Geotechnical Considerations for Design of a Nuclear Repository in Bedded Salt in the U.S.

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ABSTRACT

Geotechnical considerations for a nuclear waste repository in salt are required to provide short-term (up to 50 years) stability of the storage medium for protection of workers from unexpected radionuclide exposure during the development, operation and retrievability periods. Long-term (up to 10,000 years) geotechnical considerations are required to provide a geologic barrier to migration of radionuclides to the environment. Nuclear waste emplacement in a geologic medium such as salt presents a great challenge for all engineering disciplines and, more specifically, for geological, rock mechanics and mining engineers. Lack of extensive experience with deep mining in salt (over 800 m) and with creep and thermal stresses due to emplacement of waste in salt introduces additional challenges for the development of geotechnology for safe disposal of nuclear waste. In this paper, the major geotechnical aspects of a salt repository are examined. Some problems areas are defined, and some areas requiring further investigation are outlined.

INTRODUCTION

The Office of Nuclear Waste Isolation (ONWI) at the Battelle Memorial Institute, under the direction of the U.S. Department of Energy, has been authorized to provide technical management for the design of nuclear waste repositories in salt formations. Both bedded and domal salt formations have been investigated since 1957 as potential sites for disposal of high-level radioactive waste.

Rock salt is a prime candidate for disposal of high-level nuclear waste because of its following unique properties:

- The plastic behavior of salt promotes self-healing and will contain heat
- Salt has a high thermal conductivity compared to crystalline and argillaceous rocks and tuff
- Salt has a high thermal diffusivity and stability in comparison to basalt, granite, shale and tuff.

Other properties of salt pertinent to repository siting are as follows:

- Salt has a very low permeability
- Volatile content of salt is low
- Porosity of salt is low, about 5 percent
- Salt is essentially dry and is isolated from flowing ground water
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- Indigenous fluid is corrosive
- Salt's tectonic stability is very high and formations are located in areas of low seismicity
- Geohydrology of salt is moderately difficult to characterize
- Geologic structure of salt is relatively simple
- Salt is found in abundance, and it underlies about 1.28×10^6 square kilometers in the United States, with reserves greater than 5.45×10^{13} tons
- Salt formations are of large lateral and vertical extent and considerable depth
- Salt is easy to excavate.

The less desirable properties of salt as a repository medium are:

- Salt has high solubility in water
- Salt has negligible sorption capacity in comparison to basalt, granite, shale and tuff
- Salt has low compressive strength (20 to 40 MPa)
- Salt has a low density
- Some salt formations have potential for gas outburst (principally domal formations)
- Salt is potentially exploitable as a raw material or storage medium.

Currently, the number of potential repository sites in salt is being reduced to three areas. One of these areas is the Gulf Interior Region Salt domes in the states of Louisiana and Mississippi, and the other two are in bedded salt formations, the Paradox Basin in southeastern Utah and the Permian Basin in northwestern Texas (Figure 1).

For illustrative purposes this paper considers only the Permian Basin in Texas. The geologic information is, however, to some extent common to all bedded salt formations, and the methodology displayed can be and has been applied to any potentially suitable salt formation. Only selected major geotechnical issues related to the Permian Basin—major salt beds, repository locations, repository depth selections, repository host rock's thickness and lateral extension, maximum and minimum depth, engineering properties of salt and nonsalt rocks, repository design, creep deformation characteristics of salt, and thermomechanical analysis of a bedded salt repository—are briefly presented and discussed in this paper.

MAJOR SALT BEDS

Major salt beds in the Palo Duro Basin are defined as contiguous salt strata at least 22 m thick. The nonsalt interbeds are not greater than 2.8 m in thickness, and nonsalt layers' content does not exceed 15 percent of the salt interval thickness. In addition, only salt beds lying between 305 and 914 m are considered. The Permian salt-bearing formations consist of seven major salt beds. The upper and lower San Andres formation contain the best quality salt beds. They are persistent over large portions of the Panhandle. The upper San Andres formation is typified by a cyclic evaporite depositional sequence of limestone and dolomites at the base, overlain by anhydrites and halite, with silt-stones and shales interbedded throughout the sequence. The upper San Andres is estimated to be about 152 m thick. It includes a discontinuous major salt bed throughout most of the Palo Duro Basin with thickness up to 53.4 m in northern Deaf Smith County. The lower San Andres Cycle 5 is located at a depth of 701 m (Figure 2). Cycle 5 is composed of about 36.6 m of halite interbedded with thin shale beds. The shale beds are less than 25 mm thick, at 1.5- to 3.05-m intervals. The Cycle 5 major bed is found in the central and northern Palo Duro Basin. Its maximum thickness is about 45.7 m in Castro County. Cycle 4 underlies Cycle 5, the two cycles being separated by beds of anhydrites, dolomites and shales. The Cycle 4 salt bed's water-bearing potential is unknown at the present time. Cycle 4 is continuous across the central and northern Palo Duro Basin and is massive, reaching a thickness of 53 to 61 m in Deaf Smith, Randall, Swisher, Armstrong and Oldham counties. Methane is presumed to exist in variable quantities both in the upper and lower San Andres salt beds (Stone and Webster, 1981).

REPOSITORY LOCATIONS

Two sites within the Permian Basin are being subjected to preliminary geologic exploration. These sites are in Deaf Smith County and in Swisher County in the Palo Duro Basin, about 40 kilometers apart. The surface geologic conditions are similar at the two sites. The geologic

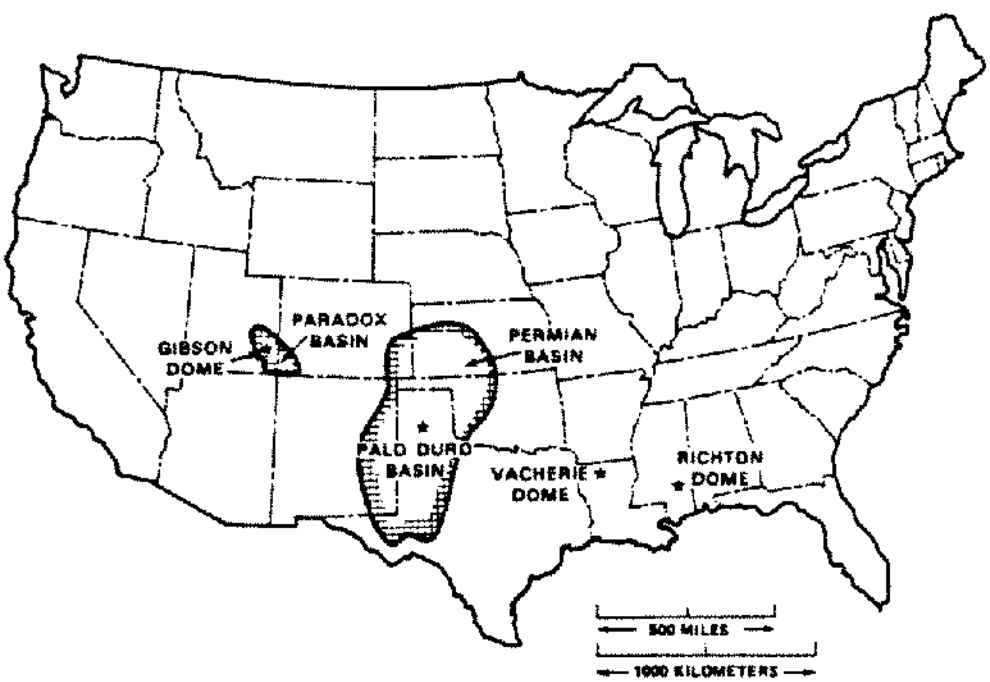


Figure 1. General Location of Salt Deposits Under Consideration to Host Nuclear Waste.

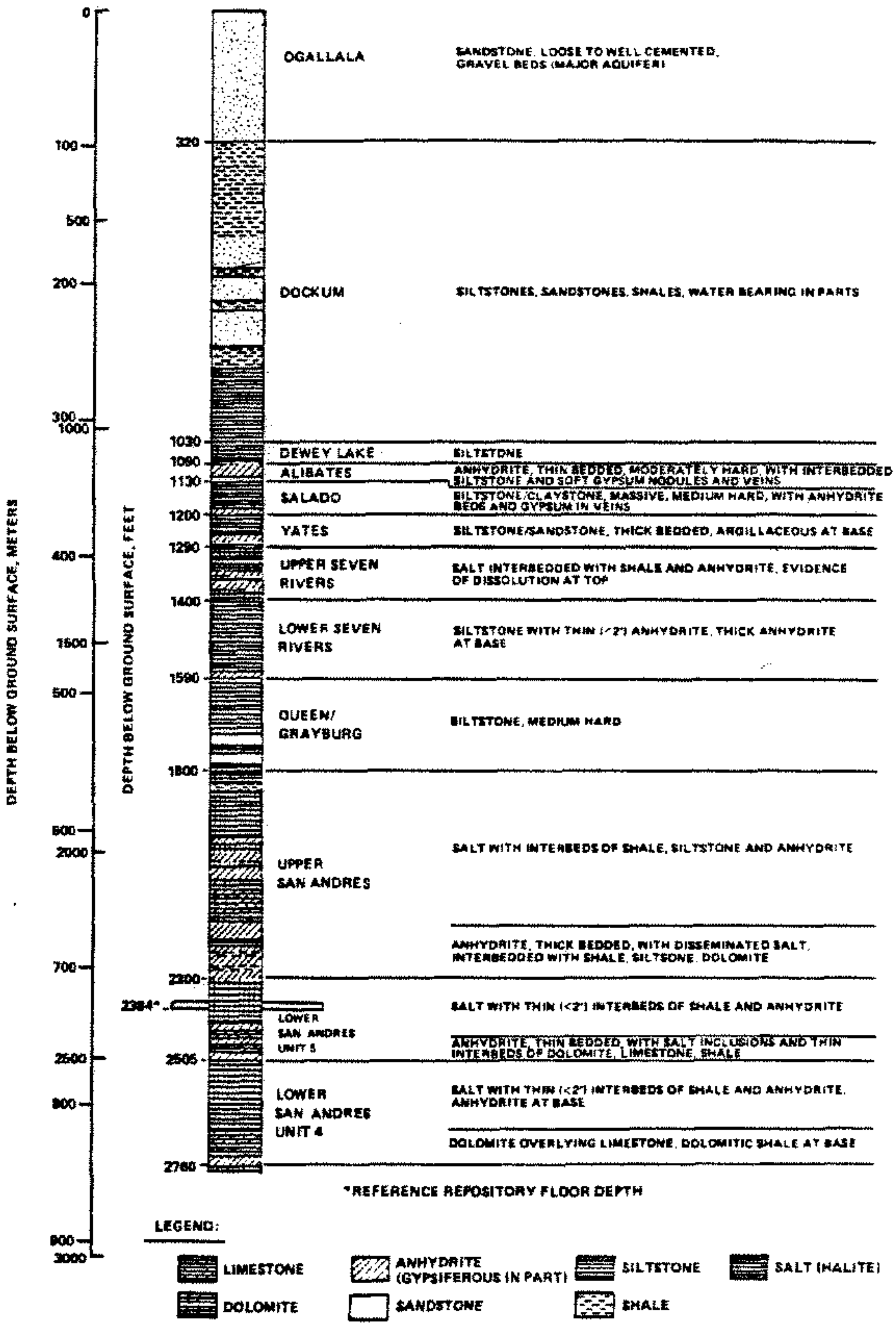


Figure 2. Stratigraphy for Permian Basin Repository.

characterization effort is being conducted by Stone and Webster as subcontractor to ONWI's exploration department (U.S. DOE, 1982). This effort has yielded geological, hydrogeological, and geotechnical rock mass properties for the Palo Duro Basin. Data are being compiled from published reports, oil and gas exploration activities and, most recently, from two boreholes, Detten No. 1 and G. Friemel No. 1 drilled by Stone and Webster in Deaf Smith County and Harman No. 1 in Swisher County (Figure 3).

Preliminary geologic investigation of the Permian Basin indicates that sites exist in Deaf Smith and Swisher counties that are suitable for a repository. Figure 4 presents a simplified preliminary site stratigraphy of Swisher County (Harmon No. 1 borehole) and Deaf Smith County (Detten No. 1 and G. Friemel No. 1 boreholes). In Deaf Smith County, the two holes are located 16 kilometers apart, and in both counties the deep boreholes are within reasonable distances (> 15 kilometers) of probable sites for further detailed study.

The stratigraphic columns are based on core logs, core photographs and geophysical logs which were available for the entire Detten No. 1 and G. Friemel No. 1 boreholes and for the lower portion of the Harman No. 1 borehole. The stratigraphic units at the Swisher County site are generally similar to those at the Deaf Smith County site.

