INFORMATION BASE FOR WASTE REPOSITORY DESIGN

Volume 3 Waste/Rock Interactions

**Charles M. Koplik Stephen G. Oston
David L. Pentz Richard Talbot**

The Analytic Sciences Corporation

MASTER

**Prepared for
U. S. Nuclear Regulatory Commission**

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FOREWORD

This report is Volume 3 of a seven volume document on nuclear waste repository design issues. A portion of the work reported in this document was performed by Golder Associates, Inc., under a subcontract to TASC. Principal Golder authors of this report are David L. Pentz and Richard Talbot. The authors would like to thank Michael Kearney and William M. Grayson of NRC for their encouragement and assistance.

ABSTRACT

This report describes the important effects resulting from interaction between radioactive waste and the rock in a nuclear waste repository. The state of the art in predicting waste/rock interactions is summarized. Where possible, independent numerical calculations have been performed. Recommendations are made pointing out areas which require additional research.

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1.

INTRODUCTION

A nuclear waste repository in bedded salt should be designed to minimize adverse interactions between the waste and the geologic formation. Waste/rock interactions will be thermal, chemical, physical and radiolytic. Problems due to increased temperatures, radiolytic damage, and the formation of corrosive chemicals may be significant for repositories in bedded salt.

1.1 OVERVIEW

This report discusses waste/rock interactions that should be controlled to assure satisfactory repository performance and provides a brief review of the state of the art in predicting potential interactions. Satisfactory repository performance includes: long-term containment of the wastes, retrievability of the waste canisters during repository operations, and safety of the personnel working within the repository. The report also shows what methodology exists for evaluating specific areas of design. No single cohesive evaluation process has been established, due to the complex and varied nature of the problem and the many design aspects that have not been satisfactorily resolved at this time.

This report discusses the temperature and irradiation history of the depository rock due to emplacement of commercial high-level reprocessed waste (HLW), military HLW, or spent fuel. Three distinct regions of interest are identified: the waste canister vicinity, the storage rooms and mine pillars,

and the repository as a whole. Potential areas of concern for each region are described and the state of the art in predicting temperatures and radiation doses in the salt is reviewed. The important parameters that affect the thermal and irradiation history are presented.

Potentially harmful radiolytic effects are discussed in detail, including recommendations for additional research. It is concluded that radiolytic effects are of lesser magnitude and concern than temperature induced effects. However, there are some areas for which additional information is required, particularly with regard to burial of spent fuel canisters.

Significant thermal effects are also treated. The analysis is divided into two parts: corrosion of the emplaced waste canisters, and rock mechanics. The latter includes waste package movement or crush due to deformations that occur in the emplacement medium. A full discussion of the structural stability of the mined excavations is deferred to Volume 4.

The theoretical and experimental work on thermal effects in the vicinity of the waste canister is summarized. Areas where insufficient information exists to evaluate potential problems are identified. It is concluded that damage to the waste package from mechanical and corrosive effects could be severe for commercial HLW. It would be relatively less severe for spent fuel and military HLW. Many of the potential problems can be mitigated by appropriate package design. This is an area where in situ experimental work is required to determine the magnitude of local effects and to try out potential designs.

A detailed discussion is given of important effects which occur far from the vicinity of the waste package. These

include expansion of the overlying rock layers and subsidence, both of which are affected by the thermal output of the waste. The methods for predicting uplift and subsidence are reviewed and relevant experience from the mining industry is presented.

1.2 ORGANIZATION OF THE REPORT

The temperature and irradiation history of the rock is discussed in Chapter 2. A detailed review of significant radiolytic effects is also given. Chapter 3 discusses the effect of the waste on the structural properties of the rock and the important consequences in terms of repository performance. Corrosion of the waste package is discussed in Chapter 4. A summary of this volume, including recommendations and conclusions, is given in Chapter 5.

Appendix A reviews numerical methods that have been used to predict stresses and displacements in the rock overlying the depository. A discussion of subsidence in mines and in a waste repository is given in Appendix B. A glossary of important technical terms appears at the end of this report.

2. INTERACTIONS BETWEEN THE WASTE PACKAGE AND THE ROCK FORMATION

The interaction between nuclear waste and the depository rock formation is primarily caused by the thermal and radiation characteristics of the waste. This will affect the strength of the surrounding rock, and may also result in chemical decomposition. This section reviews the factors that contribute to the temperature history in the rock formation, the expected temperatures both around the canister and over the whole repository area, and the anticipated effects of irradiation of the rock.

2.1 FACTORS INFLUENCING TEMPERATURE HISTORY

The factors that will influence the temperature history, both in the waste itself and also in the surrounding rock, are:

- Type and age of waste
- Thermal output per canister
- Canister spacing and thermal load
- Package/rock interface
- Thermal properties of the rock mass
- Repository ventilation.

Each of these factors is discussed in the following sections.

2.1.1 Type and Age of Waste

Two types of waste are considered here, reprocessed high-level waste (HLW) and unprocessed spent fuel. The two waste types are characterized by heat generation rates that depend on such factors as the type of reactor, the irradiation history and time of reprocessing.

For both high-level waste and spent fuel, heat generation rates decline rapidly during the first ten years following removal from the reactor. After ten years the heat generation rate declines much more slowly with an approximate half-life of 30 years. Consequently, it is usually assumed that waste will be cooled for ten years prior to emplacement in a repository; for a given limit to the thermal output per canister, far fewer canisters will be required to contain the waste. The assumption is made in this report that the waste will be ten years old at emplacement. After emplacement and during the next 30 years the decline in thermal output is roughly the same for all waste types. The relative thermal outputs of commercial reprocessed waste with U and Pu removal, spent fuel, and military high-level waste from the Hanford Reservation are shown in Fig. 2.1-1.

It is clear from Fig. 2.1-1 that the decline in heat output after 30 years is much slower for spent fuel than for other waste types. This is primarily due to the larger quantities of americium and plutonium in the spent fuel. At 1000 years, the total thermal energy released by spent fuel will be about 3.5 times that released by commercial high-level waste. The major effect associated with this higher release of heat is uplift due to thermal expansion of the rock mass. It is not yet known whether uplift will in any way reduce the effectiveness of the repository to contain waste. This issue will be discussed in detail in Chapter 3.

Figure 2.1-1 Thermal Decay Curves for Waste Forms

2.1.2 Thermal Output per Canister

The thermal output per canister is the most important factor in determining the local temperatures surrounding the waste package. It also dictates how close together canisters may be emplaced. Current Department of Energy (DOE) estimates for the expected thermal powers of canistered waste at emplacement in a depository are given in Table 2.1-1 (Ref. 1). Values for radiation intensity are included for reference in subsequent sections.

