm length. Percentage core recovery, so modified, correlates with RQD terms as follows:⁵

<u>Modified recovery (%)</u>	<u>RQD designation</u>
0-25	Very poor
25-50	Poor
50-75	Fair
75-90	Good
90-100	Excellent

The writer⁵ suggests arbitrarily that a candidate site be accepted for intensive verification only if modified core recovery is 85% or more in each of four boreholes spaced to represent both the planned repository and a suitable enclosing buffer zone--in other words, within the "excellent" RQD range and the higher third of the good range. This suggested standard is tentative and may need to be modified as experience increases.

Intensive exploration should strive for a statistically valid sample of the site and buffer zone in three dimensions; it might involve not only oriented cores, but also borehole scanning by television camera or color photography, or both.

Laboratory tests of core specimens lead to rock-quality values in terms of ultimate uniaxial compressive strength and of Young's modulus of elasticity (tangent modulus at 50% of ultimate compressive strength; see Table 2). The ratio of these two values, the so-called modulus ratio, is a fairly comprehensive indicator of rock quality for purposes of engineering design. Deere (ref. 5, pp. 4-12) correlates a modulus ratio of 500 or more with "high" quality, 500 to 200 with "average (medium)" quality, and less than 200 with "low" quality. These ranges and quality terms apply to suitability of the rock for foundations of large engineering works; other ranges and terms may prove to be more meaningful in regard to waste repositories.

Consistent values of the modulus ratio suggest homogeneous or isotropic rock. However, the ratio derives from tests on specimens of sound core and so would not measure the effects of joints, bedding-plane partings, or other discontinuities which could render the whole mass of rock decidedly anisotropic.

The more sophisticated triaxial test gives even more insight into the behavior of a rock medium under load. In this procedure the specimen is contained in a fluid under pressure, while an axial stress is applied mechanically.⁶ Again, however, the test does not measure the effect of macrodiscontinuities.

An indicator which involves the whole of a rock mass is the so-called velocity ratio:

$$V_F/V_L$$

in which V_F = compressional-wave velocity measured in situ by seismic methods, uphole or crosshole. (Seismic receivers can be so placed in boreholes, or in adits, as a means of isolating distinct zones of rock quality.)

and V_L = compressional-wave velocity measured by sonic methods in the laboratory, on a piece of sound core under axial compression equivalent to the overburden pressure in situ, and having a moisture content approximating the natural condition.

The velocity ratio approaches unity for a homogeneous rock of highest quality. Also, the square of the velocity ratio appears to be nearly equal to the RQD as defined above.⁵ As a tentative standard for verifying quality of the rock medium of a candidate repository site, Deere⁵ suggests a velocity ratio of 0.85 or more.

The test procedures outlined here, from the discipline of rock mechanics, cannot resolve all questions as to suitability of a particular rock medium for a repository to contain high-level radioactive wastes. More definitive procedures will need to be devised for individual candidate sites.

GEOLOGIC AND GEOMORPHIC SETTING

Preceding considerations of the nature and quality of the rock medium relate chiefly to engineering design of repository facilities. They have little direct bearing on the more crucial questions: Can those facilities remain mechanically and hydraulically secure during the several hundreds of thousands of years that waste constituents should be excluded from the biosphere? What geologic settings promise such security? In more specific terms and presuming that, for protective separation from the biosphere, the repository is below not only the present zone of fresh-water circulation, but is also below a 500-ft-thick isolation zone: By what natural processes might the protective cover be seriously impaired or even breached? Might the present hydrologic regime be affected drastically and adversely? By what criteria can areas potentially subject to such adverse actions by natural forces be discriminated and avoided? In this context, processes of deposition that might thicken the protective zone are not of concern. There are no comprehensive precedents for lines of reasoning by which these questions might be resolved; only general and tentative criteria are offered here.

Two basic presumptions are made: first, that geologic events of the near future will extend and repeat events of the near past; second, that although some geologic events may seem cataclysmic in the historic sense, generally, they are predictable over geologic time.

In this context, the desired future term of excluding high-level radioactive wastes from the biosphere is in the order of one-third to one-fourth of the time elapsed since the start of the Pleistocene ("glacial") epoch. Further, available evidence is reasonably conclusive that the climatic environment of historic time has been, and remains, interglacial and interpluvial. It follows that alpine, piedmont, and continental glaciers will almost certainly reoccupy parts of the northern United States within the term of waste exclusion. Other credible presumptions are that rejuvenated pluvial conditions to the south will accelerate erosion locally; also, that volcanic activity will resume intermittently in scattered areas of the westernmost United States. Thus, it should suffice to weigh the security of a candidate repository zone against the record of geologic events in the particular vicinity during the latter half of the Pleistocene epoch. Contingencies not a part of that record are not germane.

Intensive investigation would be necessary to retrace the chronology in terms of recurrence frequency and duration of the several events, and the kind and magnitude of geologic work done in each. Dating of events in terms of years, by any and all applicable methods, would of course be crucial; emphasis should focus on changes from one type of geologic work to another, and on discontinuities in and rejuvenations of a given kind of work.