REPOSITORY DEPTH SELECTIONS

In Deaf Smith County, Cycle 5 of the upper San Andres formation has been identified as one of two potentially suitable repository strata. In this location, Cycle 5 is a relatively homogeneous salt cycle in the upper 30 m. The repository depth for Cycle 5 is based on geologic information from bored holes (Detten No. 1 and G. Friemel No. 1). The upper 34 m of the lower San Andres Cycle 5 is the target repository horizon. A detailed section of Cycle 5 is presented in Figure 5. The overall thickness of the upper section of Cycle 5 is quite consistent. The anhydrite interbeds occur with minor variation in thickness at the same relative positions. However, the shale interbeds vary in thickness and in their location within the stratigraphic columns in Deaf Smith County. Generally, these thicknesses and locations are inconsistent between Detten No. 1 and G. Friemel No. 1. A different situation may exist at the canister midsection, as anhydrite interbed is present at the Detten No. 1 location (Figure 5). At the intersection of the floor and pillar, the black shale would exist. The thin interbeds of shale, salt, anhydrite and a mixture of chaotic shale and salt would exist at the roof location. If the Detten stratigraphic column is representative of the repository horizon, existence of interbeds of various thicknesses and compo-

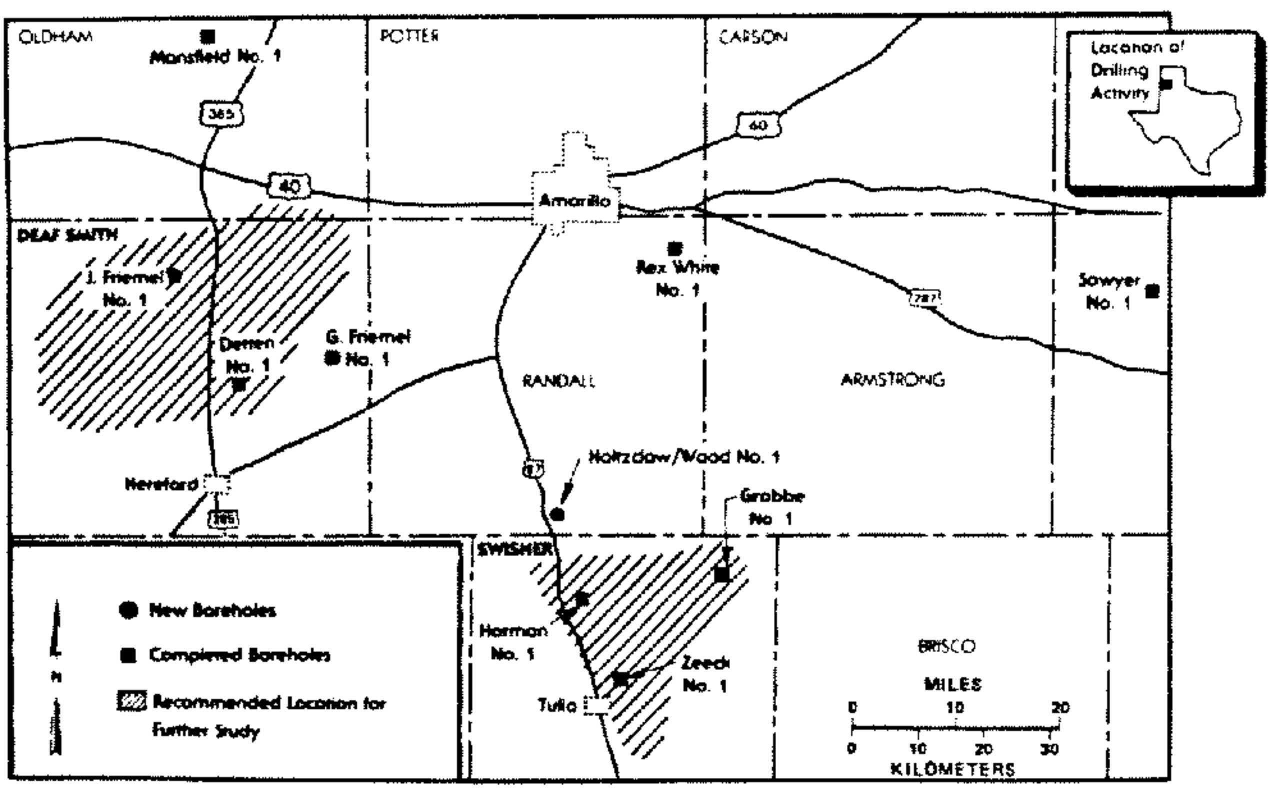


Figure 3. Study Locations and Drilling Sites in the Palo Duro Basin in Texas.

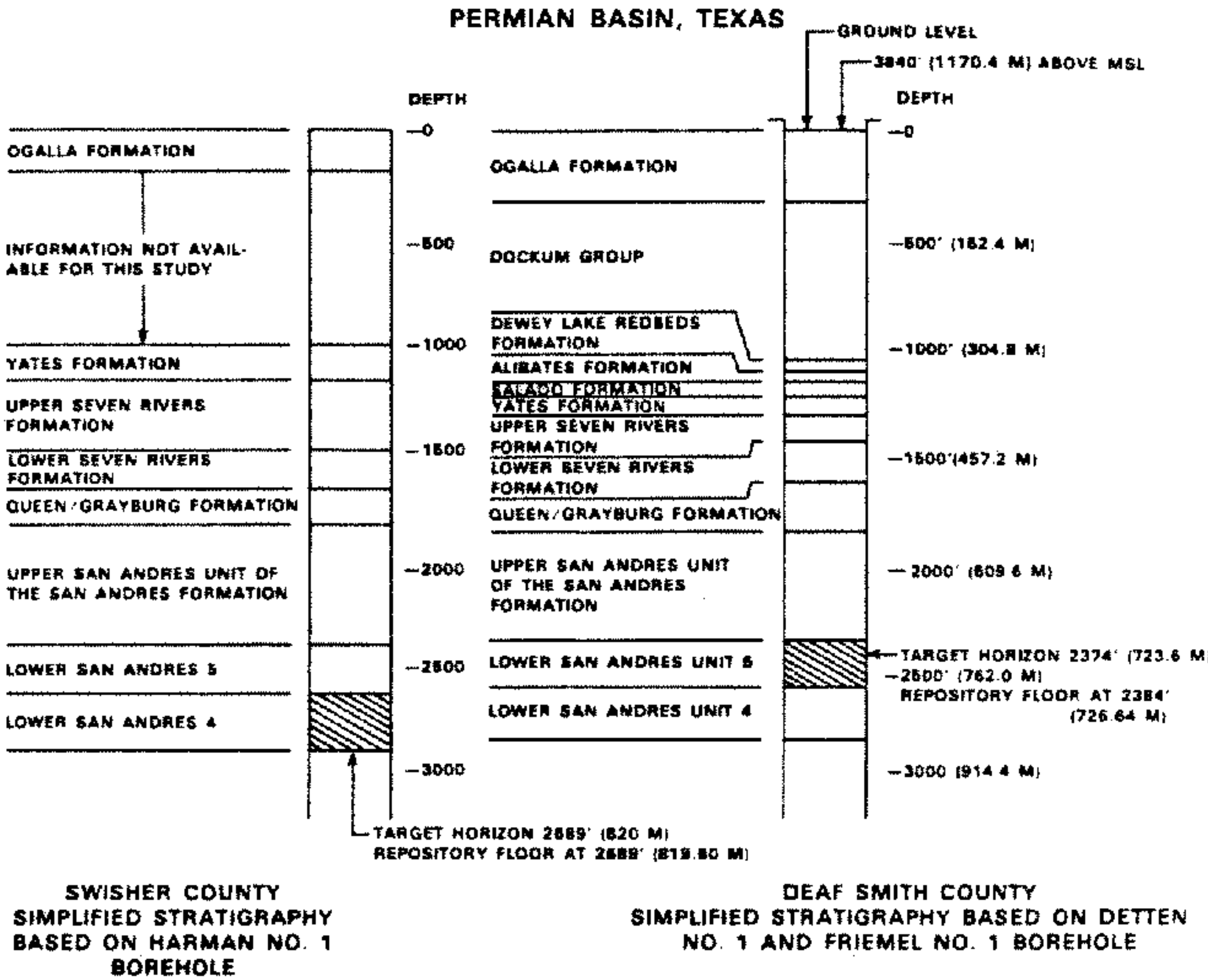


Figure 4. Simplified Stratigraphy Based on Deaf Smith County's Detton No. 1 and Friemel No. 1 Boreholes and Swisher County's Harman No. 1 Borehole.

sition would create adverse roof condition, requiring rock reinforcement by roof bolts to stabilize excavated areas. In addition, planes of weakness would exist at the intersection of the pillars with both the roof and floor. This could result in pillar slabbing.

The shale beds vary in thickness and in location and sometimes are present in the Detten core only. The selected repository horizon in Deaf Smith County is at a depth of 727 m. At this depth it is estimated that both the pillar section and canister region would be free of interbeds. A shale parting would be present at the intersection of the pillar and the roof which could result in pillar slabbing. According to stratigraphic column of G. Friemel No. 1 borehole the roof member would be a salt section at least 1.5 m thick which should produce a stable roof condition. If the repository horizon is located according to the stratigraphic column of Detten No. 1 borehole, the variation in the shale interbeds' thickness and locations in Deaf Smith County would require more site-specific data for the final design of the repository (Stearns-Roger, 1983).

The second potential strata, and perhaps the more favorable, is the Cycle 4 salt. In Deaf Smith County the thickness of Cycle 4 salt is approximately 50 m. The salt is overlain by shale and underlain by anhydrite. Shale and siltstone beds and discontinuous lenses as thick as 64 mm are detected by geophysical logs. Major anhydrite beds are absent from this salt cycle though minor anhydrite beds are indicated by the lithology. Salt Cycle 4 can be divided into upper (above 805 m) and lower (below 805 m) zones. The upper zone contains five claystone seams each more than 9.2 cm thick, whereas the lower zone contains no claystone zones thicker than 6.1 cm. The selected repository floor is at a depth of 810 m.

In Swisher County (Figure 4), Cycle 4 in the lower San Andres formation has been identified as the possible repository stratum. Cycle 4 is a relatively thick and homo-

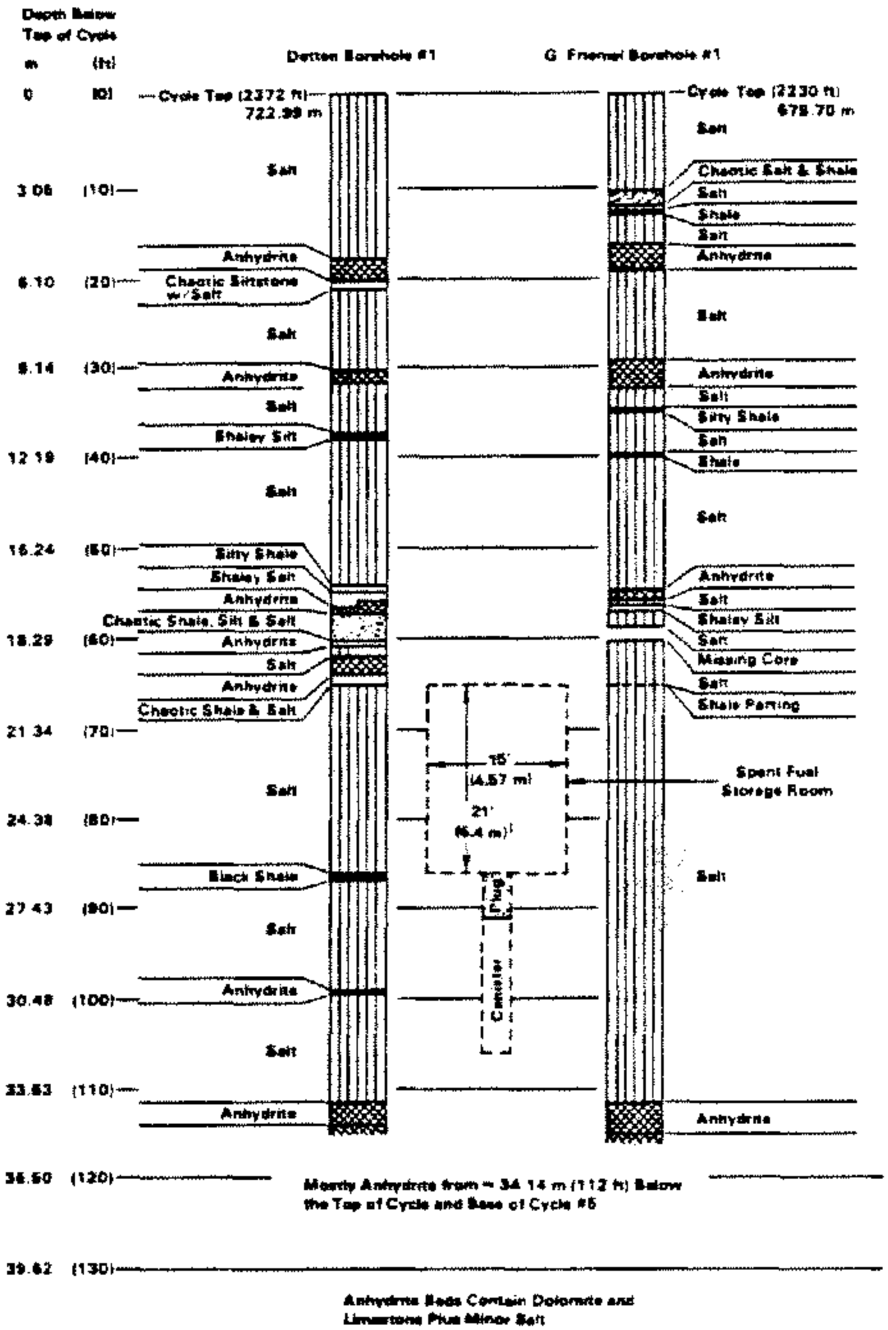


Figure 5. Lower San Andres, Cycle 5, Permian Basin, Texas (Stearns-Roger, 1983).

geneous sequence compared with Cycle 5 and the upper San Andres cycles that are generally poorer in quality and contain numerous interbeds such as anhydrite, shale and silt stone. Geologic data in Swisher County are limited to the Harman No. 1 borehole. Cycle 4 contains a number of thin interbeds such as siltstone and shale. The repository floor is at a depth of 820 m. At this depth, the roof would consist of a thick section of salt, and the canister would also rest on a floor of salt.