Estimates of the thermal power for canistered military waste are given in Refs. 2 and 3. Canisters of high-level

TABLE 2.1-1
THERMAL POWER AND RADIATION INTENSITY OF
CANISTERED WASTE AT EMPLACEMENT

Waste Form and Reference Age at Emplacement	Thermal Power in Reference Canister (kW)	Maximum Gamma Radiation Intensity at Surface (rem/hr)	Maximum Neutron Radiation Intensity at Surface (rem/hr)
<u>Once Through</u>			
Spent PWR assembly, 10 yr	0.55	4×10^4	0.4
Spent BWR assembly, 10 yr	0.19	2.5×10^4	0.25
<u>Recycle U: Pu Stored Separately</u>			
HLW; 10 yr	2.3	8.8×10^4	1.3
<u>Recycle U; Pu with HLW</u>			
HLW; 10 yr	2.6	8.8×10^4	1.5
<u>Recycle U and Pu</u>			
HLW (1/3 MOX); 10 yr	3.2	8.8×10^4	20

Source: Ref. 1

waste from the Savannah River Plant would have a thermal output of 0.340 kW if stored as a glass product, comparable to spent fuel. Waste from Hanford would be in two distinct forms. Most of the strontium and cesium in the HLW at Hanford has been removed and placed in capsules, which could be stored as a glass product in canisters with a thermal output of 2.7 kW. The remaining HLW could be stored as a glass product in canisters with a thermal output of 0.026 kW. Radionuclide removal from the salt cake is assumed. The extremely low thermal output of these remaining waste canisters should be noted.

There are a number of effects which are encountered locally near the emplaced canisters due to high temperatures. They are primarily associated with brine migration and with

movement of the salt mass. These effects are especially important during the period that waste must remain retrievable. The retrievability period is expected to be 5 years for HLW and as long as 25 years for spent fuel.

The high temperatures near the waste canisters can be reduced by diluting the waste in the canisters to lower the thermal output. Dilution will cause a substantial increase in the overall cost of waste disposal since the number of canisters to be emplaced goes up. Temperatures can also be reduced by increasing the spacing between canisters. This is discussed in the next section.

2.1.3 Canister Spacing and Thermal Load

Current conceptual repository designs call for waste to be emplaced in storage rooms that are separated by thick pillars of salt. Canisters would be placed in vertical holes drilled into the floor of the storage rooms. Other designs are possible for the depository and other methods for emplacement have been studied (Ref. 4). The room and pillar arrangement with vertical burial of the canisters is adopted here as a reference depository.

The spacing between canisters can strongly affect temperatures within the waste and in the region near each canister. This is illustrated in Fig. 2.1-2 for crystalline rock (Ref. 5). For canister spacings greater than 15 meters (in this example), the temperature at the canister is independent of spacing. However, temperatures rise dramatically when canisters are closely spaced.

The thermal load directly affects the temperatures in the pillar, roof, and floor of the storage rooms. This is a

Figure 2.1-2 Effect of Spacing on Temperature in Arrays of Buried Waste Canisters

critical factor in determining the structural stability of the excavation. The structural stability of the storage rooms is very important during the operating phase of the repository, particularly if the waste is required to be retrievable. A detailed discussion of mine structural features is given in Volume 4.

The thermal load also directly affects far-field temperatures -- i.e., the temperatures in the rock above and below the depository horizon. Higher temperatures can result in thermal stress, expansion, possible fracturing, and surface displacement. As discussed previously, for a given thermal loading the accumulated thermal energy released is much higher for spent fuel than for other waste types. Therefore, if these effects prove important to maintaining the integrity of

the repository, the allowable thermal load for spent fuel must be considerably less than for other waste types. This fact has been noted by DOE in Ref. 6.

2.1.4 Package/Rock Interface

The waste will be packaged in a metallic canister with an extremely low temperature gradient between the waste material and the outside surface of the waste canister due to the high conductivity of the metal. This temperature gradient will, however, be increased when an overpack and/or a steel hole liner is used, due to the air gap between the various metallic layers.

The steel sleeve which lines the emplacement hole protects the canister from contact with salt and brine and simplifies retrievability. The cross-section of an emplaced canister, shown in Fig. 2.1-3, was taken from Ref. 7. The sleeve can be either in direct contact with the salt or free standing to avoid contact (Ref. 8).

It has been determined (Ref. 9) that the major impact of the waste package/rock interface is on the temperature rise in the waste rather than in the rock. Figure 2.1-4 indicates that heat transfer by radiation across an air gap results in essentially the same temperature in the rock mass as when conductive heat transfer is assumed. (The maximum temperature in the waste, however, is increased. It is possible that the increased temperature within the waste canister may cause melting of the waste matrix or may lead to increased internal corrosion rates.) Therefore, analyses using a conductive heat transfer at the interface are adequate to determine the temperatures in the rock surrounding the package. They are not considered adequate to determine the stability of the waste form at elevated temperatures.

Figure 2.1-3 Details of Preliminary Waste Canister and Sleeve Design

2.1.5 Thermal Properties of the Rock Mass

The range of values for the thermal properties of different rock types is not large. Values of the mechanical and thermal properties of salt and other sedimentary rocks are presented in Table 2.1-2. (Refs. 10 through 15). These rocks can generally be classified into groups with either high thermal conductivity (salt, anhydrite, dolomite) or low thermal conductivity (shale, sandstone, limestone). Granitic rocks will generally also be classified in the lower range.