Preferably, candidate repository sites would be in upland areas of moderate or slight relief, and would be tectonically fairly stable since middle Pleistocene time; generally each candidate repository zone would be below the local base level of erosion. In such a setting the potential rate of erosion, and the projected time lapse for erosional breaching of the cover above a repository zone, might be assessed from datings of stream terraces. For this, diverse techniques might be effective, including archeologic dating of artifacts correlated with particular terraces or other land forms, or isotopic dating of the CO_2 radical in the caliche cap of a terrace.

Settings generally questionable for a waste repository would include:

- (1) Extremely rugged terrain--the principal localities for rejuvenated alpine glaciers and of accelerated erosion under rejuvenated pluvial conditions.

- (2) Regions of potentially rejuvenated piedmont and continental glaciation in the northern part of the United States. There, credible adverse events might include damming of major drainage ways by ice, with consequent rapid erosion as ponded waters escaped. Events of this very sort occurred on a grand scale in east-central Washington in the latest fourth of the Pleistocene epoch, with conspicuous channels cut hundreds of feet deep across antecedent divides and across ice-marginal uplands.⁷
- (3) Points of potential major stream piracy, under rejuvenated pluvial conditions.
- (4) Littoral and estuarine areas, especially of a presently drowned or subsiding coast; also the flood plains and inner valleys of major perennial streams.
- (5) Vicinities of major past landslides and of potential slides--in general, areas of youthful topography coupled with weak rocks. Incidentally, many such areas would have been ruled out by the preceding criteria of acceptable rock quality.
- (6) Vicinities of volcanism and of strong seismic or tectonic activity since middle Pleistocene time.

The potentiality for recurrence would be undeniable and the results unclear. In the case of strong seismic activity, the principal effect might be the opening of a conduit for circulation of water from the land surface to the repository zone, rather than mechanical damage to waste containers.

Karst or sinkhole topography is neither adverse nor favorable to a repository. It would, of course, signify active dissolution of carbonate rocks or of evaporites, currently or in the geologic past. However, as there is a base level of erosion, generally there is a base level of dissolution below which the rocks are virtually unaffected. In principal, below this base level of dissolution a repository and buffer zone could remain secure, other features being favorable. Only relevant investigation of the particular candidate site can resolve the issue.

HYDROLOGIC SETTING

General limitations

Three lithologic specifications have been given for a rock medium favorable to deep placement of high-level radioactive wastes. Of these, two imply a first basic limitation on the acceptable hydrologic setting--that the medium have only nominal hydraulic conductivity from intergranular pore space and little from fractures. The geometry of fractures that has been specified (median width not more than 0.1 mm and average spacing at least 1 m) would correspond to a mean fracture porosity not exceeding 0.03%. Maximum acceptable intergranular porosity is set tentatively at 0.5%; maximum hydraulic conductivity at 1 gpd/ft².

The second basic limitation is that the horizon of the repository must be isolated hydraulically from all water bodies which sustain the biota. In regard to the land masses, this limitation is equivalent to hydraulic isolation from the zone of fresh ground water or, in other terms, to classifying the zone of fresh ground water as part of the biosphere from which high-level radioactive wastes would be excluded until decay has rendered them innocuous. In this concept the biosphere would include all ground waters that conceivably enter food chains, either naturally or by act of man, such as extraction for use, including desalination or as a source of raw materials. Generally, the repository horizon would be in the zone of unusable brackish or saline water, or would be virtually devoid of water.

Isolation is necessary because waste containers inevitably will fail in time. Hence, waste toxins will be in contact with the surrounding medium and its ground water, if any; they may be redissolved freely by the ground water; having been dissolved, they will move with that water into, and conceivably beyond the medium. Accordingly, for each repository site, it must be possible to anticipate the prospective reach of toxins so dispersed, and to dedicate an adequate zone in the repository horizon to receive and contain the dispersed toxins. In this context, the greater the conductivity and the smaller the porosity of the repository medium, the more extensive the dedicated zone must be.

A minimum isolation barrier or buffer zone, say at least 500-ft thick, seems desirable between repository horizon and the overlying fresh-water zone. It may or may not be lithologically distinct but, like the repository medium, should be virtually devoid of water. A greater thickness of buffer zone may be indicated by hydrologic features of the vicinity.

The third and final general limitation is that the hydraulic isolation just outlined must persist so long as waste toxins must be excluded from the biosphere, however long that term of exclusion might be. Thus, over the long term, the hydrologic setting which qualifies each repository site must withstand the potential effects of geologic or climatic changes which have been noted. To a large extent these potentials can be anticipated, presuming that the geologic and hydrologic appraisals of a candidate site have been comprehensive; serious potential effects would disqualify the site. Over the short term, the hydrologic setting of a repository site must be proof against adverse actions by man in the vicinity, such as large and sustained extraction of water, or drilling numerous deep boreholes not tightly cased. Actions by man are less predictable than geologic or climatic events that might recur; thus, the short-term risk of serious adverse effects is probably greater than the long-term risk.