THICKNESS AND LATERAL EXTENT OF HOST ROCK

Geological investigations in the northern and central Palo Duro Basin have confirmed that the thicker salt beds are continuous for up to tens of kilometers in all directions (Long, 1982). The salt thickness appropriate for a repository excavation and acceptable to the Department of Energy (DOE) is approximately 38 m for waste canisters emplaced in vertical holes in the floor (e.g., spent-fuel rods and other heat-generating wastes that require shielded emplacement). Other types of waste such as transuranic (TRU) waste may not require such thicknesses since emplacement configurations would differ.

A minimum bed thickness of 23 m may accommodate such emplacements. A major salt bed is defined as a salt-bearing interval (or bed) that is at least 23 m thick, with nonsalt interbeds, each of which is not more than 3 m thick and cumulatively do not exceed 15 percent of the interval thickness.

At the Deaf Smith County location of the Lower San Andres Cycle 5, there is a major salt bed more than 30 m thick, but at the Swisher County location there is no major Cycle 5 salt bed.

At the Swisher County location of the Lower San Andres Formation, the major salt bed is Cycle 4 and it exceeds 46 m in thickness. At the Deaf Smith County location, its thickness exceeds 53 m. Both locations possess adequate thicknesses of salt in Cycle 4.

MINIMUM AND MAXIMUM DEPTH OF HOST ROCK

The host rock must be deep enough to isolate a repository from potentially harmful surface processes such as erosion and denudation. A minimum depth of 305 m has been used in this program. Whereas 305 m of cover is expected to provide adequate isolation, deeper host rock would provide a greater margin of safety, insofar as depth can be increased without compromising stability of the mined openings. All potential host salt beds occur in portions of both locations at depths greater than 610 m.

One of the principal reasons that salt has been recommended as a repository host rock is its high ductility (National Academy of Sciences/National Research Council, 1957). Because salt tends to creep at very shallow depths, fractures (possibly induced during the construction operation of a repository) will heal through creep closure after repository sealing. Absence of fractures in the host rock is important to the long-term isolation of the waste. The host rock depth range of 305 to 610 m, specified by U.S. DOE (1982), encompasses conditions favorable to creep healing of fractures, and although the rate of salt creep increases with depth, there is no evidence to indicate that conditions are significantly more favorable to creep healing below the shallower depth.

ENGINEERING PROPERTIES OF SALT AND NONSALT ROCKS IN THE PERMIAN BASIN

The cored geotechnical boreholes of Mansfield #1, Rexwhite #1 and Grabbe #1 have been subjected to laboratory analysis (Figure 3). The compressive strength of the Permian Basin salt, like other salt and potash rocks, is difficult to determine because of its creep characteristics. Figure 6 presents Mohr's failure envelopes for Cycles 4 and 5 salt in the Permian Basin. A summary of the strength and mechanical properties of salt and nonsalt rocks in the Permian Basin is presented in Table 1. The strength as a function of temperature for various salts tested at 10 MPa confining pressure is presented in Figure 7. The unconfined compressive strengths range from 21 to 35 MPa. The lower unconfined strength applies to the Permian salt (bedded) in Texas and Richton salt (domal) in Mississippi and the higher unconfined compressive strength applies to the Paradox Basin salt in Utah. Similarly, other related physical properties of Permian rocks vary as shown in Table 2. The variation in strength of salt and potash is known and is reported by Menzel et al (1972) and others in the literature. Triaxial strength results presented in Figure 7 indicate that the Permian Basin (Texas) salt Cycles 4 and 5 at repository horizons (730 m) are of lower strength in comparison to the Paradox Basin (Utah) Cycle 6 salt bed. Additional comprehensive testing will be required to verify strength of the Permian Basin salts in relation to other salts. Data on salt and

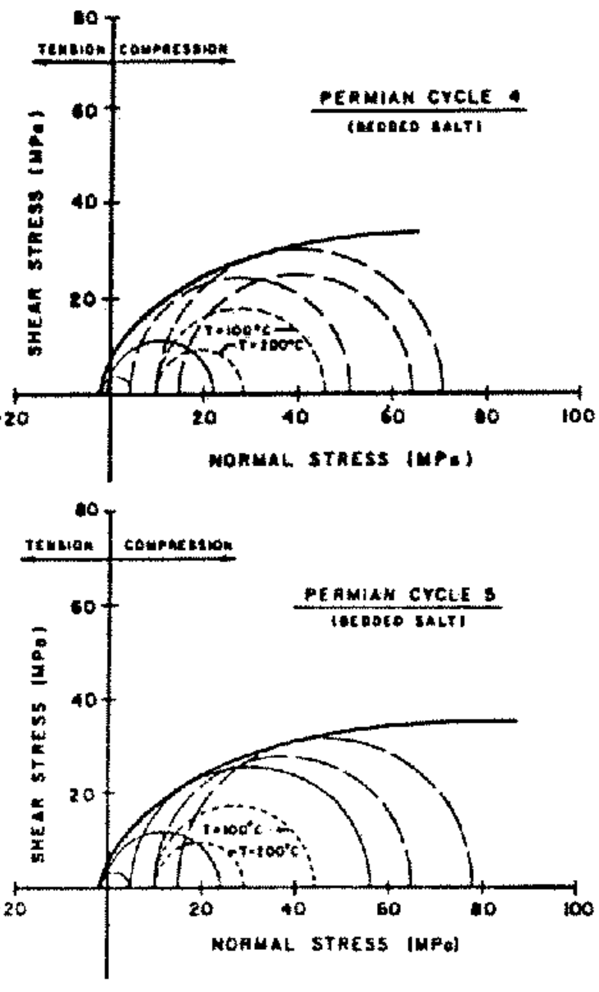


Figure 6. Mohr's Circles at Failure for Salt Near Expected Repository Horizons (Pfeifle et al, 1982).

TABLE 1

Strength and Mechanical Properties of Salt and Nonsalt in the Permian Basin (Pfeifle et al, 1982)

Material	S_0 Cohesion (MPa)	ϕ Angle of Internal Friction (degrees)	τ_0 Apparent Tensile Strength (MPa)	E Young's Modulus (GPa)	ν Poisson's Ratio	ρ Density (kg/m^3)
Anhydrite	43.4	29.0	11.7	59.1	0.36	2650
Chaotic Shale	3.7	46.0	2.5	25.4	0.31	2200
Salt (Cycle 4)	4.0	49.0	2.5	29.1	0.33	2180
Silty Shale	7.5	45.0	5.4	6.4	0.34	2300

nonsalt rocks' physical, mechanical and geochemical properties are required; the data will be used as input for the design and numerical simulations of the repository to interpret its thermomechanical behavior, both in the long and short terms.

REPOSITORY DESIGN

The design of a high-level nuclear waste repository is complex because of the variation in heat sources, i.e., wastes that are to be emplaced in a salt repository during its operating life of 26 years and to be retrievable for 50 years after the start of emplacement. For the design of underground openings in a salt repository, published literature related to salt and potash mines is being reviewed. This review has consisted of a compilation of data on the pillar design, creep characteristics, convergence rate, subsidence, modes of instability, excavation techniques, etc.

The design of underground salt and potash mines traditionally has been based on field experience rather than on application of rock mechanics principles, namely, rock properties, laboratory analysis, modeling and in situ measurements. However, in recent years emphasis has been placed on the use of more scientific principles of design and development. For instance, the Boulby (Hebblewhite, 1977) and Meadowbank (Potts, 1964) potash mines in England and potash mines in the Esterhazy area of Saskatchewan, Canada (Marz, 1972 and 1980) have been sub-

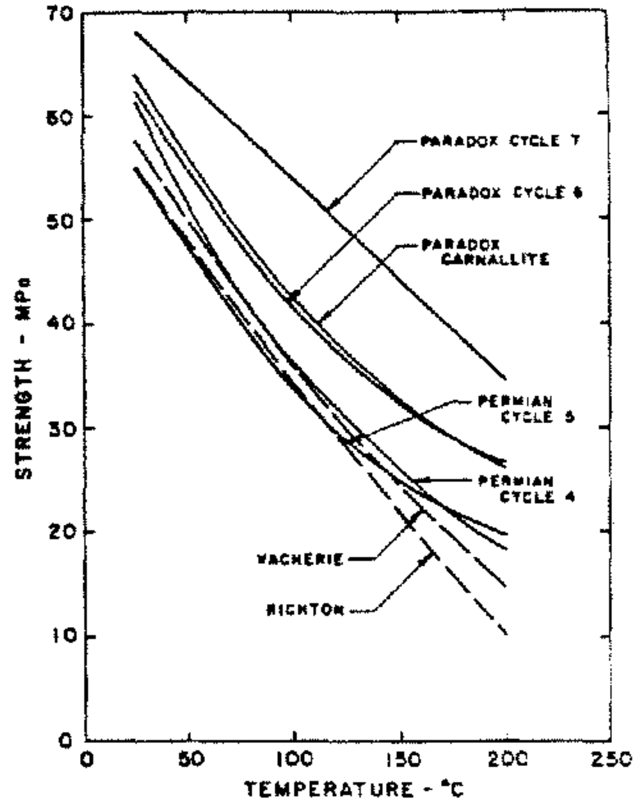


Figure 7. Strength as a Function of Temperature at a Confining Pressure of 10 MPa for Salt of Permian Basin and Other Salts and Carnallite of Paradox Basin (Pfeifle et al, 1982).

TABLE 2

Rock Properties of the Permian Basin (Pfeifle et al, 1982)

Horizon	Elastic Parameters[a]						Strength[b]			
	E Min	E Mean	E Max	ν Min	ν Mean	ν Max	Min	Mean	Max	τ_0
Permian Cycle 4	19.0	26.6 ± 3.0	33.4	0.24	0.33 ± 0.05	0.41	C_0	C_0	C_0	−0.82
Permian Cycle 5	22.2	29.1 ± 4.0	33.4	0.31	0.33 ± 0.01	0.35	Min	Mean	Max	−0.83
Mudstone 335 m	6.6	9.4 ± 2.4	12.1	0.21	0.25 ± 0.05	0.33	22.6	34.5 ± 8.9	43.1	−5.0 ± 0.1
Chaotic Mudstone/Salt 390 m	1.5	2.2 ± 0.9	3.6	0.24	0.32 ± 0.10	0.49	9.2	11.2 ± 1.8	13.4	−2.4 ± 0.3
Siltstone[c] 503 m	1.8	2.5 ± 0.8	3.3	0.19	0.26 ± 0.06	0.30	13.9	15.3 ± 2.0	17.5	—
Anhydrite 655 m	54.6	59.1 ± 3.7	63.4	0.30	0.36 ± 0.04	0.40	72.0	148.1 ± 43.8	177.6	−11.7 ± 0.4
Dolomite 832 m	18.2	32.2 ± 16.2	54.4	0.24	0.32 ± 0.05	0.36	61.2	81.3 ± 27.0	124.3	−15.0 ± 5.1
Mudstone 975 m	3.5	6.4 ± 1.6	7.7	0.27	0.34 ± 0.05	0.40	26.8	38.7 ± 7.2	46.1	−5.8 ± 0.3
Chaotic Mudstone/Salt 1042 m	2.8	3.1 ± 0.4	3.8	0.20	0.30 ± 0.10	0.46	20.7	23.7 ± 1.9	25.5	−2.6 ± 0.2

[a] E = Young's modulus (GPa); ν = Poisson's ratio.
[b] C_0 = Unconfined compressive strength (MPa); τ_0 = Tensile strength (Brazilian) (MPa).
[c] Insufficient number of specimens available to complete matrix.

jected to extensive geomechanical investigations since their development.