TABLE 2.1-2

MECHANICAL AND THERMAL PROPERTIES OF BEDDED SALT AND OTHER SEDIMENTARY ROCKS

T-2659

Rock Type	Thermal Conductivity (Watt/cm°C)	Melting Point	Linear Thermal Expansion Coefficient (μ /°C)	Heat Capacity (Btu/lb°F)	Specific Gravity	Modulus of Elasticity (psi)	Unconfined Compressive Strength (psi)	Poisson's Ratio	Tensile Strength (psi)	Angle of Friction	Cohesion (psi)
Halite NaCl	5.01×10^{-2} (e) 5.33×10^{-2} (b)	800°C (c)	1.2×10^{-3} (b)	0.10 (f) 0.22 (e)	2.20 (a) 2.10 (b) 2.16 (c)	0.19×10^6 - 0.55×10^6 (d) 2×10^6 (e) 4.06×10^6 - 5.11×10^6 (b)	4700 - 5700 (d) 3750 (e)	0.33 (e)	250 (e)		
Polychalcite $\text{K}_2\text{SO}_4 \cdot \text{MgSO}_4$ $2(\text{CaSO}_4 \cdot 2\text{H}_2\text{O})$	1.55×10^{-2} (b)	880°C (c)			2.76 (b)						
Selenite KCl	6.4×10^{-2} (0.1°C) (1) 1.04×10^{-2} (100°C) (b)	770°C (c)	2.9×10^{-3} (b)		1.984 (a)						
Langbeinite $\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4$		910°C (c)			2.820 (a)						
Corinthite Cl MgCl ₂ · 6H ₂ O		160°C 425°C (c) * 265°C (c)			1.61 (c)						
Kunipite KCl · MgSO ₄ · 3H ₂ O					2.11 (c)						
Leucite $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ H ₂ O		670°C (c)			2.01 (c)						
Halite	1.62×10^{-2} (15°C) (b) 1.17×10^{-2} (c) 2.18×10^{-2} (1)	1100°C (c)	8×10^{-4} (1)	0.14 (1)	2.17 (b) 2.67 - 3.01 (f)	1.71×10^6 - 6.88×10^6 (f) 1.17×10^6 - 5.95×10^6 (f)	1.01 - $21,650$ (f)	0.01 - 0.12 (f) 0.01 - 0.07 (b)	115 (f)	30 - 15° (f)	200 - $1,061$ (f)
Anhydrite CaSO_4	1.40×10^{-2} (b) 1.09×10^{-2} (1) 5.71×10^{-2} (b)				2.83 (b) 1.02 (b)	10.11×10^6 - 10.71×10^6 (b)		0.09 (b)			
Sandstone	2.81×10^{-1} (b) 1.90×10^{-2} (c) 1.90×10^{-2} - 2.81×10^{-2} (b)		0.11×10^{-5} (c) 8×10^{-4} - 1.2×10^{-3}	0.18 (c)	2.64 (b) 2.24 (c)	1.5×10^6 (c) 0.87×10^6 - 11.50×10^6 (b)	7500 (c)	0.29 (c) 0.06 - 0.115 (b)	500 (c)		
Siltstone					2.61 (1)	6.18×10^6 (dry) (b) 2.75×10^6 (wet) (b)		0.12 (b)			
Clay	0.1×10^{-2} (1.4°C) 0.8×10^{-2} (c) 0.001 (c)				1.05 - 1.51 (c)						

*Minimum value; (b) = best; (c) = Ref. 11; (d) = Ref. 12; (e) = Ref. 13; (f) = Ref. 14.

Source: Ref. 9

Figure 2.1-4 Temperatures in a Salt Repository Model for Radiative and Conductive Interfaces

The thermal conductivity of salt appears to be quite sensitive to temperature (Ref. 16). The thermal conductivity of a single halite crystal is shown as a function of temperature in Fig. 2.1-5.

The decrease in conductivity over the range of temperatures considered for the repository is approximately 50 percent and indicates that, at higher temperatures, salt is a less efficient conductor of heat. Thus, analyses using a high, constant value of thermal conductivity will tend to underestimate the near-canister temperatures. It is also noted that the thermal conductivity of bedded rock is generally greater in the horizontal direction (parallel to bedding) than in the vertical direction, due to the presence of thin layers of lower conductivity material within the salt.

Figure 2.1-5 Variation of Thermal Properties of Salt with Temperature

Coefficients of linear thermal expansion are also given in Table 2.1-2, and it is noted that the linear thermal expansion coefficient for salt is approximately four times greater than that for shale. Values for linear thermal expansion coefficients are generally quoted for a specific temperature range.

The mild temperature dependence of the specific heat of halite crystals is reported in the International Critical Tables and is presented in Figure 2.1-5. This dependence is not significant.

No information has been obtained on the change in thermal properties of salt due to radiation. Because the volume of salt exposed to radiation will be small, changes in the thermal properties due to irradiation would only effect temperatures near the waste canisters. Other factors such as brine migration could also affect the thermal conductivity of the salt near the canisters. There is no evidence and no reason to suggest that any significant changes in thermal properties will occur.

2.1.6 Repository Ventilation

The flow of ventilating air through the emplacement rooms will provide a considerable heat sink, removing significant amounts of the heat with the mine air. The extent to which this benefit is utilized will depend on the time period over which the emplacement rooms are kept open. The benefit of ventilation in terms of reduced temperatures over the repository area will be felt for some time after the flow of air is stopped. It has been stated (Ref. 17) that the effect of ventilation at the midplane of the repository is noted for up to an order of magnitude longer than the ventilation period;

that is, if ventilation is stopped after 30 years, the temperatures in the mid-plane are reduced for almost 300 years.

The principal advantage of ventilation is a cooling of the pillar, roof, and floor of the storage rooms prior to decommissioning. There is also a reduction in the temperatures in the immediate neighborhood of the waste canisters. The reduction in the accumulated thermal output of the waste is expected to be small. Ventilation cannot be used to significantly reduce the long-term problems caused by thermal expansion and uplift. This conclusion is predicated upon a 5-yr ventilation period for HLW and a 25-yr ventilation period for spent fuel.

2.1.7 Other Factors

The diameter and length of the canister, and the depth of burial will have an influence on the local temperature distribution around a canister. Of these, the depth of burial is the most significant. The depth of burial is usually determined by criteria on allowable levels of radiation in the storage room.

The structural stability of the floor of the storage room can be strongly influenced by a reduction in the burial depth. This could result in buckling of the floor and thus hinder retrievability. A greater burial depth would improve performance. However, too large a burial depth would create difficulties due to the placement of a long steel sleeve in the emplacement hole. This might necessitate an increase in the height of the storage room.

For a given thermal output, the diameter of the waste canister can have a significant effect on the local temperatures.

This point is illustrated in Fig. 2.1-6 for a 6-in. diameter canister (Ref. 1). The salt temperatures for a 12-in. diameter canister will be near the values given in Fig. 2.1-6 at distances greater than 6 in. (Ref. 1). It can be seen that the temperatures at the canister surface are up to 100°F higher for the 6-in. diameter canister. These higher temperatures, however, extend only over a short distance (about 3 inches).

R-38893

Source: Ref. 1

Figure 2.1-6 Salt Temperature vs Distance from Center of Waste Package, Midplane

Differences in the local temperature distribution are important only if they affect the integrity of the waste package. The mechanisms that can affect package integrity and their temperature dependence are discussed in Chapters 3 and 4.