Consider, for example, the extensive and large hydraulic stress along the Capitan aquifer in southeastern New Mexico and adjacent counties in Texas.⁸ There, beginning in the forties, water has been extracted from the cited aquifer in an aggregate volume of about 0.7 million acre-ft through 1969. As a result, the piezometric surface of the aquifer currently has been depressed about 700 ft (fresh-water equivalent) at the regional center of extraction near Kermit, Texas; some 200 ft in the recharge area of the Glass Mountains, 100 miles to the south; and 500 ft near Eunice, New Mexico, 40 miles north of Kermit. In large part, this great piezometric depression has formed during three decades; it continues to deepen, and in Lea County, New Mexico, in 1970 and 1971, it deepened by about 20-ft per year. Thus, all along a 175-mile reach of this aquifer the natural pattern of hydraulic gradients and of ground-water movements has been modified profoundly; the ultimate magnitude and reach

of effects is conjectural. Had there been a repository site close at hand, the hydrologic setting which qualified the site could have been vitiated.

Scope of hydrologic investigation

Clearly, to assess a candidate repository adequately, it must be possible to anticipate directions of ground-water movement, also linear velocities and volume rates of such movement, both in the repository medium and in other rock types which may intervene between it and the overlying zone of fresh ground water. To that end it will be necessary to determine, in the field, the 3-dimensional geometry of the several rock types, the porosity and hydraulic conductivity of each type, and the hydraulic gradients in and between them. No rock type can be presumed to have zero hydraulic conductivity in the absolute, timeless sense. Data that are representative in 3 dimensions should be sought, within and beyond any zone which might be dedicated to, or conceivably might be invaded by, redissolved waste toxins.

Horizontal and vertical conductivities must be determined separately for rocks that may be directionally anisotropic. Vertical hydraulic gradients, actual or potential, should not be overlooked. Conventional methods of investigation may be ineffective, in view of the very small conductivities. Commonly, innovative test procedures will need to be adapted to each particular site, such as pumped circulation between boreholes, combined with an isotopic tracer;⁹ injecting water at less-than-critical pressure; pumping boreholes by depth zones isolated between packers; and so-called slug tests.¹⁰

Volume rates of water movement are usually derived from an assumption that Darcy's law applies, even though hydraulic conductivity is extremely small. (Darcy's law states that the rate at which water is transmitted through a permeable medium is proportional to the hydraulic gradient and to the cross-sectional area through which the transmission takes place, other variables being constant.) Although the law probably fails at some extremely small hydraulic gradient coupled with extremely small conductivity of the medium, such failure has not been demonstrated

under precisely duplicated conditions. For purposes of this report, the presumption that Darcy's law holds at all conductivities and gradients, however small, is conservative in that it leads to calculated potential movement of waste constituents somewhat greater than the actual.

Distinctive features of the several rock types

Among the rock types that have been listed as potentially favorable to deep placement of high-level radioactive wastes, only salt may be expected generally to furnish an ideally dry setting. A salt deposit exists because it has long been water-free; to qualify a repository site in salt is to demonstrate that its surroundings presumably will remain water-free through any likely changes in geologic and climatic settings. For one candidate repository site in southeastern New Mexico, projected integrity has been assessed by the writer in earlier reports.^{8,11,12}

Shale and mudstone range greatly in porosity (Table 2) but, as has been stated, their thickest bedded and least porous varieties may favor waste repositories. Being notably elastic-plastic, their fractures generally may be expected to be less planar and less extensive than in brittle rocks; thus, their conductivity through fractures may also be expected to be less. Intergranular hydraulic conductivity perpendicular to bedding planes might commonly be less than that parallel to bedding planes.

At the Savannah River Plant of the Atomic Energy Commission, hydraulic conductivity of one 60-ft section in mudstone of Triassic age has been calculated to be about 6×10^{-6} gpd/ft².¹⁰ This value of conductivity is fully two orders of magnitude less than that ascribed to so-called nontransmissive metamorphic rock of the same vicinity; it is the least value known to the writer to have been determined for any granular rock medium. Rock so nearly water free would seem to be extremely favorable for a waste repository. Representative values of hydraulic conductivity for other promising masses of shale or mudstone are not available.

Among the massive, brittle media (the holocrystalline igneous rocks and certain metamorphic rocks) hydraulic conductivity is generally by way of fractures and is commonly variable from one point to another, but

in an extensive mass of the rock tends to be equal in all orientations. For this class of media, geologic and hydrologic features of one candidate repository (Savannah River Plant, reconstituted liquid waste) have been explored extensively. Two categories of rock have been discriminated: (1) transmissive rock, in which fractures are spaced rather closely and probably are interconnected, hydraulic conductivity averages about 1 gpd/ft², and mean porosity is about 0.08%; and (2) nontransmissive rock, in which hydraulic conductivity is estimated to be about 0.001 gpd/ft² and calculated mean porosity is about 0.004%.^{9,13,14} The cited porosity of transmissive rock could be simulated by three series of orthogonal planar fractures, each 0.1-mm wide, parting the rock into cubes 37 cm on a side; the corresponding cubic parting of nontransmissive rock would average 7.5 m on a side. However, actual geometry and dimensions of the fracture system are virtually unknown.¹

Under local hydraulic gradients of this candidate site, calculated mean velocities or horizontal ground-water movement would be in the order of 40/year in transmissive rock and 0.8 ft/year in nontransmissive rock (132 and 6,600 year/mile, respectively). Thus, during a minimum 1,000-year term of exclusion, waste components would, in principle, move down-gradient 0.15 mile in nontransmissive rock, and 7.5 miles in transmissive rock. Neither of these distances would be excessive for the dimension of a zone dedicated in perpetuity to containing wastes. However, were the desirable term of exclusion to be 250,000 years, the calculated down-gradient reach of waste components would be 38 miles in nontransmissive rock and 1,900 miles in transmissive rock. For the long term, therefore, the required dimension of a dedicated zone would be of doubtful feasibility even in wholly nontransmissive rock, and would be incredible in wholly transmissive rock. But, as will be demonstrated next, the horizontal component of anticipated waste mobility is not the crucial hydrologic feature of the site.