The design of salt and potash mines is based on two known approaches: stress control technique (SCT) and yield pillar technique (YPT). The SCT was introduced by Serata (1976) after its successful application at the Saskatchewan potash mines of Cory and Rocanville in Canada. The SCT is based on the well-known phenomenon of stress redistribution around an opening created in a continuum. There are three specific methods of application of the SCT, two of which (parallel room and time control methods) apply to "weak ground," while the third method (stress-relief) is applicable only to "uniform ground." The first and second rely on stress relief around two or more individual openings by redistribution of stresses to form a composite stress envelope around the openings. The third method relies on the development of a larger stress-relieved zone or larger stress envelope by widening the openings. In southeastern Saskatchewan, SCT's stress-relief method has been relatively successful, where initially these potash mines were developed based on the room-and-pillar approach. The SCT technique was developed because of stability problems.

SCT has been applied to known geologic formations of the Saskatchewan potash deposits, where the ore is more than 914 m deep, overlaid by up to 30 m of salt containing a few disseminated clay bands. At the International Minerals and Chemical Corporation's K2 mine at Esterhazy, Marz (1978) attempted to develop a two-room layout panel separated by 55-m barrier pillars. The rooms were 20 m wide and separated by a 15-m-wide pillar. A steady closure rate of 25 mm per year was recorded, but when pillar width was reduced to 4.6 m closures occurred at excessive rates. The SCT and yield pillar approaches in the United States have been applied at Kerr-McGee's potash mine in Carlsbad, New Mexico. At this site the stratigraphic column in and above the ore zone at depths of 488 to 579 m contains two clay seams and a polyhalite bed which control roof behavior and restrict the room width and extraction ratios of the mine (Kuhn 1979). A test panel consisting of four 7.6-m-wide, 2- to 4-m-high rooms separated by 3.7-m pillars was developed. The outer rooms were developed, then the inner rooms. The outer rooms started closing after one week, followed by rapid closure of the inner rooms over a period of one month to several hundred days. This rapid closure of the entire panel indicated that either a stress-relieved zone and stress envelope had not developed or the roof rock could not carry the concentrated stresses. Consequently the envelope collapsed. Later Kerr-McGee developed five parallel rooms, each 7.6 m wide and 2.4 m high, separated by 30-m-wide pillars. Closure rates for these rooms were 30 cm in 3 years and 60 cm in 10 years.

At the Cayuga mine (Plumeau and Peterson, 1981; Peterson et al, 1977), the yield pillar approach has been successfully applied. The salt is mined from a Silurian sequence interbedded with dolomite and dolomite shale at depths of 701 to 914 m. Salt Cycle 6 is mined at present at a depth of 835 m; it is 3.7 m thick, overlain by 9.45 m of dolomite shale, 2.7 m of salt Cycle 5, and 38.4 m of dolomite and shale in ascending order, and underlain by Vernon shale and salt Cycle 7. The large pillars that had been initially developed were reduced to smaller pillars, 8.5 m by 8.5 m with 33-m-wide rooms. The pillar reduction improved stability but introduced immediate convergence of several centimeters. However, stability was improved by continuous extraction.

The reduction in convergence is attributed to small pillar yieldings. The yield pillar approach at the Cayuga mine has been successful in stabilizing the roof and has resulted in the transfer of stresses to higher roof beds, thus relieving stresses at the immediate roof and resulting in better roof conditions.

The yield pillar design approach applied to the design of shaft and room pillars in a salt repository, and referred to as the confined core approach, was introduced by Wilson and Ashwin (1972) and Abel and Hoskins (1976). This approach estimates the load carrying capacity of pillars and permits the strength evaluation for variable pillar geometries and rock properties. Abel (Stearns-Roger, 1978) applied the confined core pillar design approach to recalculate safety factors of pillars in operating salt and potash mines (Table 3) and concluded that all the reported mines were relatively stable even though the majority had safety factors of less than one. The stability of these salt and potash mines, according to Abel, means that many in situ salt or potash masses have stronger engineering properties than the low strength properties assumed.

To design salt repository pillars, two parameters are used—pillar strength and areal heat loading. The first parameter is based on the confined core pillar design approach. The minimum factor of safety for the design of pillars is assumed to be 2.0 (Stearns-Roger, 1983). The length of time that underground excavations will be open varies from 5 to more than 50 years. It is assumed that a 10 percent closure due to creep is acceptable during the time underground excavations are open or re-excavation is necessary. It is also assumed that the closure rate at both sides of the opening will be 3.3 percent per year, based on average closure rates for a 3-year period computed by Pfeifle et al 1981. These rates have been computed for a high-level waste storage room in the Permian Basin. Because of variations in dimension and heat loads of various waste packages, storage rooms must be of different dimensions. In addition to the height of the waste package, continuous excavation machinery dimensions and closure rates are taken into account for computation of storage room dimensions. Table 4 shows the dimensions of the waste storage room, pillar width, pillar safety factor, storage room spacing, the number of rows of waste packages per room, waste package pitch, local extraction ratio, and areal heat loading density.

A conceptual design of a repository in bedded salt is pre-

TABLE 3

Indicated Factors of Safety for Pillars in Operating Salt and Potash Mines (Abel, 1981)

Mine Identification and Type	Product	Depth, m	Pillar Width, m	Pillar Length, m	Room Height, m	Room Width, m	Extraction, %	Design[a] Strength, KPa	TAL[b] Stress, KPa	Apparent Factor of Safety
1977 Cote Blanche—Dome	Salt	393	30.5	30.5	7.0	15.3	56	20,684	18,754	1.10
1977 Belle Isle—Dome	Salt	363	12.2	—[c]	7.0	18.3	60	17,030	19,374	0.88[d]
1964 Winsford—Bedded	Salt	146	27.5	27.5	6.1	61.0	90	10,342	33,094	0.31[d]
England			30.1	30.5	6.1	30.5	75	10,549	12,410	0.85
1972		177	19.8	19.8	6.1	19.8	75	9,790	14,341	0.68
1974 Dravo (1)*	Salt	603	24.4	24.4	5.2	15.3	56	31,716	28,820	1.10
Dravo (2)	Salt	396	33.5	33.5	18.3	24.4	66	13,169	25,097	0.53
Dravo (3)	Salt	323	18.3	18.3	3.2	19.8	77	19,167	29,716	0.64
1971 Headley, Canada—Bedded	Salt	536	64.1	64.0	12.2	12.2	40	27,992	18,822	1.49
			45.7	45.7	12.2	13.7	41	24,821	19,236	1.29
1970 Hutchinson—Bedded	Salt	312	15.3	—[c]	1.8	6.1	71	18,960	23,166	0.82
			15.3	15.2	3.0	15.2	75	18,064	26,475	0.68
			15.3	15.2	3.7	15.2	75	17,168	26,476	0.65
			12.2	12.2	3.0	15.2	80	16,961	33,508	0.51
1970 Goderich, Canada—Bedded	Salt	536	61.0	61.0	13.7	19.8	43	26,476	19,995	1.33
1974 Dravo (4)	Evapor	304	18.3	18.3	1.7	9.7	57	20,202	15,168	1.33
Dravo (5)	Evapor	326	12.8	12.8	3.0	8.5	64	17,788	19,236	0.93
Dravo (6)	Evapor	243	7.6	7.6	2.4	7.6	75	13,169	20,684	0.63
Dravo (7)	Evapor	958	38.4	38.4	2.4	20.4	36	60,536	31,716	1.91
1965 Barr, Germany—Bedded	Potash	820	7.0	7.0	2.2	3.6	35	40,610	26,682	1.52
1971 Barr, Canada—Bedded	Potash	957	16.5	—[c]	3.0	6.1	27	53,641	27,786	1.93
1973 Esterhazy—Bedded	Potash	960	27.4	—[c]	2.4	18.6	40	64,190	34,198	1.73
1958 U.S. Potash—Bedded	Potash	305	17.7	17.7	3.9	9.7	58	17,306	15,582	1.11

[a]Design strength based on $\gamma = 2162$ Kgr/m^3; $\phi = 30°$; cohesion = 310 KPa.
[b]TAL = Tributary area load—halfway to adjacent pillar, all the way to surface.
[c]Long rib pillars of unspecified length.
[d]Pillar deterioration indicated.
*Numbers (1) thru (7) refer to references within DRAVO's technical report.

TABLE 4

Waste Storage Room Parameters (Stearns-Roger, 1983)

Waste Package	Storage Room Dimensions* Height, m	Width, m	Length, m	Pillar Width, m	Storage Room Spacing m	Rows of Waste Pkgs. per Room	Waste Pkg. Pitch, m	No. Waste Package Room	Pillar Safety Factor	Local Extract Ratio, %	Areal Heat Density, *** W/m^2
Spent Fuel	6.4	4.6	152.4	15.5	20.1	1	18.3	9	2.0	21.7	15
CHLW[a]	5.8	4.6	152.4	21.6	26.2	1	12.2	13	2.0	17.4	30
DHLW[b]	5.2	5.8	152.4	14.0	19.8**	2	2.1	133	2.0	29.2	20
TRU[c]	5.2	8.2	152.4	17.4	25.6**	3	2.1 Triangular	200	2.0	32.1	N/A
Contact TRU						3	N/A	480			

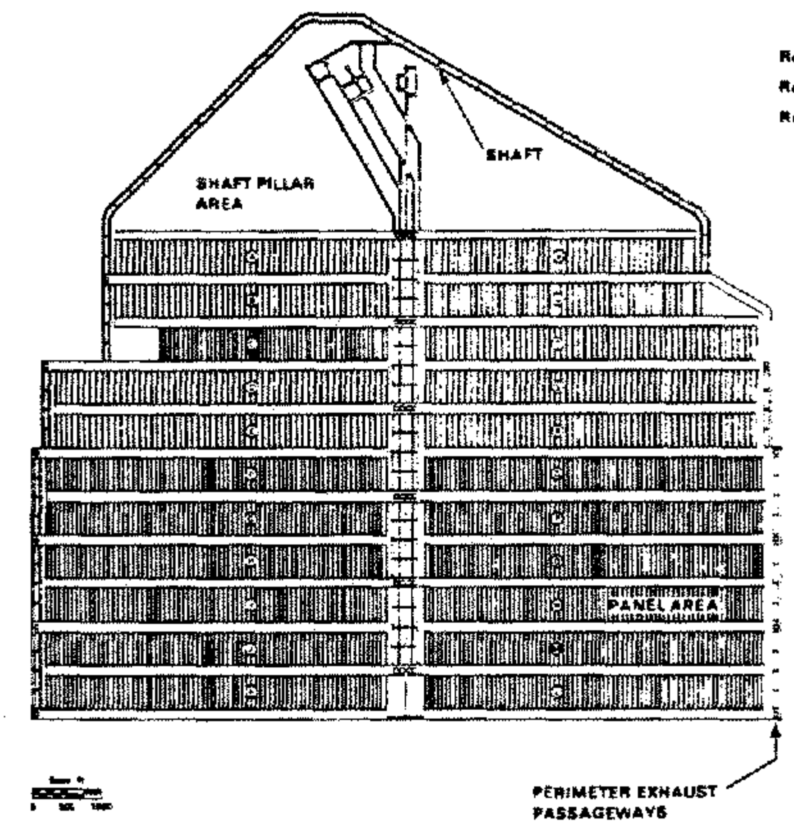
* As-mined dimensions. Room roof is flat.
** Based on pillar safety factor of 2.0.
*** Unit Cell.
[a] CHLW: Commercial high-level waste.
[b] DHLW: Defense high-level waste.
[c] TRU: Transuranic.

sented in Figure 8. The waste package dimensions for spent fuel (SF), chemical high-level waste (CHLW), and defense high-level waste (DHLW) are presented in Figure 9. Figure 10 presents a possible layout of the repository emplacement rooms. For possible retrieval of the waste package one of the following two methods is considered: removal of the entire package either directly or by overcoring, or cutting the overpack lid and removing the waste form. After emplacement of the waste package, the overpack is expected to function as a containment barrier to radionuclides for several hundred to a 1,000 years. The containment barrier could be destroyed either by the closure force of salt creep acting to restore lithostatic pressure, or by corrosion resulting from the presence of moisture in the salt. Both these processes are affected by the thermal performance of the emplaced package. The thermal performance of waste packages during the containment period is presented in Figure 11. Table 5 presents the waste package performance parameters. The thermal response of waste packages (CHLW, DHLW, and SF) peaks in about five years after emplacement and the temperature drops sharply to about 50 percent of the peak in about 90 years after emplacement.

CREEP DEFORMATION CHARACTERISTIC OF ROCK SALT

Creep or time-dependent deformation of elastic and plastic materials subjected to stress is common. The stress-strain relationship for an elastic material such as steel is simple and well-known. Some rocks behave elastically, and laboratory measurements of elastic coefficients can be readily carried out. Tests of plastic rocks, such as rock salt and potash, show that these materials, under varying stress, behave both as pseudo-elastic and plastic material. The plastic characteristics of rock salt and potash have been reported by Potts (1964), Nair and Deere (1966), King and Acar (1966), and Baar (1972, 1974) and Marz (1972, 1973, 1980). Certain investigators have stated that rock salt behaves elastically at low stresses, but beyond a limit they behave plastically.