2.2 EXPECTED TEMPERATURE HISTORY

The temperature history for nuclear waste repositories has been extensively studied by DOE. The assumptions and the parameters used have varied considerably but have encompassed a range of data that could reasonably be expected to prevail. Therefore, while direct comparisons of the results are not possible, the data does indicate a likely range of behavior and enables bounds to be established.

The thermal analysis has been performed at three levels of detail.

- Local analysis in the immediate vicinity of a waste canister
- Near-field analysis which includes the floor, roof and pillars of the storage room area
- Far-field analysis which includes the overall repository.

The local temperatures are required to assess the retrievability of the waste canister and any potential damage to the waste form or waste package. The near-field temperatures determine the structural stability of the pillars and storage room area. The principal effects are closure of the storage room, and spalling of rock from the roof. Far-field temperature analysis is used as input to examine thermal expansion

effects in the overlying rock formation, increased fracturing of the rock, heating of aquifers, and surface displacements.

The temperature within a nuclear waste repository may be determined by several methods, with some variation in both cost and precision. These methods include finite element, finite difference, or analytic techniques.

A precise determination of the local temperature distribution will generally require three-dimensional analysis. This is needed in order to include the presence of other waste canisters and the effect of ventilation. It is also possible to determine local temperatures using an axisymmetric two-dimensional analysis about a single canister. It is difficult to include the effect of ventilation; to date axisymmetric solutions have not been used for a ventilated repository.

Two-dimensional solutions are considered appropriate for determining the near-field temperatures in the depository (Refs. 7 and 9). The two-dimensional solution represents a row of canisters as a volume source with the waste equally distributed along the row. Temperatures in the salt are assumed not to vary along the direction parallel to the canister row. This analysis will underestimate the temperatures near the waste package. For depositories in shale or crystalline rock, which have lower thermal conductivity, the error in two-dimensional prediction of local temperature will be significantly increased. It is essential in these cases to evaluate local temperatures with a three-dimensional thermal analysis.

Two-dimensional solutions are also quite adequate for determining temperatures over the whole repository area, for example, to determine surface uplift due to thermal expansion. In this type of analysis the waste region can be represented

as a cylindrical volume source. The thickness of the cylindrical region can be taken to be the height of the waste canister. It would also be appropriate to represent the waste region as a flat disc. Temperature is assumed to vary only in the axial and radial directions, with symmetry about the axis of the disc.

2.2.1 Predicted Local Temperatures

The available literature was reviewed to determine near-canister thermal data for bedded salt. One study, using canisters with an initial power of 5 kW, gave results obtained from three-dimensional analyses of ventilated repositories (Ref. 7). The storage room in this study had an 18-ft x 18-ft cross-sectional area and was 558 ft in length. Canisters were located 18 ft apart and the thermal load was 158 kW/acre. The analysis predicted that the peak temperature rise near the waste canister would be about 187°F, occurring five years after emplacement. Values were not given for the unventilated repository. The canister power assumed in this study is higher than is currently contemplated for commercial HLW canisters.

The local temperatures in an unventilated repository for both HLW and spent fuel were reported in Ref. 1. The values for HLW are shown in Fig. 2.1-6 and the values for spent fuel in Fig. 2.2-1. The spent fuel estimates were obtained in Ref. 1 by scaling Fig. 2.1-6 so that the thermal output of the HLW canister was reduced to that of a spent fuel canister. The dotted vertical line in Fig. 2.1-6 shows the estimated location of the sleeve and solid salt interface in retrieval emplacement of a spent fuel assembly. The estimated location of the sleeve and solid salt interface for HLW burial is 0.75 ft from the center of the canister. The peak temperature rise in salt for HLW occurs at about 20 years and is 430°F.

Source: Ref.1

Figure 2.2-1 Salt Temperature vs Distance from Center of Waste Package, Midplane

The peak temperature rise in salt for spent fuel also occurs at about 20 years and is 72°F.

The extremely low temperature rise for spent fuel is directly related to the reduced thermal loading relative to HLW. It is not believed that any detrimental local effects would occur for such a low temperature rise. Discussion of temperature related local effects is given in Chapters 3 and 4.

The temperature rise and thermal load in the above examples are directly proportional to the thermal output, for a constant spacing of canisters. Therefore, it is possible to predict local temperatures for other scenarios. For example, for a repository with 1.74 kW canisters and a 100 kW/acre thermal load, the temperature rises are obtained by multiplying the values given in Fig. 2.1-6 by 0.543.

Temperatures in the depository area for other rock types have not been determined in detail, and further work is required. The lower thermal conductivity expected for shale and crystalline rocks implies that local temperatures will exceed those predicted for bedded salt. It may be necessary, therefore, to consider reducing the power per canister.

2.2.2 Predicted Near-Field Temperatures

Studies have been conducted using the HEATING5 code (Ref. 18) to determine temperatures around a salt depository resulting from burial of high-level and spent fuel waste canisters. Two depository geometries incorporating 18-ft wide rooms were used, corresponding to extraction ratios of 30 percent and 20 percent. Two ventilation cases were considered, that of no ventilation and of ventilation for 5 or 25 years. These analyses and the results obtained are discussed in Volume 4.

2.2.3 Predicted Far-Field Temperatures

Temperature contours in the rock surrounding the repository were simulated with a two-dimensional axisymmetric model. The geometry used in the thermal simulation is illustrated in Fig. 2.2-2. The region considered is a large cylinder extending from ground level to a depth of 9000 ft and

Figure 2.2-2 Model Geometry for Far-Field Temperature Analysis

and with a 9600-ft radius. The central portion of the cylinder contains bedded salt and the waste region, while the top 400 ft and bottom 5000 ft contain shale. The waste is assumed to lie in a disc with a radius of 3300 ft and a height that depends on waste form: 8 ft for HLW and 13 ft for spent fuel. The top of the disc is 2000 ft below ground level.

The thermal properties of the various materials are summarized in Table 2.2-1. The values chosen were based on

TABLE 2.2-1
THERMAL PROPERTIES OF THE MEDIA

Parameter	Shale (Ref. 19)	Salt and Waste Region (Ref. 16)
Horizontal Conductivity (Btu/hr-ft ^{°F})	2.4	2.2
Vertical Conductivity (Btu/hr-ft ^{°F})	1.2	2.0
Density (lb/ft ³)	125	135
Specific Heat (Btu/lb-°F)	0.16	0.21

the references indicated. The thermal properties of the depository are assumed to be the same as the salt since this region contains approximately 2000 times as much salt as waste. The method by which the value of the vertical conductivity of the salt was determined is discussed in detail in Volume 4.