Owing primarily to man's extractions of water from an overlying regional aquifer during the last several decades, there exists, in the metamorphic rock in the central part of the Savannah River Plant reservation, a substantial hydraulic gradient that is vertically upward. In consequence, the calculated vertically-upward component of mean ground-

water velocity is from 30 to 49 ft/year in nontransmissive rock, and from 1,500 to 2,400 ft/year in transmissive rock.¹ (The range in these calculated velocities is the effect of a discontinuous layer of clay which intervenes between the metamorphic-rock medium and the regional aquifer.) Granting such velocities, waste components moving with the ground water might pass through the 500-ft-thick isolation zone within a decade or two in nontransmissive rock, but within a few months in transmissive rock.

Clearly, the isolation zone would fail its purpose in the oversimplified case just calculated. To bypass complexities of the actual case, it was concluded that the candidate site was only marginally qualified for the minimum exclusion term of 1,000 years. In this particular instance, marginal suitability of the site is due largely to the potential for upward migration of waste constituents. General significance of such a potential is examined further in the closing section of this report.

Little can be said as to distinctive features of the distinctly stratified media--limestone, chalk, and, in some instances, tuff. Porosity can range greatly, and only the least porous of each medium would promise satisfactory repository sites. Hydraulic conductivity perpendicular to bedding planes is likely to be notably less than that parallel to bedding planes. Commonly the dryness of these media, and their suitability as waste-repository sites, depend less on their internal characteristics and more on the effectiveness of confining impervious strata. In other words, in these media a candidate site would be qualified largely according to stratigraphic and hydrologic settings; consequently, each case would be unique.

Significance of vertical hydraulic gradients

Vertical gradients in ground-water heat exist, though commonly they are neither discriminated nor measured. A gradient vertically downward to a candidate repository horizon would be generally favorable, and redissolved waste would tend to be constrained within the horizon. Conversely, a vertical gradient upward would denote a potential that redissolved waste toxins would move upward from the horizon, across stratification.

Thus, the preliminary appraisal of a candidate repository site should seek any vertical gradients that may exist between the repository horizon and overlying fresh-water zones, as measured in boreholes by piezometers isolating successive depth zones. Also, evidence of vertical water movement should be sought in chemical-composition variation of pore waters with depth. Because this sort of evidence may be vague, the examination should cover minor and trace constituents, and indicators of geochemical history, such as isotopic ratios. Such piezometric and chemical examination is crucial because, although natural vertical gradients may be either upward or downward, upward gradients may be created or aggravated, perhaps grossly, by man's extractions from fresh-water aquifers.

As a hypothetical example of vertically upward movement of water assume: (1) an aquifer at the base of the fresh-water zone, 50-ft thick, porosity 25%, hydraulic conductivity $1,000 \text{ gpd/ft}^2$, horizontal hydraulic gradient 0.001 or about 5 ft/mile; (2) a repository zone 500 ft beneath the aquifer, in a rock medium of porosity 5%, isotropic hydraulic conductivity 0.01 gpd/ft^2 , and horizontal hydraulic gradient 0.001 as in the overlying aquifer; and (3) a vertically-upward hydraulic gradient of 0.02 or 10 ft of differential head between zone and aquifer. These assumed dimensions and hydrologic coefficients are of median magnitude within ordinary ranges of the several factors.

Under the assumptions that: (1) calculated horizontal flow in each foot-wide strip of the aquifer would be 50 gpd; (2) vertical movement into the aquifer from the repository zone would be 1 gpd per down-gradient mile along the aquifer (i.e., 2% of aquifer flow per mile of repository-zone length); (3) in the aquifer, mean ground-water velocity would be about 200 ft/year horizontally; and (4) in the repository zone, ground-water velocities would be about 0.01 ft/year horizontally, but 0.2 ft/year vertically. Thus, in the repository zone, the vertical (upward) component of velocity would be 20-fold greater than the horizontal component.

In this hypothetical example, assume further that the fluid in the repository zone is redissolved waste, in a concentration equivalent to that of typical initial waste already described, liquid and unfractionated; also, that density and viscosity of the redissolved waste equals those of the native repository-zone water. (The second half of this assumption may be ill-founded.)