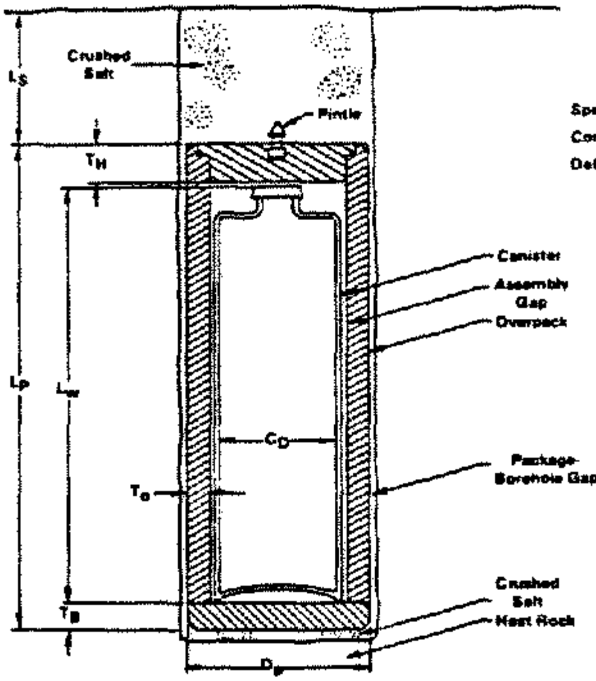
Creep is an important and complex factor in excavations in evaporite rocks (salt and potash). Laboratory testings of salt and/or potash samples often reveal complex and variable behavior making it difficult for underground design engineers to design a successful underground evaporite mine or storage cavern. For designing openings in evaporite



	Acres	Meter Square
Repository Operations Area	2,000	8.09×10^6
Repository Controlled Area	2,000	8.09×10^6
Repository Surface Area	400	1.62×10^5

PANEL TABLE		
PANEL	WASTE	NUMBER ROOMS
A	TRU	46
B	TRU	46
C	DHLW/CHLW	26/29
D	CHLW	54
E	CHLW	55
F	SF	76
G	SF	76
H	SF	76
I	SF	75
J	SF	76
K	SF	76
L	SF	75
M	SF	76
N	SF	75
O	SF	76
P	SF	76
Q	SF	76
R	CHLW	58
S	CHLW	58
T	DHLW/CHLW	26/29
U	TRU	47
V	TRU	47

Figure 8. Underground Layout (Stearns-Roger, 1983).

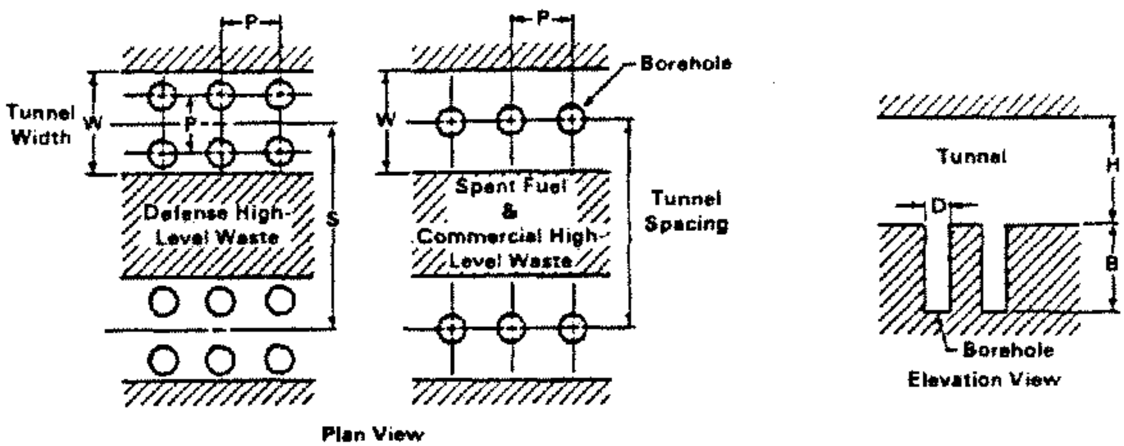


	All Dimensions in cm							
	L_P	L_S	L_W	T_H	T_P	T_B	D_P	C_D
Spent Fuel (PWR)	460	140	410	20	12	18	84	57
Commercial High-Level Waste	457	173	409	21	15	21	89	56
Defense High-Level Waste	338	112	300	15	10.4	18	84	61

Figure 9. Waste Package Dimensions for Spent Fuel, CHLW, and DHLW (Westinghouse, 1982).

rocks, past experience and "rules-of-thumb" approaches are frequently used instead of more rigorous scientific methods such as rock mechanics engineering techniques.

The creep mechanism is difficult to quantify and remains a controversial issue among experts actively studying the behavior of plastic materials such as rock salt and potash. The idealized creep curve is presented schematically in Figure 12. The strain-time graph can be divided into four subsections. Section OA refers to the instantaneous strain when the load is first applied and it is independent of time (elastic deformation); Section AB refers to the primary creep phase (transient) under constant stress and tempera-



	All Dimensions in Meters					
	B	D	H	P	S	W
Spent Fuel	5.9	0.93	7.4	10.4	27.5	4.0
Commercial High-Level Waste	6.3	0.94	7.2	10.0	31.6	4.0
Defense High-Level Waste	4.5	0.89	6.1	2.4	25.8	5.0

Figure 10. Layout of Reference Repository Emplacement Rooms (Westinghouse, 1982).

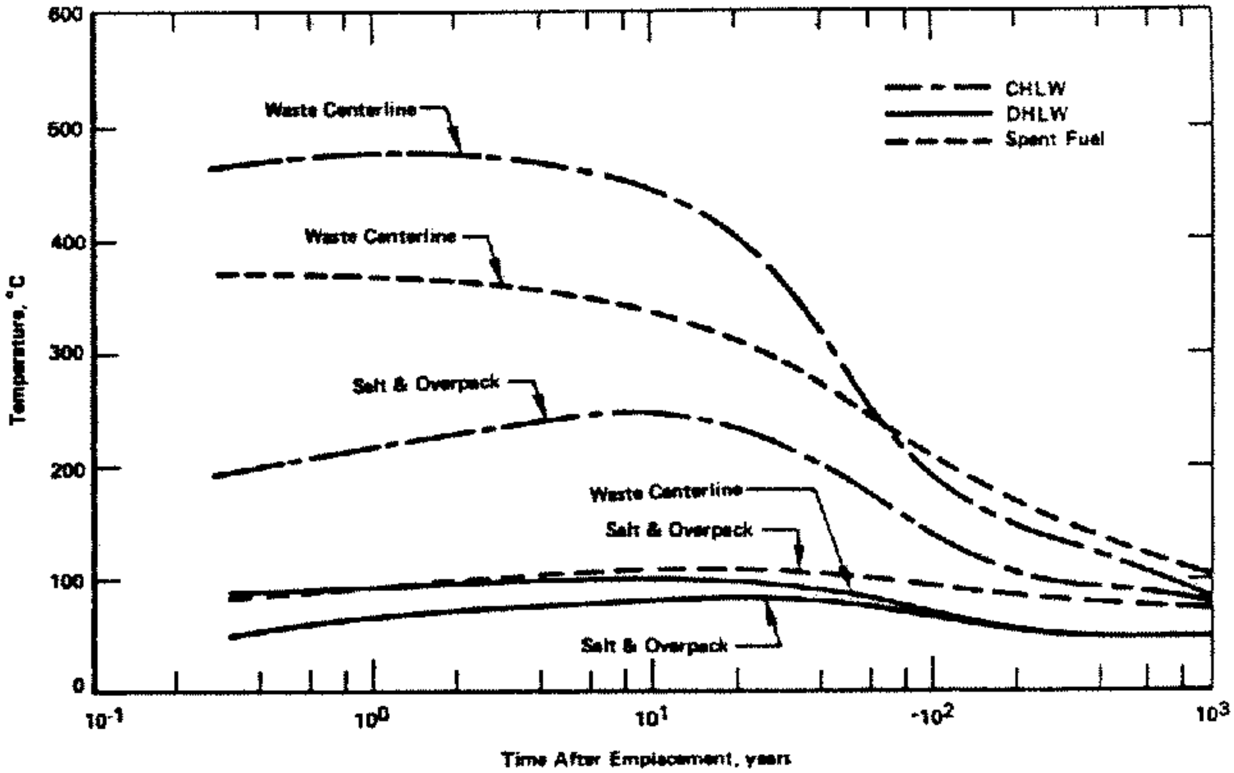


Figure 11. Thermal Performance of Waste Packages During Containment Period (Westinghouse, 1982).

TABLE 5

Waste Package Performance Parameters (Westinghouse, 1982)

	Spent Fuel	CHLW	DHLW
Brine Quantity Per Package, liters	80.0	80.0	13.0
Metal Quantity Reacted, kg	104.0	104.0	17.0
Equivalent Uniform Thickness of Corrosion, cm	0.1	0.1	0.03
Total Overpack Thickness, cm	12.0	15.0	10.4
Crush Resistant Thickness Required, cm	9.5	10.0	9.5
1,000-Yr Corrosion for Limited Area Reaction (Unlimited Brine Assumption), cm	2.5	5.0	0.9

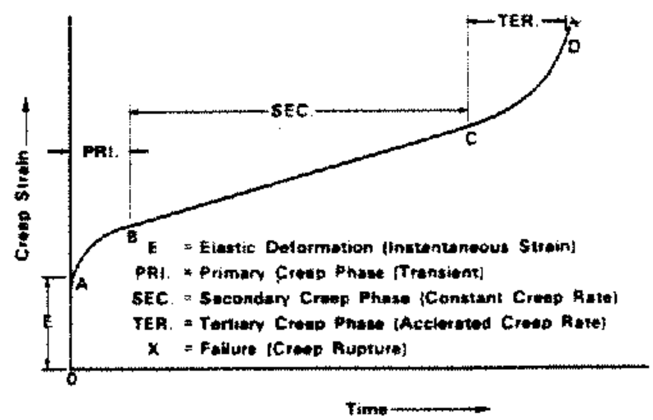


Figure 12. Idealized Creep Curve.

ture, where the strain rate is decreasing with time; Section BC refers to the secondary creep phase, "constant creep rate" or "quasi-viscous creep" stage. This occurs when the applied stress is relatively high and deformation takes place with a constant speed following the primary creep phase; Section CD refers to the tertiary creep or accelerated creep stage toward failure (creep rupture). The tertiary creep phase is the most undesirable phase. Underground rock salt and potash mines, in general, are designed to behave according to the secondary creep phase so that the chances of sudden collapse or crush of mine pillars is minimized.

In the past, the creep behavior of evaporite rocks has been investigated extensively by salt rock mechanics experts who would have been active in the design of underground rock salt and potash mines. The main factors liable to affect the creep behavior of a rock material, according to Potts et al (1972), are applied stress, diameter-to-height ratio of tested specimens and their volume, duration of test, climatic conditions (temperature and humidity), mineralogical composition and structure of specimens, and location of tested specimens with respect to clay partings.

Constitutive laws used to describe salt creep in a nuclear waste repository have been reviewed and reported by Senseny (1981a). Creep deformation occurs in all materials, but it is usually negligible in engineered materials. Creep deformation in salt is significant, since stresses, temperature and times are important for designing a nuclear waste repository, caverns (underground storage medium in salt) and salt mines. The eight constitutive laws (Table 6) reported by Senseny (1981a) are models for primary (transient) or secondary (steady-state) creep phases; no law covers the tertiary creep phase. These constitutive laws describe the deformation of salt for ranges of stress and temperature expected in a nuclear waste repository. These laws are largely empirical and cannot be used to handle complex thermomechanical histories with the exception of the unified creep-plasticity model (Senseny, 1981a). The main drawback of all these models is that they have been developed for a single dimension but extrapolated to three dimensions. Extrapolation for stresses, temperatures and times not investigated in the laboratory are of limited validity (Senseny, 1981a). After reviewing all the pertinent creep laws, Senseny selected eight of them that were applicable to evaporite rocks (Table 6).

The exponential-time law has been selected as a baseline to assess the performance of a nuclear waste repository. The exponential-time law model (primary and secondary creep phases) is used to model the behavior of salt in the canister and in and around the emplacement rooms. Because these creep laws have been laboratory-derived, they can only provide creep data within the range of stress, temperature and time investigated in the laboratory. They have not been continued in the field, although as noted, properties derived in the laboratory (and therefore models based on these properties) are in all probability conservative. Hence, the need remains for long-term investigations of the deformation behavior of salt both in the laboratory and in the field (i.e., operating salt and potash mines) to understand the deformation characteristics of salt within a nuclear waste repository. Exploratory shafts sunk at candidate repository sites will, by 1985, allow this field confirmation to occur on a site-specific basis.