The only heat transfer mechanism considered is conduction. Because the thermal properties of the materials are taken to be independent of temperature, the heat transfer problem is linear. Consequently, the geothermal gradient as an initial condition need not be explicitly included in the model. Furthermore, the computed temperature rises in the rock mass will be directly proportional to the thermal output of the waste region. The initial thermal loadings are assumed to be 100 kW/acre for HLW with U and Pu removal and 50 kW/acre for spent fuel. The corresponding thermal energy densities for the waste regions are 8500 Btu/hr-ft³ for HLW and 2600 Btu/hr-ft³ for spent fuel. Adiabatic boundary conditions were

were imposed at the sides and bottom of the model region. The temperature at the top of the region was fixed at 70°F.

Figures 2.2-3 and 2.2-4 show the temperature rise contours for HLW and spent fuel at the time of maximum uplift due to thermal expansion for the two waste forms. An upper bound for the surface uplift can be roughly estimated using the following simple equation:

$$U = \alpha \int_0^{9000} \Delta T(0, z) dz \quad (2.2-1)$$

where,

- U is the estimated uplift at the surface at the center of the depository (r=0) (ft)
- α is the coefficient of linear expansion for salt (2.2×10^{-5} in/in/°F)
- $\Delta T(r, z)$ is the temperature rise (°F) at depth z(ft) and radial distance r (ft).

The estimated peak uplift is 2 ft at 250 years after emplacement for HLW and 3 ft at 2500 years after emplacement for spent fuel. The calculated uplift is directly proportional to the thermal load. More precise calculations which take into account the changing stress conditions in the rock would somewhat reduce these values. It should be noted that the effect of mine closure and subsidence will reduce the overall uplift at the surface. This is discussed in Appendix B.

Figures 2.2-5 and 2.2-6 show the temperature rises at various radial distances from the center of the depository at a depth of 2000 ft. The temperatures in the depository peak within 50 years for both waste forms; however, the

Figure 2.2-3 Temperature Rise Contours for a
HLW Repository at 250 Years, 100 kW/acre

temperatures of the salt several hundred feet from the depository edge continue to rise for several thousand years. The magnitude of this rise decreases sharply with distance from the depository edge.

The peak temperature rise in a shaft located 1200 ft from the edge of the storage rooms is on the order of 10°F (5.5°C). This distance from the storage rooms to the shaft is similar to that given by the Office of Waste Isolation (OWI)

Figure 2.2-4 Temperature Rise Contours for a Spent Fuel Repository at 2500 Years, 50 kW/acre

in their conceptual design for a repository in bedded salt (Ref. 20). No detrimental effects to the shaft are anticipated from such a small rise in temperature.

2.3 EFFECTS OF RADIATION ON ROCK

The radiation emitted from high-level solid waste or spent fuel can interact with the surrounding geologic medium. It is almost entirely in the form of gamma radiation

Figure 2.2-5 Temperature Rise at Repository Level: High Level Waste

Figure 2.2-6 Temperature Rise at Repository Level: Spent Fuel

from decay of fission products, and fast neutrons from spontaneous fission of the actinide elements. Other types of radiation such as alpha and beta particles are short-ranged and do not escape the waste package.

The intensity of radiation reaching a given point in the rock near a canister depends on the age of the waste, the form (i.e., HLW or spent fuel), the shielding and geometric characteristics of the package (e.g., the sleeve thickness), and the distance from the surface of the waste. In general, the shielding characteristics of salt are similar to concrete -- i.e., similar density and average atomic number.

2.3.1 Expected Dose and Dose Rate

Figure 2.3-1 illustrates the effect of waste age on dose rate in salt for three different distances from the canister centerline (Ref. 21). Note the rapid drop-off in dose rate with both time and distance. These curves are for a 5-kW source, but may be linearly scaled for other power levels. Figure 2.3-2 gives the accumulated dose integrated over time for the same conditions as apply to Fig. 2.3-1. After about 20 years subsequent to burial the increase in accumulated dose with time is not appreciable.

Figure 2.3-3 gives more detail on the dependence of accumulated dose on distance for 5-kW canisters, again from Ref. 21. Although this figure applies to a 6-in diameter canister, the dose in salt at the canister/salt interface for a 12-in. diameter canister can be obtained, to a good approximation, by using the dose at a 6-in. (15 cm) distance from the center of the canister. This gives about 5×10^{10} rad for a 5-kW canister at 100 yr after burial, or about 3×10^{10} rad scaled to a 3.2-kW canister. The doses in Ref. 21 are

Source: Ref. 21

Figure 2.3-1 Variation in Dose Rate at the Canister/Salt Interface with Time

Figure 2.3-2 Accumulated Dose in Salt at the Canister/Salt Interface

Source: Ref. 21

Figure 2.3-3 Variation in Accumulated Dose with Distance from the Canister Centerline

consistent with more recent calculations from Jenks (Ref. 1) presented in Table 2.1-1 for a 12-in. diameter, 3.2-kW HLW package and for spent fuel assemblies at lower power. Table 2.1-1 gives canister surface dose rates of 8.8×10^4 rem/hr for both 10-yr old spent fuel and HLW.

Doses for various HLW reprocessing options are very similar for the same irradiation history; although the actinide content of the various recycle schemes shown in Table 2.1-1 is different, the fission product contents are the same, and it is the fission products that contribute the preponderance of the gamma radiation external to the waste package. The neutron dose rates are many orders of magnitude below gamma dose rates and can, therefore, be neglected. Moreover, because the neutron flux at the canister surface is low, of the order of 10^5 neutrons/cm²-sec, activation of salt constituents such as chlorine is insignificant. Calculations indicate that induced salt activities are roughly 10 orders of magnitude less than the fission product activities in a canister at burial.

Based upon radiation effects data to be presented in subsequent sections, the volume of salt that will be subjected to a significant radiation dose will be comparatively small, limited to the immediate region around the waste package. Integrated doses two orders of magnitude less than those occurring at the canister surface (i.e., about 3×10^8 rad) will produce negligible radiolytic and energy storage effects. Such dose is to be found at roughly 1.5 ft from the centerline of a 3.2-kW canister. The volume occupied by the region bounded by the canister and an annulus 1.5 ft from the canister centerline is only a few tenths of a percent of the total salt volume.