Then: (1) In the 1,000-year minimum term of exclusion from the biosphere, waste would have reached 0.003 mile horizontally from the repository; in the maximum 300,000-year term, 0.6 mile. In the limited sense of horizontal movement, therefore, a buffer zone of 1 mile surrounding the repository would have contained the waste until all its radioactive toxins had decayed to innocuous concentrations. (2) However, the redissolved waste would have moved largely upward and, after a residence time of about 2,500 years in the 500-ft-thick isolation barrier, would have entered the aquifer. (3) Residual toxins entering the aquifer, in concentrations at least 100-fold greater than permissible in public drinking water, would include the actinide ^{239}Pu ; the long-lived fission products previously listed, chiefly ^{79}Se , ^{93}Zr , ^{99}Tc , ^{129}I , and ^{135}Cs ; and the three nonradioactive constituents Hg , NO_3^- , and NO_2^{2-} . (4) In the aquifer, the residual toxins would move down gradient about 200 ft/year (26 year/mi) and, assuming uniform dispersal in the aquifer, would be diluted about 50-fold within the first mile. Farther down gradient, the dilution factor would diminish and concentrations of certain toxins would probably remain greater than the permissible maximum. (5) In principle, down-gradient reach of these toxins in 300,000 years would be about 11,000 miles, an obviously unrealistic distance.

Thus, unfractionated waste having been placed in the repository initially, the intended exclusion from the biosphere would have failed after about 2,500 years of decay. Thereafter, the fresh-water zone would have been invaded by the residual toxins listed in the preceding paragraph.

The preceding hypothetical example is simplified from actual conditions at the Savannah River Plant, already described. It is fairly realistic and is acceptable as an order-of-magnitude demonstration of potential behavior of a repository under the conditions assumed. Considering the hydrologic coefficients cited, the site probably would have been considered suitable if the vertically-upward hydraulic gradient had not existed, or if it had not been detected when the site was first appraised. On the other hand, even with the vertical gradient, the aquifer would not have been in hazard had the waste been stripped initially of its actinides, long-lived fission products, and nonradioactive toxins.

Thus, the example suggests: (1) For a term of a few thousand years only, numerous sites probably would meet the limitations and criteria previously outlined, in regard to a repository for high-level radioactive wastes from rejuvenating nuclear fuel; also, during that term, a repository could effectively contain wastes that had been desiccated, but not chemically modified, and that had been put into metallic canisters. (2) Effective containment of unmodified high-level waste for terms longer than a few thousand years would require a repository medium virtually water free in the absolute sense; only bedded (and possibly domal) salt offers such an environment widely. (3) Criteria for a repository site could be relaxed substantially if the waste were modified by removing, or rendering insoluble (virtually in the absolute sense), the actinides, nuclides with half-lives exceeding 1,000 years, and nonradioactive toxins; or, if the vicinity of a repository were to be so controlled that the maximum permissible concentrations of the more persistently toxic constituents could be relaxed two orders of magnitude from those applied to public drinking water.

REFERENCES

1. National Research Council, 1972, An evaluation of the concept of storing radioactive wastes in bedrock below the Savannah River Plant site: National Academy Sciences, Washington, 86 p.
2. National Research Council, 1970, Disposal of solid (solidified) radioactive wastes in bedded salt deposits: National Academy Sciences, Washington, 28 p.
3. Deere, D. U., and Miller, R. P., 1966, Engineering classification and index properties for intact rock: U.S. Air Force Weapons Laboratory Tech. Rept. AFWL-TR-65-116, Kirtland AFB, New Mexico.
4. Roberts, A., 1968, The measurement of strain and stress in rock masses; Ch. 6 in Rock mechanics in engineering practice: John Wiley & Sons, New York.

5. Deere, D. U., 1968, Geological considerations; Ch. 1 in Rock mechanics in engineering practice: John Wiley & Sons, New York.
6. Hendron, A. J., Jr., 1968, Mechanical properties of rocks: Ch. 2 in Rock mechanics in engineering practice: John Wiley & Sons, New York.
7. Bretz, J. H., 1959, Washington's channeled scabland: Washington Div. Mines and Geol. Bull. 45, 55 p.
8. Piper, A. M., 1974, The four-township area near Carlsbad, New Mexico--vulnerability to future subsrosion: Unpublished rept. to Union Carbide Corp., 32 p.
9. Webster, D. S., Proctor, J. F., and Marine, I. W., 1970, Two-well tracer test in fractured crystalline rock: U.S. Geol. Survey Water-Supply Paper 1544-I, 22 p.
10. Cooper, H. H., Jr., Brederhoeft, J. D., and Papadopoulos, I. S., 1967, Response of a finite-diameter well to an instantaneous charge of water: Water Resources Res., v. 3, no. 1, p. 263-269.
11. Piper, A. M., 1973a, In-situ dissolution of marine evaporites--Principles and concepts: Unpublished rept. to Union Carbide Corp., 18 p.
12. Piper, A. M., 1973b, Subrosion in and about the four-township study area near Carlsbad, New Mexico: Unpublished rept. to Union Carbide Corp., 28 p.
13. Christl, R. J., 1964, Storage of radioactive wastes in basement rock beneath the Savannah River Plant: E. I. duPont deNemours & Co., Report DP-844, 39 p., 66 p. append.
14. Siple, G. E., 1967, Geology and ground water of the Savannah River Plant and vicinity, South Carolina: U.S. Geol. Survey Water-Supply Paper 1841, 39 p.