The exponential-time creep law used for the nuclear waste repository modeling investigations (Senseny, 1981a) is expressed as follows:

$$\dot{\epsilon}_{ij} = A(3J_2)\,\frac{n+1}{2}\,\exp(-\lambda/T)\left\{1 + B^{\xi}_{t} - \frac{B\epsilon_a\xi}{(J_2)^{n/2}\exp(-\lambda/T)} \int_0^t (J_2)^{n/2}\exp(-\lambda/T)\exp\left[-\int_{t''}^{t}\xi\,dt'\right]dt''\right\}\frac{S_{ij}}{2J_2} \qquad (1)$$

where

$$\xi = \begin{cases} BA(3J_2)^{n/2}\exp(-\lambda/T) & \text{if} \quad \dot{\epsilon}_{ss} > \dot{\epsilon}^*_{ss} \\ B\dot{\epsilon}^*_{ss} & \text{if} \quad \dot{\epsilon}_{ss} > \dot{\epsilon}^*_{ss} \end{cases}$$

$$\dot{\epsilon}_{ss} = A(3J_2)^{n/2}\exp(-\lambda/T)$$

and

$\dot{\epsilon}_{ij}$ = creep strain rate (s^{-1})
J_2 = second invariant of deviatoric stress (MPa^2)
T = temperature (K)

TABLE 6

Comparison of Creep Laws for Salt (Senseny, 1981a)

Law/Criteria	Transient Creep	Steady-State Creep	Basis of Law	Fit to Large Data Set	Parameter Values Easily Determined	Decrease in Stress Permissible	References
Power	Yes	No	Empirical	Yes	Yes	Yes	Finnie (1960)
Exponential—Temperature	Yes	No	Empirical	No	Yes	Yes	Senseny (1981)
Modified Power	Yes	Yes	Empirical	No	Yes	Yes	Senseny (1981a)
Modified Exponential—Temperature	Yes	Yes	Empirical	No	Yes	Yes	Senseny (1981a)
Exponential—Time*	Yes	Yes	First-order kinetics	Yes	Yes	Yes	Herrman, et al (1980) Webster, et al (1969)
Multiple Exponential—Time	Yes	Yes	First-order kinetics	No	Yes	Yes	Gangi (1981)
Deformation mechanism	Yes	Yes	Deformation mechanisms	Yes	Yes	No	Munson & Dawson (1979)
Unified Creep-Plasticity	Yes	Yes	Internal variable	No	No	Yes	Krieg (1977; 1980)

*Used as baseline.

t = time (s)
S_{ij} = deviator stress tensor (MPa)
$\dot{\epsilon}_{ss}$ = steady state strain rate (s^{-1})
$\dot{\epsilon}^*_{ss}$ = critical strain rate which divides the creep strain into two regions where the relationship between transient and steady-state are different (s^{-1})
A, n, λ, $\dot{\epsilon}^*_{ss}$, ϵ_a, and B = laboratory determined constants.

Characterizing the behavior of salt includes a tangent modulus function which considers independent variables of temperature, deviatoric stress and elastic modulus. The tangent modulus function is based on quasi-static testing of salt specimens and can be expressed as:

$$E_T = \frac{\partial\sigma}{\partial\epsilon} = E \cdot \exp\left(-\sqrt{3J_2}\left(\frac{\alpha_0 + \alpha_1 T}{-I_1}\right) + C_0 + C_1 T\right). \quad (2)$$

where

E_T = tangent modulus (MPa)
E = Young's modulus (MPa)
I_1 = first stress invariant (MPa)
J_2 = second invariant of the deviator stress (MPa^2)
T = temperature (°C)
$\alpha_0, \alpha_1, C_0, C_1$ = laboratory determined constants.

Equations 1 and 2 together are used in modeling the behavior of salt in the canister and emplacement areas of a nuclear waste repository (Pfeifle et al, 1982; Senseny, 1981a).

CREEP MODEL VERIFICATION

The exponential-time creep law (identified and used as a baseline for laboratory data verification and for modeling a nuclear waste repository) must be confirmed in situ by means of field instrumentation and measurements to develop confidence in the model or to modify it so that it will be representative of site-specific conditions. Additional laboratory experiments should be carried out simultaneously to verify the model for long durations, possibly up to a year.

Field data on the variability of creep closure between two specific potash mines is presented in Table 7 (Abel, 1981). Despite greater extraction and mining height and depth, Rocanville mine's creep closure rate (1.6%/year) is less than that of Kerr-McGee mine (2.8 to 7.5%/yr). The higher closure rate at Kerr-McGee is attributed to lower compressive strength (14 MPa) of its potash compared to the higher compressive strength (28 MPa) at Rocanville mine. Hence, the strength of individual salt horizons must be studied in relation to measured creep. Also, the geologic environment of an underground salt or potash mine, such as mining-horizon depth, thickness of salt beds and the thickness and location of clay partings, could influence creep closure rates, and therefore the geologic environment must be investigated further. For candidate repository sites, this additional characterization is ongoing and will continue for the next several years.

THERMOMECHANICAL ANALYSIS OF A BEDDED SALT REPOSITORY

The main purpose of thermomechanical analysis of a repository is to evaluate the repository design parameters such as thermal loading, based on prescribed performance constraints. Determination of thermomechanical response of a repository is based on:

(1) evaluation of thermal and thermomechanical responses such as temperature, displacements and stresses of the waste package (Westinghouse, 1982) and conceptual repository design parameters (Stearns-Roger, 1978, 1983) (Table 8 summarizes the repository design parameters)
(2) performance constraints prescribed for canister,

TABLE 7

Reported Room Closures at the Rocanville[1] and Kerr-McGee Potash Mines in Carlsbad, N. Mexico (Abel, 1981)

Mine	Depth (m)	Initial Height (m)	Opening Function	Extraction (approximate percent)	Closure Measured (mm)	Closure Measured (%)	Elapsed Time (yr)	Closure Rate (%/yr)
Rocanville	958.6	2.44	Main Entry	35	30	12.5	8	1.6
Kerr-McGee	579.0	1.52	Shaft Pillar	20	5	3.3	10	0.3
Kerr-McGee	579.0	1.52	Main Entries	25	13	8.3	3	2.8
				25	3–46	20–30	5	5.0–75
Kerr-McGee	579.0	1.52	Submains	32	3	20	3	6.7
				32	61	40	10	4.0
Kerr-McGee	579.0	1.52	Entries	NA	34	21.7	5	4.0

NA: Not available, but probably 32 percent and for submain entries.
[1] Rocanville Mines is owned by the Potash Corporation of Saskatchewan Mining Limited, Canada.

TABLE 8

Repository Design Parameters for Hypothetical Deaf Smith Site in Permian Basin (Westinghouse, 1982)

Waste Type	CHLW	SF	DHLW
Age (Years Out-of-Reactor)	10	10	5
Waste:			
Diameter (m)	0.54	0.57	0.59
Height (m)	3.68	4.06	2.28
Canister-Overpack:			
Outer Diameter (m)	0.88	0.91	0.93
Wall Thickness (m)	0.17	0.17	0.17
Top Head Thickness (m)	0.355	0.205	0.54
Bottom Head Thickness (m)	0.185	0.185	0.185
Borehole:			
Diameter (m)	1.0	1.0	1.0
Depth (m)	6.07	6.10	4.9
Disposal Room:			
Height (m)	5.8	6.4	5.2
Width (m)	4.6	4.6	5.8
Room Spacing (m)	26.2	20.1	19.8
Rows/Room	1	1	2
Row Spacing (m)	—	—	2.1
Canister Spacing (m)	12.2	18.3	2.1
Repository:			
Capacity (Canisters)	3673	8123	6720
Canister Heat Load (W)	9500	5500	423
Thermal Loading (W/m^2)	30	15	20
Required Area (km^2)	1.17	2.99	0.14
Provided Area (km^2)	1.46	3.55	0.20
Emplacement Efficiency (%)	84	84	70
Percent of Repository (%)	28	68	4

disposal room and repository. (Table 9 presents a summary of performance constraints.) These performance constraints are subject to change as more site-specific details become available in the near future.

Data required to perform thermal and thermomechanical analyses of the entire salt repository include site-specific parameters, nuclear waste form characteristics, material properties and repository design parameters.

Site-specific parameters required for repository evaluation include repository depth, thermal gradient, surface temperature, initial repository temperature, in situ stress condition, and initial repository stress level.

Nuclear waste consists of three heat-generating waste forms: commercial high-level waste (CHLW), which results from reprocessing of commercial power reactor fuels; spent fuel (SF) made up of individual fuel rods in a consolidated array; and defense high-level waste (DHLW).

Material properties required for thermal and thermomechanical analyses of a salt repository include salt properties, waste package thermal properties, canister region and disposal room region nonsalt material properties, and repository region material properties.

The salt itself, such as in Cycles 4 and 5, is the most important part of the investigation because they characterize the canister and room regions of the repository, and their deformation characteristics affect both the radial pressure

TABLE 9

Performance Constraints for Nuclear Waste Disposal in Bedded Salt (Loken et al, 1982)

Region	Response	Limit
Canister (Very-Near-Field)	1. Waste (CHLW, DHLW) Temperature	500°C
	2. Cladding (SF) Temperature	375°C
	3. Canister (Carbon Steel) Temperature	375°C
	4. Host Rock (Salt) Temperature	250°C
	5. Normal Pressure at Canister Overpack Midheight	30 MPa (CHLW) 28.5 MPa (SF)
Disposal Room (Near-Field)	6. Room Closure	10% roof-to-floor closure in 5 years
Repository (Far-Field)	7. Salt Temperature Above Disposal Room Region	100°C
	8. Rock Temperature Above "15% Repository Depth" Region	75°C
	9. Shaft Temperature	75°C
	10. Near-Surface Temperature Rise	4°C
	11. Surface Uplift	3 m
	12. Depth of Perturbed Fissure Zone	Near-surface aquifer
	13. Aquitard Stability	Shear strength ratio > 4
	14. Shaft Pillar Stability	Shear strength ratio > 4

against the canister overpack and the disposal room closure (Loken et al, 1982). The remaining materials in the canister region include the waste package components such as nuclear waste forms, the air surrounding the waste package and in the disposal room, the crushed salt above the waste package, and the carbon steel canister overpack.

Nonsalt layers (interbeds of anhydrite and shale), investigated by use of the stratigraphic column for the Deaf Smith site in the Permian Basin, are incorporated into a computer model because of variation in their material properties and thickness and their closeness to the emplaced waste within the canister and room regions. The repository region includes the entire stratigraphic column at a given site, primarily composed of nonsalt materials.

Salt's thermal properties include thermal conductivity, specific heat capacity, density and the coefficient of linear thermal expansion. These properties have been determined from laboratory testing of core samples for specific locations and are reported by Tammemagi et al (1981). The mechanical properties of salt and nonsalt layers such as modulus of elasticity, Poisson's ratio, tensile strength, angle of failure envelope, material and joint cohesion and in situ stress ratio have been determined by laboratory testing procedures and reported by Pfeifle et al (1982). The exponential-time creep law model is used as a baseline for thermomechanical modeling analysis of salt (refer to Equations 1 and 2) in canister and room regions of the repository. Table 10 presents the basis for comparison of the potential repository sites in the Permian and Paradox Basin bedded salt formations.

With respect to waste package, two material properties are used: thermal and thermomechanical properties. The materials used for the waste package are chemical high-level waste (CHLW), spent fuel (SF), air, crushed salt and carbon steel. The properties needed for the waste forms are density, specific heat and thermal conductivity. The canister and disposal room region nonsalt material properties include anhydrite and shale layers located between and within the salt cycles at the Permian site.

Similarly, nonsalt thermomechanical properties are determined by laboratory testing of core samples. The repository region material properties, i.e., thermal and thermomechanical properties, are difficult to find for nonsalt layers which dominate the repository region. The reason is that these salt formations are extensive and cannot easily be defined. However, the material characteristics of these rock formations can be gathered from the published literature, recent exploration activities for ONWI by Stone-Webster as subcontractor, and laboratory testing of cored samples. Thermomechanical properties of nonsalt materials found at the Permian site are presented in Table 11.

Repository Design Parameters

The classical repository design concepts (Bechtel, 1979; Kaiser Engineers, 1978 and Stearns-Rogers, 1978, 1983) provide for the long-term containment of each waste form placed in stainless steel canisters. Each canister in turn is placed in a carbon steel overpack designed to resist the external pressure caused by the in situ stress state and the salt's thermal expansion and creep (Figure 9). The overpack also serves to resist the corrosive effects of brine for 1,000 years. The waste package is emplaced in boreholes in the disposal room floor of a deep underground salt formation (Figure 10). The repository design parameters required for thermomechanical analysis of a salt repository are presented in Table 8. The areal thermal loading is approximated as

$$Q'' = nL/(sp), \tag{3}$$

where

Q'' = thermal loading (w/m^2)
n = number of canister rows per room
L = canister emplacement heat load (W)

TABLE 10

Bases for Comparison of the Bedded Salt Potential Repository Sites (Loken et al, 1982)

Region (Response)	Thermal (Temperatures)	Thermomechanical
Canister (Very-Near-Field)	Canister Surface	Radial Compressive Stress on Canister Sleeve
Room (Near-Field)	Floor Roof Pillar Center	Disposal Room Deformation
Repository (Far-Field)	Within "Specified Region"*	Surface Uplift
	Upward and Outside "Specified Region"* Ground Surface	Tensile Stress Zones

*"Specified Region" extends from the room region to a distance equal to 15 percent of the repository depth.

s = disposal room spacing (m)
p = canister spacing, or pitch (m)

The calculated areal thermal loadings for the given repository dimensions presented in Table 8 for each repository region are 30, 15 and 20 w/m² for CHLW, SF and DHLW, respectively.