2.3.2 Radiolytic Effects

The presence of brine in the vicinity of a waste canister will cause the formation of a number of radiolysis products. The species formed will depend upon the composition, temperature, and pressure of the brine; the pressure will be determined, in part, by the degree to which the brine is encapsulated and gaseous products cannot escape. Radiolysis products include H_2 , O_2 , Cl_2 , Br_2 , ClO_3^- , BrO_3^- , ClO_2^- , ClO_2 , and HCl in unconfined brine and H_2 , O_2 , ClO_3^- and BrO_3^- in encapsulated brine. Chlorine gas will react radiologically to form HCl , and it is anticipated that the ClO_2 will decompose thermally. Jenks (Ref. 22) has concluded that the quantities of radiolysis products from unconfined brine are well below those associated with migrating, encapsulated brine.

In addition to radiolysis of brine, radiolysis could occur from irradiation of any moist air present near a canister, for example in crushed salt. Formation of HNO_3 and O_3 would then take place. It has been considered unlikely that ozone will accumulate because of its instability and extreme reactivity at elevated temperatures.

Although this section is devoted to radiolytic effects a discussion of the production of chemical species by other means -- i.e., hydrolysis and corrosion -- is included as well. The purpose is to offer a side-by-side comparison between radiolytic and non-radiolytic sources. Table 2.3-1 is a summary of the principal conclusions from Ref. 22 regarding the chemical species appearing in the vicinity of waste canisters due to radiolysis, hydrolysis, and corrosion.

For 2-kW canisters, as can be seen from Table 2.3-1, the rate of H_2 evolution is about 5 moles per year, assuming

TABLE 2.3-1
SPECIES APPEARING AROUND A WASTE CANISTER
AND MAXIMUM RATE OF APPEARANCE

T-2852

Species	Source	Max. Rate of Appearance (mole/yr)	Time of Maximum (yr)	Balancing Oxidized Species	Remarks
H ₂	Radiolysis product within encapsulated brine	4	<1	O ₂ , chlorates, bromates	Comparable rates for 2 and 5 kW canisters.
H ₂	Radiolysis of solution around canister	0.8 followed by 0.3	0.1 0.5	O ₂ , Cl ₂ , Br ₂ , ClO ₂ , ClO ₃ ⁻ , BrO ₃ ⁻	For 2 kW canisters insignificant period of time with 5 kW canisters because of rapid heat up
H ₂	Corrosion of canister	400	<1		Assumed brine inflow rate of 7 l/yr with all H ₂ O reacting with canister.
HCl	Hydrolysis of MgCl ₂	20	<1		Assume brine inflow rate of 7 l/yr, 3M MgCl ₂ within brine, and 50% hydrolysis of MgCl ₂
HNO ₃	Radiolysis of moist mixtures of N ₂ and O ₂	0.50	<0.1		Likely that all N ₂ will have been expelled at <0.1 yr after burial.
O ₂ and other oxidized species	Radiolysis				To balance radiolytic H ₂ .

the concentration of radiolytic H₂ in brine will not exceed 1 molar. This assumption, however, is based upon the principal of reverse migration of two-phase droplets away from waste canisters, which is of unknown veracity. The radiolytic H₂ evolution rate is very much less than that expected from corrosion of the canister.

The formation of corrosive HNO₃ is limited by the quantity of nitrogen available. It is considerably less than the amount of HCl produced by hydrolysis of MgCl₂, a reaction which proceeds to completion in brine at high temperatures if the HCl can move away from the MgCl₂. In Ref. 22 it is estimated that at least half the MgCl₂ will be hydrolyzed. The

radiolytic HCl evolution rate is very much less than that calculated for hydrolysis of MgCl_2 .

In addition to the chemical species formed by radiolysis and hydrolysis, HCl is expected to react with the steel canister to form gaseous hydrogen. The rate of corrosion may be limited by the amount of brine flowing into the canister region. A conservative assumption is that the corrosion reaction rate equals the water inflow rate. The maximum formation rates of HCl and H_2 by the hydrolysis and corrosion processes, respectively, given in Table 2.3-1 reflect this assumption and are, therefore, upper bounds. Based on this model, corrosion rates of the order of tens of mils per year are sufficient to cause a peak hydrogen formation rate of 400 moles per year. The corresponding peak HCl rate of appearance is 20 moles per year. Both HCl and H_2 formation rates were estimated in Ref. 22 for a 5-kW waste canister. The calculations account for brine inflow rates enhanced by fracture of salt. A more complete discussion of corrosion is found in Chapter 4.

Finally, H_2 is generated upon aqueous dissolution of the irradiated salt. Experimental results quoted in Ref. 23 showed that the amount of H_2 generated is 5.2×10^{-6} mole/cal. At 40 cal/g, the salt that dissolves to saturation in 1 ml of water would generate and release 1.7 cm^3 of H_2 at STP. It was also found that the irradiated salt may dissolve much more rapidly than unirradiated salt. Normally, there will be no occasion to introduce large quantities of water into the spaces around a waste can, and there will be no H_2 evolution hazard from aqueous dissolution of irradiated salt.

The formation of these various chemical products may lead to:

- Buildup of gas pressure if confined conditions are maintained
- The possible formation of explosive gaseous mixtures or chemicals
- Increased corrosion of the canister due to the presence of oxidizing agents.

The work that has been done to evaluate these problems is generally not conclusive, and recommendations are made to continue investigations, particularly in the form of in situ experiments. It is possible, however, to draw some tentative conclusions:

- The formation of radiolysis products makes only a negligible contribution to the potential problems of gas buildup and corrosion
- The volume of products formed is related to the dissolution of irradiated salt. The volume of irradiated salt is expected to be small (several cubic meters), and the available water for dissolution is also small (several tens of liters over the operating life of the repository)
- During repository ventilation, any gaseous products such as H_2 or HCl released into the rooms will be adequately diluted and carried away
- Confinement around the canister is limited due to the shallow depth of burial; it is probable that thermal stress effects will provide sufficient gas permeability to dissipate any gas pressures

- It is unlikely that explosive mixtures of hydrogen and oxygen will form unless a gas tight seal develops in which case an explosive mixture could collect below the plug. However, Jenks (Ref. 22) has concluded that neither ejection of the canister nor serious dispersal of radioactivity would result after the room has been backfilled
- Radiolytically formed, potentially explosive chlorates and perchlorates are not a hazard subsequent to backfill since insufficient energy could be released to disperse radioactivity. Additional work is required to determine the potential hazard prior to backfilling.

2.3.3 Stored Energy Considerations

A concern in salt repositories is whether gamma-ray energy emitted from waste canisters can be stored in the rock adjacent to the waste and released at some later time. Possible consequences could be either rapid release of thermal energy causing excessive temperatures, or release of mechanical energy sufficient to fracture the rock.