APPENDIX B:

ADVANCED BOREHOLE PLUGGING BY MELTING*

L. B. Lundberg**

C. A. Bankston**

January 1975

---

*Work performed under ORNL purchase order 78X-41866V.

**Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544.

**ADVANCED BOREHOLE PLUGGING BY MELTING:
FINAL REPORT**

I. INTRODUCTION

The disposal of radioactive wastes in underground salt deposits depends on the long-term physical integrity of the salt formation. Pre-existing boreholes, those formed for site evaluation, vault construction, and monitors must be sealed to restore the integrity of most of the salt formations proposed for radioactive waste storage. The plugs used to seal these holes must not represent a threat to the integrity of the salt formation during the hazardous lifetime of the wastes.

The work described in this report represents a study of the feasibility of forming borehole plugs by melting and resolidifying salt similar to that found in the formation. It was thought that a plug with physical and chemical properties close to those of the formation could be formed by this technique. Since melting and resolidification of rock salt causes practically no change in the chemical properties, only the physical properties of the plugs prepared in this study were examined. The properties that were thought to be most important were the physical structure of the plug on both a macro and a micro scale, the fluid permeability of the plug, and the strength of the plug. The plugs formed were evaluated on these bases relative to the rock salt into which they were formed.

It was felt that a representative borehole plug should have a length-to-diameter ratio of about ten. Consequently, a simple melting tool was designed, constructed, and used to prepare a plug 85 cm long by 7.7 cm in diameter in rock salt originally obtained from a mine located near Lyons, Kansas. This report describes the preparation and evaluation of this plug. Some attempt is also made to indicate the relationships of the data gathered from these experiments to the possibility of field application.

BLANK PAGE

II. EXPERIMENTAL

A. Sample Preparation

The first experiments in the project were performed by melting plugs into predrilled 7.7-cm diam by about 8-cm deep holes in blocks of Lyons, Kansas rock salt. The blocks were about 20-cm sq by 10 to 15-cm high. It was decided that this specimen was too short to obtain plugs even remotely comparable to an actual borehole plug. Consequently, a specimen was prepared by stacking and grouting five predrilled blocks of rock salt into a large cardboard tube (see Fig. 1). The sample was 86-cm high, and the predrilled hole came to within 5 cm of the bottom.

This sample was placed in the facility shown in Fig. 1 for plugging the borehole. This facility is equipped with the electrical power required to operate the heater that was used to melt the salt, and a servo-controlled electrohydraulic system used to extract the heater from the hole in a controlled manner as it was being filled. The sample was placed on a rotatable table to make it possible to turn the heater in the hole. Turning the heater was necessary because the heating element was not cylindrically symmetric.

A closer view of the heater assembly and the top of the filled long borehole specimen is given in Fig. 2. The heater element used in this experiment was a metallic strip made of Haynes 25. Previous experimentation had indicated that Haynes 25 was the better choice for heater material as compared to Haynes 188 or Hastelloy N. The heater strip was clamped into a water-cooled copper holder that was mounted on the end of a piece of drill stem. Direct electrical current was passed through the heater strip to provide the heat necessary to melt the rock salt. The heater was operated at 2 kW (4 V, 500 A) to fill the 7.7 cm diam hole at a rate of about 0.1 mm/sec. The heater temperature was maintained at close to the melting temperature of the rock salt (1077 K) because there was little thermal resistance between the heater and the melt, and the melt was not allowed to superheat.

The hole was filled by manually pouring granulated Lyons, Kansas salt down on the heater; whereupon, the rock salt melted with much popping and snapping (caused by occluded water in the salt crystals).

Fig. 1. Borehole plugging test facility.

Fig. 2. Closeup view of filled borehole and heater assembly.

A molten pool was maintained as the heater was extracted from the hole. The power-heater removal rate relationship had been previously established by melting a plug into a shallow hole in a block of livestock salt. It was necessary to both rotate the specimen and stir the melt with a long rod to keep the incoming granulated salt moving into the melt. There was a strong tendency for the molten pool to be bridged by partial melting of the incoming granules. Caking of the incoming granules was also a problem. The caking seemed to be enhanced by residual water being driven from the hole by the heat.

B. Plug Evaluation

The first step in evaluating the plug was to remove the salt blocks from the grout and section them longitudinally. The sectioning was performed dry with a horizontal band saw.

A typical view of the cross section of the experimental borehole plug is seen in Fig. 3. The plug appears to be well bonded to the hole wall. The plug is progressively more porous toward its centerline and there are a few large, extended cracks through it. The physical structure of the plug is typical for materials that undergo substantial shrinkage during solidification and cooling. The large volume reduction during the liquid-solid phase transformation (19%) is the primary cause of the porosity, and the cracking is caused by the large amount of thermal shrinkage (10% reduction in volume) which occurs when the plug cools to room temperature. The darker color (actually, it's bluish) of the plug is caused by the corrosion products from the heater strip. Some cracking of the surrounding, unmelted rock salt was also observed.

The microstructure of the parent rock salt, the plug, and the interface between the plug and the salt can be seen in Fig. 4. As will be noted in Fig. 4(a), the grain size of the parent salt is quite large - several millimeters across. The typical microstructure of the plug can be seen in Fig. 4(b). It is immediately obvious that the plug has a large amount of porosity. The permeability data which is presented below (see Table I) indicates this porosity is essentially closed. A magnified view of the typical plug-parent rock salt bond is given in Fig. 4(c). The view is down the axis of the plug. As will be noted,

Fig. 3. Sectioned segment of long borehole plug.