Thermomechanical analysis of the conceptual salt repository is being conducted (Loken et al, 1982) by using finite element computer programs for heat transfer (SPECTROM-41) and thermomechanical (SPECTROM-21) stress analysis that were developed specifically for dealing with thermal/viscoelastic problems associated with investigations of nuclear waste disposal in salt formations.

Hypothetical sites in Deaf Smith County in the Permian Basin have been subjected to thermal and thermomechanical analysis. The repository depth was considered to be 730 m, located within the Cycle 5 salt layer. The thermal and thermomechanical analysis has been conducted for the canister, room and repository regions, and their results are reported by Loken et al (1982). The canister-region thermal and thermomechanical analysis of the conceptual repository design for the emplacement of CHLW with areal thermal loading of 30 w/m² is shown in Figure 13. The three canister-region temperatures studies were the maximum waste (canister) centerline temperature, the maximum waste (CHLW)/canister interface temperature, and the maximum salt temperature at the borehole surface. The maximum waste (canister) centerline temperature reached 419°C after approximately one year of emplacement with no backfill. The same temperature was reached after 5 years when backfilled with crushed salt. At the interface of the waste canister and overpack the maximum temperature reached 266°C after approximately 16 years and salt temperature reached 237°C after approximately 18 years. If the disposal rooms are not backfilled the respective maximum temperatures decrease by approximately 6°C.

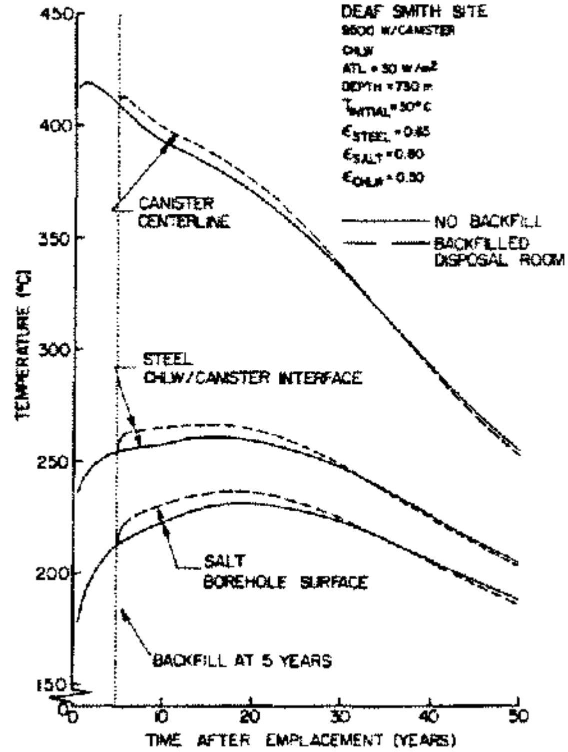


Figure 13. Predicted Maximum Canister Region Temperatures for a CHLW Repository at the Hypothetical Deaf Smith Site for Salt Cycle 5 (Loken et al, 1982).

Comparison of the above predicted temperature with the thermal performance constraints (Table 8) of 500°C, 375°C and 250°C for the CHLW, CHLW/canister interface, and salt, respectively, show that all the canister region temperatures were below the above limits.

Thermal and thermomechanical analysis of disposal room region has also been conducted. The thermal results are presented for three waste forms, CHLW, SF and

TABLE 11

Thermomechanical Properties for Material Types Found at Permian Site (Loken et al, 1982)

Material	Location	Density[2], kg/m^3	Specific Heat[2], J/kg-K	Thermal Conductivity[2], W/m-K	Coefficient of Thermal Expansion[2], 10^{-6}/K	Elastic Modulus[1], GPa	Poisson's Ratio[1]	Angle of Internal Fraction[3], degree	Unconfined Compressive Strength[1,4], MPa
Sandstone/ Mudstone	Permian	2100	712	2.6	9.0	5.3	0.30	37.2	27.0
Siltstone/ Shale	Permian	1800	837	1.7	16.2	2.5	0.26	32.1	15.3
Dolomite/ Limestone	Permian	2500	837	3.9	12.6	32.2	0.32	32.5	81.3
Anhydrite	Permian	2900	837	4.9	23.4	59.1	0.36	29.4	148.1

(1) Callahan (1981).
(2) Pfiefle et al (1982).
(3) Goodman (1980).
(4) Unconfined compressive tests were performed on 2.5-inch-diameter cores which were 5 inches in length.

DHLW with areal thermal loading densities of 30, 15 and 20 w/m², respectively (Figure 14). The temperature history for the five-year period between waste emplacement and room backfill is presented for three locations within the disposal region, floor centerline, roof centerline and the pillar centerline. These locations provide representative evaluation points for studying thermal behavior within the disposal room region.

Table 12 presents disposal room performance summary for the Permian site. The thermomechanical results of the disposal room region are presented in terms of roof-to-floor closure rate (deformation). The roof-to-floor closure rate of 10 percent in less than 5 years is an arbitrarily selected performance constraint for purposes of thermomechanical analyses. Thermomechanical analyses indicate that at the Permian site, at a depth of 730 m and initial temperature of 30°C, the 10 percent initial closure rate after 5 years of waste emplacement is exceeded for each of the three waste forms (Table 12). To adjust for 10 percent closure, either the depth of repository must be reduced (relocate repository at Cycle 4) or the thermal loading must be lowered. According to the baseline design closure crite-

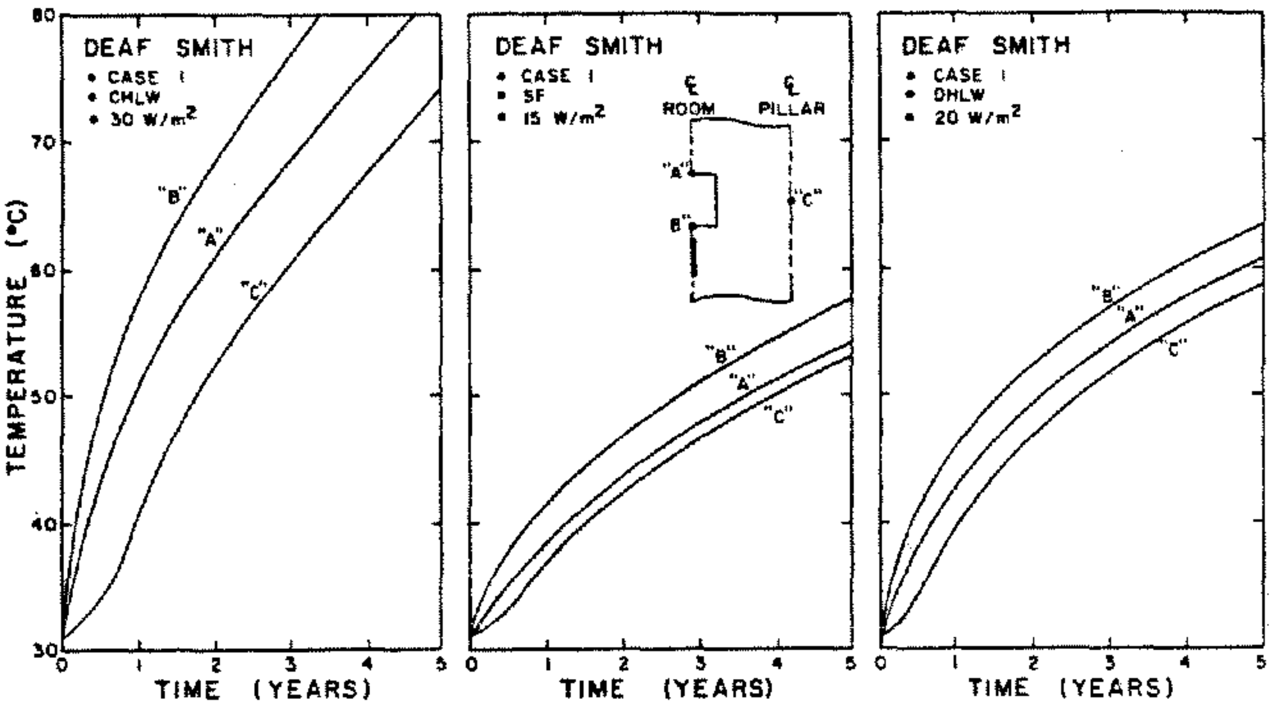


Figure 14. Temperature Histories Associated with the Three Types of Disposal Rooms at Deaf Smith Locations (Loken et al, 1982).

TABLE 12

Disposal Room Performance Summary: Permian Site[1] (Loken et al, 1982)

	CHLW (W/m²)			SF (W/m²)			DHLW (W/m²)		
Calculated Response	**30**	**10**	**0**	**15**	**10**	**0**	**20**	**10**	**0**
Temperature (°C) at 5 Years									
Floor Centerline	89	49	30	58	48	30	63	46	30
Roof Centerline	82	47	30	54	46	30	61	45	30
Pillar Centerline	74	44	30	53	45	30	58	44	30
Roof-to-Floor Closure at 5 Years (%)	40.0	6.6	2.5	17.0	11.0	4.7	33.0	14.2	6.3
Time to Reach 10% Roof-to-Floor Closure (years)	2.5	>5	>5	3.6	4.5	>5	2.4	3.8	>5
Areal Thermal Loading for 10% Roof-to-Floor Closure at 5 Years (W/m²)		13.5			8.5			6.0	

[1]Depth = 730 m, initial temperature = 30°C.

rion of 10 percent at 5 years, the corresponding thermal loadings for CHLW, SF and DHLW would be 13.5, 8.5 and 6.0 w/m^2, respectively, in order to satisfy the room closure constraints (Figure 15). Note that reducing repository depth may be technically feasible. As is pointed out by Loken et al (1982), relocation of the repository at a shallower depth may reduce closure rate substantially. Since there is insufficient stratigraphic data on nonsalt layer thicknesses the assumption that a 3-m nonsalt layer exists at the immediate roof is questionable, and therefore additional field investigations are necessary in order to provide reliable stratigraphic data on thickness of nonsalt layers and their location with respect to repository horizon. Lowering thermal loading means more acreage for the repository, which in turn means more development work and additional cost. Since the 10 percent closure rate was chosen arbitrarily, field investigation (in situ stress and convergence measurements) at an operating salt mine is needed to define closure rate accurately. These data, then, can be used with confidence as input in thermomechanical analyses.

Thermal and thermomechanical analyses of the repository as a whole have also been conducted by Loken et al (1982) for the assumed Deaf Smith location in the Permian Basin. The thermal loadings for CHLW and SF were assumed as 30 and 15 W/m^2, respectively. Performance constraints and the results of thermal and thermomechanical analyses are summarized in Table 13; the thermal analysis results are presented in Figure 16. The highest temperature of 93°C after 50 years was reached for CHLW at a depth of 715 m, approximately 6 m above the disposal room. The maximum temperature of 62°C above the "15-percent-of-repository-depth" region was reached at a depth of 622 m after 300 years. This temperature was less than the performance constraint of 75°C. The maximum shaft temperature, at a depth of 730 m in the San Andres Formation for the CHLW region of the repository at a horizontal distance of 730 m, is 32°C. This temperature is achieved after 5,000 years and is much less than the performance constraint of 75°C. In addition, the expected maximum near-surface temperature rise at the shaft site after 100 years of operation is negligible.

The results of the thermomechanical analysis of the repository region are presented in Table 13 and in Figure 17. These results show that the maximum surface uplift is 0.94 m and occurs directly above the center of the SF portion, approximately after 1,500 years, which is less than the recommended performance constraint. The maximum depth of the tensile stress zone (perturbed fissure zone) is 116 m after about 1,000 years. The performance constraint on depth is exceeded by approximately 17 percent, and since depth of the tensile stress zone is proportional to thermal loading, the loading should be reduced by this amount in order to satisfy the performance constraint of 98 m. However, Loken has not considered subsidence effects due to an approximate extraction ratio of 20 percent, where the net effect will be downward, not upward, movement of surface.