The following discussion is largely taken from Jenks and Bopp (Ref. 23) who showed that the maximum rate of formation of stored energy in salt in a waste repository will be 1.4×10^{-9} cal/g-rad, independent of temperature, dose rate (at $<10^8$ rad/hr), dose, and type of salt. This rate applies to temperatures below 145°C , where annealing is not appreciable. The maximum amount of stored energy that will accumulate in the salt adjacent to a waste canister under those conditions is given by the product of the maximum formation rate, 1.4×10^{-9} cal/g-rad, and the dose in the salt. The gamma doses from a 3.2-kW, 10 year old HLW canister in salt immediately adjacent

to a waste canister will be about 2.8×10^{10} rad, 3.1×10^{10} rad, and 4.3×10^{10} rad after 90, 1000, and 10^7 years of burial (Ref. 1). The corresponding values of stored energy are 39, 43, and 60 cal/g, respectively. Doses would be similar for a repository containing spent fuel or military waste for a given thermal output per canister.

Some annealing of defects in the salt will take place depending on the temperature and other factors. At temperatures above 150°C , thermally activated annealing will be the dominant process and can limit the accumulation of stored energy to negligible amounts. The rates of thermally activated annealing increase with temperature, but are independent of the amounts of stored energy in the irradiated salt.

The salt that is located within 6 to 7 in. of a HLW canister and receives significant gamma-ray doses will, for an unventilated repository, have maximum temperatures above 200°C , and the maxima will occur 10 to 20 years following the burial of 10-yr old wastes (see, for example, Fig. 2.1-6). The temperatures will exceed 150°C after 1 to 2 years of burial and will remain above 150°C for more than 50 years. Accordingly, energy storage in salt in a burial area can be negligible for more than 50 years following the burial of 10-year-old wastes because of annealing. These conclusions were drawn for a 183 kW/acre repository with 3.2-kW canisters at a 10-ft pitch. Temperatures for other repository designs will depend strongly on thermal load, canister spacing, canister power, and ventilation.

A conservative estimate of the hazards associated with stored energy from HLW can be made by ignoring thermal annealing and assuming a mechanism for energy release exists. With a 12-in. canister containing high-level waste, which at

burial was 10 years old and had a power output of 2.25 kW, Jenks and Bopp computed a maximum temperature rise from the release of stored energy after 55 years of burial in salt of about 130°C and 9°C near the edge of the canister and at 7 in. from the edge, respectively (Fig. 2.3-4). If the salt column undergoing these ΔT 's is 8 ft high and the overburden pressure is 2000 psi, the mechanical energy released ranges from about 10^4 cal to 10^5 cal, depending upon the rate of the release. For the maximum stored energy at 100 years, the respective values are about 1.3×10^4 cal and 2.4×10^5 cal. The larger amount results when the temperature rise is so rapid that no immediate expansion of the salt takes place; instead, the local pressure increases by an amount determined by the compressibility of the salt. The explosive effects of the 2.4×10^5 cal of mechanical energy would be practically negligible (4.9×10^5 cal corresponds to the heat of detonation of 1 lb of heavily confined TNT). The maximum amount of mechanical energy that would be released in the wastes within the 12-in. canister as a result of the release of the saturation amount of stored energy (<50 cal/g) would be about 0.8×10^5 cal. The sum of the explosive energies from the mechanical energy released in the wastes and in the surrounding salt would also be practically negligible.

The above model may be appropriate for spent fuel, since temperatures in the salt near single assemblies are likely to be lower than for canisters with thermal outputs between 2 and 5 kW. Hence, annealing would not be expected to take place.

If appreciable thermal expansion of the salt accompanies the transient temperature rise resulting from the sudden release of stored energy, the contraction of the salt upon cooling would leave some crevices and cracks in the temperature-affected salt, probably along crystal boundaries. These would

Source: Ref. 23

Figure 2.3-4 Maximum Stored Energy, Temperature Change, and Volume in Salt after 55 Years of Burial

disappear with time as the salt reconsolidated under the pressure of the overburden. Small amounts of brine, which might be located on the crystals' boundaries, would be free to move about through the temperature-affected region around the canister while the cracks remained open. The brine would be re-trapped during the reconsolidation. It is conceivable,

although unlikely, that the cracks would extend to the room above a canister and that some of the brine associated with the canister (<40 liters) would escape into the room.

Reference 23 concludes that no conditions that would promote a sudden release of stored energy in repository salt or in the contained waste are apparent other than rapid heating of the salt or waste to a few hundred degrees by a source other than the contained stored energy. No source of such external heat is known. However, even if a sudden release of all the stored energy in the waste within a canister and within the surrounding salt occurs in some unforeseen way, it was stated that there will be no serious adverse effects on waste containment, and safe operation of the repository will continue.

2.4 SUMMARY

The waste/rock interactions of concern to repository design are primarily due to heat produced by the buried waste. Effects of radiation, gamma or neutron, are secondary.

Local temperature distributions that affect potential damage to the waste package and retrievability require 3-D thermal analyses, knowledge of the waste and rock properties at elevated temperatures, and the heat transfer characteristics of the waste depository region including, for example, heat removal via ventilation. These calculations are the most difficult to perform accurately, although the state of the art is sufficiently well developed in thermal analysis to bound problem areas.

Near-field temperatures can be easily determined by 2-D code calculations, given the thermal load, ventilation,

and depository geometry parameters. Far-field analyses of the entire repository require an even simpler 2-D model, whose accuracy may depend most upon the anisotropic thermal properties of mixed rock layers.

In general it is concluded that thermal calculations can be performed reliably and accurately. This fact has frequently been directly verified by comparison to measured temperature distributions. However, care must be exercised to obtain realistic thermal parameters, because the effects of elevated temperatures and severe thermal gradients on the rock medium are very important in determining the integrity of the underground disposal scheme.

The effects of radiation on rock are not well established. Dose rates in rock, chiefly by gamma rays, are easily obtained as a function of time and distance from a waste canister. The types and quantities of chemical species produced by radiolysis of brine can only be guessed at the present time. Their effects on the waste package are even more speculative. From the work that has been performed in this area there should be further analysis with reference to:

- Buildup of gas pressure in a confined environment
- Formation of explosive gas mixtures or chemicals
- Corrosion of the steel sleeve protecting the canister
- Unknown interaction of radiolysis products with HLW following canister failure.

These problem areas have not been adequately resolved. It is believed, however, that hydrolysis and corrosion products are

a potentially far more serious problem with respect to gas buildup and corrosion than radiolytic products.

Stored energy in the rock formation has received considerable attention. Its consequences do not at all appear to be hazardous for HLW because of annealing and the improbability of a rapid energy release mechanism. Annealing is less applicable to spent fuel where lower temperatures prevail, but it is unlikely that spent fuel burial offers more problems from stored energy than HLW.