Fig. 4. (a) Microstructure of Lyons, Kansas rock salt, (b) experimental borehole plug material, and (c) bond between plug and rock salt.

Table I

Sample No.	Density (Mg/m ³)	Permeability (darcys)	Crush Strength (MPa)
Lyons, KA Rock Salt			
2-4	2.1	0.5	29.1
2-5	2.0	0.9	16.8
2-6	2.2	0.2	37.9
Avg.	2.1	0.5	27.9
Experimental Borehole Plug Materials			
5-1	1.6	0.4	8.7
5-2	1.6	0.3	15.7
5-3	1.6	0.2	9.8
5-4	1.5	1.0	14.0
5-5	1.7	0.2	13.3
2-2	1.4	0.6	8.2
Avg.	1.6	0.4	11.6

the bond is quite sound, and it appears to be as strong as the parent rock salt. The radial cracks which intersect the bond region are typical for the plug. They are probably caused by thermal shrinkage of the plug.

The samples seen in Fig. 4 were removed from the larger samples by dry sawing with a band saw, and they were final shaped by dry sanding. The samples were shaped to parallelepipeds 19-mm sq by about 30-mm long. Dry preparation methods were used because it was felt that wet methods would bias the permeation data toward lower permeabilities. These specimens were used for bulk density, permeability, and crush strength measurements. The bulk density was obtained by measuring the external dimensions of the sample and weighing it. The data are listed in Table I. It will be noted that the plug material is only about 76% as dense as the parent rock salt.

Permeability measurements were obtained for samples of both parent rock salt and plug material. The measurements were made with a Ruska Gas Permeameter using nitrogen gas. All measurements were made at room temperature and 1 atm pressure. The permeability, K , was calculated in darcys from the equation:

$$K = \frac{\mu \bar{Q} L}{A P}$$

where

μ = viscosity of the gas in centipoise.

$\bar{Q}$ = average rate of flow through the specimen in cm^3/sec .

L = length of the specimen in cm.

A = cross-sectional area of the sample in cm^2 .

P = pressure gradient along the length of the specimen in atm.

The permeability data listed in Table I show little difference in the permeability of the rock salt and the plug material. This indicates that the porosity seen in the plug is essentially closed. Several samples contained major cracks which extended the complete length. These samples leaked so badly that the permeameter could not measure the rate.

After permeation testing, the samples were loaded uniaxially to destruction at room temperature in an Instron test machine. The samples were loaded without confinement in a subpress which was set on the load

platen of a 44 kN (10,000 lb) Instron load cell. The lateral deformation friction between the specimen and the load platen was reduced by placing 0.3-mm thick pieces of cardboard on the ends of the specimen. The crush test data are listed in Table I. The crush strength of the parent rock salt is slightly more than twice the value measured for the plug material. The large scatter in the data for both types of material can probably be attributed to the general poor quality of the specimens (see Fig. 4). It was difficult to obtain specimens free from chips and cracks.

III. DISCUSSION

The extrapolation of the data obtained on a crudely prepared salt plug in a simulated borehole to the field situation is at best difficult. However, it is worthwhile to indicate some of the implications of the data obtained in this modest study. We shall first examine the plug formed in these experiments relative to the requirements in the field, and then we will consider some of the obvious changes in tools and techniques which should greatly improve the quality of the plug.

The main function of any plug in a preexisting borehole in the salt formations is to prevent the passage of ground water. The salt plugs formed by melting at 1 atm would not be expected to be as impervious as the surrounding formation immediately after deposition because of the large number of extended cracks (see Fig. 3). The flow should be expected to reduce with time, however, due to the deposition of impurities, such as clays and carbonates from the ground waters. Reynolds and Gloyna¹ have demonstrated that the permeation of impure brines through some rock salts causes them to plug or clog.

The permeation data listed in Table I above would lead one to expect the plug to be as sound as the formation when and if the cracks stopped passing significant quantities of brine. However, this is only an indication since these data are for the permeation of nitrogen gas and not brine.

The permeability of the plug does not seem to be related to the density as indicated by the data in Table I. This is not too surprising since the density does not necessarily reflect the physical structure of

the solid, which is the real governing factor for permeability. The insensitivity of permeation to density is a good indication that the large amount of visible porosity is essentially closed.

The bond between the plug and the parent material appears to be as sound as the parent rock salt [see Figs. 3 and 4(c)]. The nitrogen permeability of one specimen which had been removed from the bond region was found to be 0.6 darcy. This specimen was 28-mm long and had the bond line about half-way down its length. The flow path for the measurement was normal to the parent salt-plug interface. It will be noted this permeability is comparable to the values listed in Table I for both the plug and the parent rock salt.

The comparison of the crush strengths of the parent rock salt and the plug material indicate the plug is definitely not as mechanically stable as the formation material. However, this does not imply that the plug will necessarily become degraded as a result of crushing due to overburden and other tectonic stresses. It simply implies that the plug will undergo some change in structure as time passes and the formation rock salt creeps in around it.