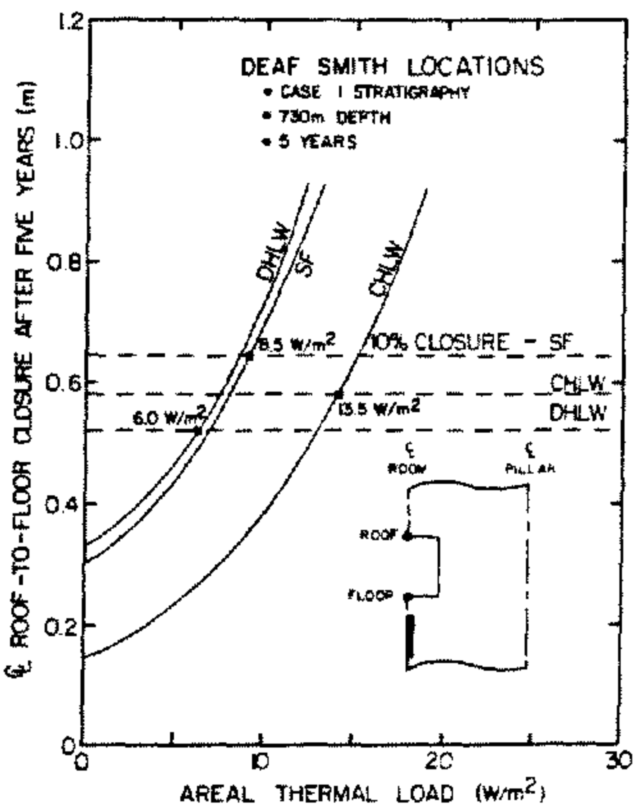


Figure 15. Roof-to-Floor Closure at Five Years for Various Thermal Loadings (Loken et al, 1982).

TABLE 13

Repository Region Performance Summary: Permian Site (Loken et al, 1982)

Calculated Response	Computed Value	Time of Occurrence (years)	Performance Constraint
Thermal			
Maximum Temperature Above Near-Field Region	93°C	50	100°C
Maximum Temperature Above "15%-of-Repository-Depth" Region	62°C	300	75°C
Maximum Shaft Temperature	32°C	5,000	75°C
Maximum Near Surface Temperature Rise	0.1°C	10,000	4°C
Thermomechanical			
Maximum Surface Uplift	0.94 m	1,500	3 m
Maximum Depth of Perturbed Fissure Zone	116 m	1,000	98 m
Minimum Shear Strength Ratio in Overlying Aquitards	5.5	150	4.0
Minimum Shear Strength Ratio in Shaft Pillar	5.2	200	4.0

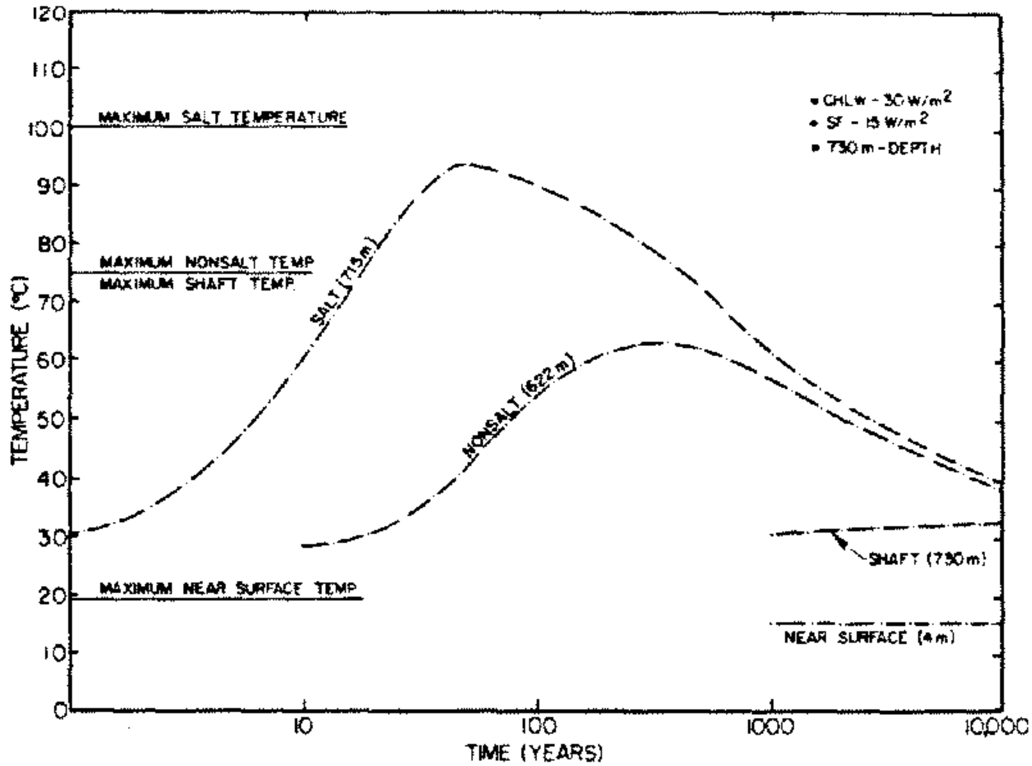


Figure 16. Repository Region Thermal Responses for the Hypothetical Deaf Smith Site (Loken, et al, 1982).

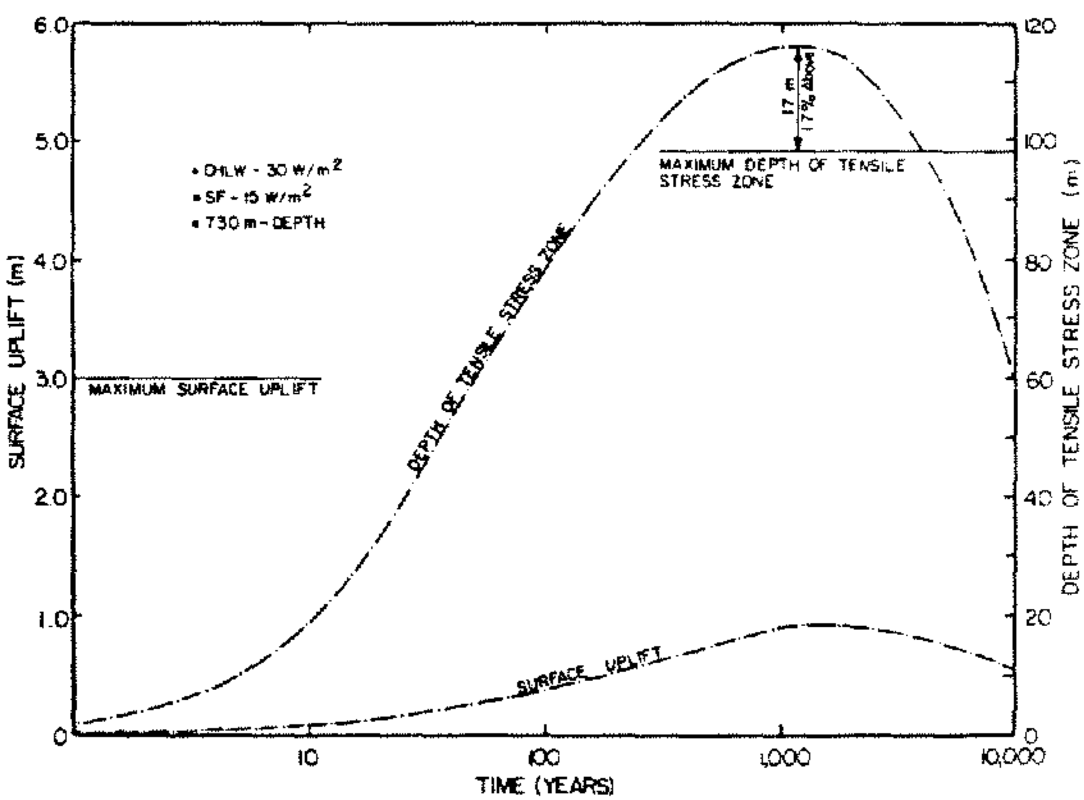


Figure 17. Repository Region Thermomechanical Results for the Hypothetical Deaf Smith Site (Loken et al, 1982).

The minimum shear strength ratio outside the "15-percent-of-repository-depth" region occurs at a depth of 622 m directly above the edge of the CHLW region in about 150 years and is equal to 5.5. Thus, the performance constraint of aquifer stability is satisfied (greater than 4). The minimum shear strength ratio in the shaft pillar along the repository midplane, 137 m from the repository, is equal to 5.2 after 200 years; thus, the performance constraint of the minimum shear strength ratio (greater than 4) in the shaft pillar is satisfied.

In summary, all the performance constraints affecting the thermomechanical response of the Deaf Smith site are satisfied except the depth of the tensile stress zone, which can be satisfied by 17 percent thermal loading reductions of CHLW and SF. After analyzing the thermal and thermomechanical response of the repository, Loken concluded that the canister region of the repository is affected by salt temperature resulting from CHLW and waste temperature resulting from SF. The disposal room region is affected by roof-to-floor closure and the repository region is affected by depth of tensile stresses.

The general conclusions for the thermal and thermomechanical aspects of a conceptual repository in the Permian Basin are as follows:

> The performance constraints are arbitrarily chosen (10 percent roof-to-floor closure rate). The exponential-time creep law needs field verification, possibly in an operating salt or potash mine, in order to modify or increase confidence in the application of the law and rate of closure. Areal thermal loading, which affects the temperature level and the salt's thermal expansion and deformation (creep), need to be analyzed in detail. They form a base for repository performance constraints. Design parameters such as depth and extraction ratio of the repository need further attention because they affect the rate of closure and subsidence of the room region significantly. Additional modifications required are change in design of canister room and emplacement design. Optimization of depth, areal thermal loading, extraction ratio and backfilling techniques are also needed. Additional laboratory tests and in situ investigations are needed for salt and nonsalt material properties, backfilling, thermal conductivity and stress measurements. Thermal and thermomechanical computer codes of SPECTROM-41 and SPECTROM-21 should be checked against other available numerical codes to verify predicted results with reasonable assurance.

CONCLUSIONS AND RECOMMENDATIONS

Geotechnical aspects of repository design, development and emplacement, decommissioning and retrievability present a unique opportunity for engineers to develop new technology for nuclear waste packaging, transportation, emplacement, rock mechanics and mining and geological sciences. Up to now geologic exploration of salt formations has been limited to a few exploratory drill holes, and additional geologic data have been compiled from previous oil, gas and/or mineral exploration activities. The geologic data are limited as drilling sites are located kilometers apart. Once a site has been selected, additional site-specific geologic data will be available. These data will be used for reevaluation of conceptual design of shaft sinking techniques, design of repository and modification of thermal and thermomechanical analysis of the repository. Since safety of workers and long-term stability of the repository are important factors in the view of the Nuclear Regulatory Commission (NRC), a comprehensive research and development program is in progress for the safe disposal of nuclear waste in salt. Design and development of a nuclear waste repository in salt has to a great extent been based on past experience from mining of salt, potash and hard rocks, with the following differences:

> In underground mining, short-term stability (approximately 5 years) and higher extraction ratios (over 40 percent) are required, whereas for a salt repository long-term stability (over 50 years) and lower extraction ratios (about 20 percent) are desirable. In underground mining practice geo-gradient temperature is of concern for the safety and productivity of labor and for ventilation design; in a salt repository waste canisters are sources of temperature increase around canister hole (very near-field), room (near-field) and repository (far-field), which generally affect the stability of the repository and, hence, a better understanding of the long-term stability of the repository requires thermal and thermomechanical analysis of the repository.

In this paper the stability of a potential repository on the Permian Basin site is explored, based on limited data and information; additional detailed site-specific geological and geomechanical investigations of the Permian Basin are recommended.

Following is a summary of the identified research areas needing further investigation.

Field Investigations

- Geological, geophysical and hydrological exploration of bedded and domal salt stocks
- In situ stress and convergence measurements in salt
- Identification of geologic anamolies, i.e., oil and brine pockets, faults, interbeds and gas outbursts
- Influence of depth and thickness of salt and nonsalt layers on deformation characteristics of salt
- Influence of geo-gradient and nuclear waste temperature on salt's deformation characteristics
- Influence of interbeds such as anhydrite shale, clay, dolomite, etc., on thermal and thermomechanical characteristics of salt

- Thermal conductivity measurements for salt
- Creep model verification
- Influence of subsidence and uplift on the stability of the repository
- Backfilling material characteristics and backfilling techniques
- Smooth wall blasting applications in salt
- Corrosion effects on waste canisters (due to moisture content of salt)
- Borehole plugging and sealing of repository
- Rock reinforcement of repository in unstable areas
- Ventilation aspects of repository
- Retrievability of the waste canisters.

Laboratory Investigations

- Determination of physical, geochemical, geomechanical, and thermal and thermomechanical properties of salt and non-salt rocks
- Deformation characteristics of salt (creep) and influence of interbeds on salt's deformation behavior
- Properties and recrystallization characteristics of mined salt backfill
- Thermomechanical modeling analysis of salt repository in canister hole, room and repository region
- Repository optimization with respect to depth, areal thermal loading density and extraction ratio
- Thermal conductivity measurements.

Repository Design Parameter Investigations

- Repository design techniques (yield pillar design approach)
- Changes in dimensions of canister holes, rooms, mains and submains
- Optimization with respect to dimensions of openings, depth, extraction ratio and areal thermal loading density.

The National Waste Terminal Storage Program has in the past and will continue to pursue these areas of investigation.

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