When a rock salt plug is formed at 1 atm pressure, there is little chance to prevent shrinkage voids and cracks. However, it is a well known fact that polycrystalline sodium chloride is quite plastic above about 470°K (see refs 2 through 5). Data compiled by Stokes,³ for instance, indicate that polycrystalline sodium chloride at 520°K can be elongated 30% under uniaxial tensile loading after starting to yield at 3.4 MPa. Increasing the temperature to 620°K lowers the proportional limit to 1.4 MPa and causes the polycrystalline sodium chloride to elongate 100% before failure. This suggests that modest pressurization of the cooling plug would be extremely beneficial. Pressurization would tend to heal or prevent gross defects in the plug and in the bond between the plug and the surrounding formation.

A computer analysis of the heat flow in this experimental setup was made to determine the thermal gradients in the salt block and power-velocity relationship for filling the hole. The model for which the calculations were made was somewhat idealized. It consisted of a cylindrical mass of salt 0.077-m diam by 0.18-m long maintained at its melting

point, and moving at a constant rate along the centerline of a salt cylinder 2.55-m diam. The thermal properties data used in the calculation were obtained from ref. 6. The temperature dependence of these properties was factored into the calculations. The calculations were made using the finite element code called AYER.⁷ Results were obtained for three different velocities: $V = 0.016, 0.032, \text{ and } 0.064 \text{ mm/sec}$. The power required to maintain these velocities was calculated to be 1.95, 2.21 and 2.65 kW, respectively, and the thermal gradients generated around the hole are represented graphically in Figs. 5 and 6. The 2 kW required to make the long borehole plug at an approximate rate of 0.1 mm/sec is comparable to the calculated values. One very interesting point derived from this analysis is that small increases in power input can provide significant increases in hole-filling rates. This is primarily due to the relatively high thermal conductivity of sodium chloride ($7.2 \text{ W/m} \cdot ^\circ\text{K}$ at 290°K) which causes rapid heat removal from the molten pool and the newly formed plug.

The equipment used to prepare the borehole plug in this brief study was quite rudimentary. Nevertheless, it did perform well enough to provide a rock salt borehole plug almost 1-m long which was of sufficient quality to be worthwhile evaluating in some detail. It was also useful in providing some baseline operating experience from which design improvements can be made. One of these improvements, which has already been discussed, is a capability for pressurizing the melt and the cooling plug. Another feature which will be essential in a full scale borehole plugging device is a capability for stirring or agitating the molten pool. This is needed to best distribute both the heat and the melted rock salt. Although Haynes 25 was found to be an adequate material against the corrosive attack of molten rock salt in these experiments, it is felt a better material would have to be found to construct a reliable full scale device. A full scale plug-forming device would also have to include a system to control the rate of addition of rock salt to the heated region. Surface equipment capable of moving the plug former out of the hole at a constant rate would also be essential. The rate of removal would be governed by the power available downhole. A sketch of a device which incorporates these concepts is presented in Fig. 7. In this device the auger would

Fig. 5. Radial temperature distribution at the bottom of a 77-mm-diam borehole in rock salt which contains molten rock salt.

Fig. 6. Axial temperature distribution away from the bottom of a 77-mm-diam borehole in rock salt which contains molten rock salt.

Fig. 7. Conceptual design of a rock salt borehole plugging tool.

provide both the positive feed for the rock salt fill and the pressure needed to consolidate the plug. Most of the heat would be required inside the device to melt the rock salt, but enough heat must go to the outside to prevent the device from becoming stuck in the hole and to make a good bond between the plug and the formation.

IV. CONCLUSIONS AND RECOMMENDATIONS

The data generated in this brief study would lead one to be encouraged about the possibilities of forming a rock salt plug in boreholes in rock salt formations using a melting technique. Even though the quality of the plugs formed in these experiments is probably below that required to seal a borehole in the near term, it is felt that this situation can be easily rectified with more sophisticated tools and techniques. A major improvement would be realized with a plugging tool which maintained a pressure over the forming plug. An engineering study of a prototype field device utilizing a pressurized melt should be undertaken.

REFERENCES

1. T. D. Reynolds and E. F. Gloyna, "Reactor Fuel Waste Disposal Project - Permeability of Rock Salt and Creep of Underground Salt Cavities," University of Texas report TID-12383 (December 1960).
2. P. LeComte, "Creep in Rock Salt," Jour. of Geology 73, 469-484 (1965).
3. R. J. Stokes, "Mechanical Properties of Polycrystalline Sodium Chloride," Proc. Brit. Ceram. Soc. 6, 189-207 (1966).
4. P. M. Burke, "High Temperature Creep of Polycrystalline Sodium Chloride," Ph.D. dissert., Stanford Univ. (1968).
5. N. L. Carter and H. C. Heard, "Temperature and Rate Dependent Deformation of Halite," Am. Jour. of Science 269, 193-249 (1970).
6. D. W. Kaufmann, Sodium Chloride, Reinhold Pub. Corp., New York (1960).
7. R. G. Lawton, "Description of the AYER Heat Conduction Computer Program," Los Alamos Scientific Laboratory report, LA-5613-MS, (May 1974).