As indicated in the previous chapter, the most significant effects on rock properties caused by burying heat-generating waste in a geologic formation will occur in the vicinity of the waste package. The particular effects and their significance on emplacement, storage, and retrieval of the waste package are discussed in more detail in the remainder of this report. In addition to treating rock mechanics in the vicinity of the wastes this chapter discusses long-term displacements in the rock formation overlying the depository. The determination of depository structural design requirements is included in Volume 4.

The interaction between the nuclear waste and the rock formation includes:

- The change in the strength and deformability characteristics of the rock mass as a result of temperature and radiation effects
- The effect of rock deformation on the waste package.

The effect of temperature and radiation on the strength and deformability characteristics of the rock type can be examined independently of the waste package and emplacement configuration; the effects of rock deformation on the waste package, however, depend significantly upon the design of the waste package and the emplacement scheme.

3.1 STRENGTH AND DEFORMABILITY CHARACTERISTICS OF THE ROCK MASS

Strength of the Rock Mass - The strength of a rock mass depends on the characteristics of both the intact rock material and the discontinuities present within the mass. Intact rock material is generally considered to consist of a cohesive assemblage of minerals, and its strength properties are usually determined by laboratory testing of comparatively small samples. On this scale, the strength is usually observed to decrease with increase in specimen size, with a constant strength being achieved in specimens which are sufficiently large that the flaw distribution is unaffected by size. This maximum size will vary with rock type. Decreases in strength with a decrease in specimen size may also be caused by disturbances during sample preparation.

In summary, the intact rock material is that part of the rock mass considered to be physically continuous for design purposes. The strength properties of the discontinuities (i.e., macro-scale features such as joints and faults) must be determined separately, and these features, together with the rock material, constitute the rock mass.

Deformability of Rock Mass - In general terms, rock failure is merely a specified stage in the deformation history of an overloaded zone of rock, and the resulting macro-deformations which occur when the peak strength is reached should be considered as part of the deformation characteristics of the rock. In practical terms the prefailure behavior is generally moderately well-defined and is approximated by appropriate simplified constitutive models. This generally linear behavior (for stress levels well below the material strength) has resulted in the widespread use of the linear

elastic model for the purpose of stress and deformation prediction around underground openings. The linear elastic approach is less suitable when details of "failure" zones within the rock mass are to be determined -- i.e., zones in which the rock has been stressed beyond its peak strength resulting in large deformations.

An understanding of the complete deformation behavior of the rock mass allows the determination of the resulting stress field based on a knowledge of the loading conditions and the geometry of the underground opening. Comparison of calculated stresses with measured strengths indicates zones of possible failure, and this process may require the use of iterative, nonlinear modeling to obtain a complete solution. In the design of a depository in salt this approach must be modified to account for the nonlinear deformation of the salt (creep) and the additional effects of the significantly increased temperatures in the rock around the waste canister. Thus, linear modeling approximations are not valid under any circumstances.

Comparatively limited information on the complete stress-strain behavior of most rock materials is available. This is due to the general use of testing machines which cause catastrophic collapse of the specimen following the achievement of peak material strength. The influence of a large confining pressure, which does not occur in the laboratory, has a pronounced effect on the postpeak deformation characteristics of the rock material. There is a tendency not only to greater strength but also to increased ductility. These effects are very significant in relation to a depository pillar design where larger pillars may become virtually indestructible due to confinement of the central core. In the vicinity of the waste canister, however, the degree of confinement is less

certain, and the rock around the emplacement drill hole and at the floor level of the storage room may easily fail. Thus, any model used must define the rock strength (or failure criterion) in terms of the principal stresses to account for changing stress conditions.

The deformation behavior of the rock mass can be described in terms of the rock material characteristics and the discontinuity behavior. For the material around the waste package the discontinuity behavior is considered relatively insignificant. Further detailed treatment of the strength and deformability of rock masses is included in Volume 4. The factors that may modify these fundamental rock properties in the vicinity of the waste package are considered briefly in the following sections.

3.1.1 Influence of Time

The compressive strength of rocks usually increases with an increase in the rate of loading. At low loading rates (anticipated in the depository after emplacement) deformations greater than those observed in a conventional laboratory test are developed, and this will subsequently influence the developed stress field. The relative importance of time-dependent deformation (creep) on rock strength depends upon the rock type; some fine-grained sedimentary materials such as siltstones show a limited response, while rock salt demonstrates an extreme ability to creep. It is important that rock property data used for simulation and predictive models is determined under suitable loading rates, and that the model is validated against one or more observed in situ test cases.

3.1.2 Influence of Moisture

Most rock contains moisture ranging from less than one percent for some evaporites to over 35 percent for porous sandstones. The strength of the rock mass may be reduced by:

- Washing out of softer materials by flowing water
- Dissolution of the more soluble minerals
- Expansion or contraction on wetting and drying.

The most noticeable effect would be deterioration of rock surfaces; the contribution to repository deterioration is expected to be small. The effect of an increase in temperature on rocks with high moisture content may be much greater, however, and this is discussed below.

3.1.3 Influence of Temperature

Comparatively little work has been done on the effect of temperature on the compressive strength of rocks and further investigation may be warranted. Existing experimental information generally indicates that higher temperatures are associated with lower strength, although the magnitude of the effect is different for different rock types. For crystalline rocks the strength reduction will rarely approach 50 percent.

Laboratory tests have been conducted (Ref. 24) to determine the behavior of bedded salt at 20°C and 200°C. These tests indicated that the behavior of salt is only slightly dependent on the orientation of the sample, that is, parallel or perpendicular to the bedding planes. This conclusion may not be true, however, with samples from different salt deposits or

strata. The stress-strain curves determined for bedded salt are shown in Fig. 3.1-1. It can be seen that there is more strain per unit of stress in the 200°C test, and the salt exhibits marked nonelastic behavior. The values of elastic modulus, compressive strength, yield strength, and apparent elastic limit that were derived from this data are shown in Table 3.1-1. It is noted that the apparent decrease in compressive strength is quite small -- i.e., the rock strains without failure occurring. The yield strength and the apparent elastic limit are used to indicate the marked nonlinear deformation of the salt at elevated temperature.

Figure 3.1-1 Effect of Temperature on Compressive Strength and Deformability of Bedded Salt

TABLE 3.1-1
TYPICAL STRENGTH PARAMETERS FOR BEDDED SALT

Direction of Loading	Temperature °C (°F)	Compressive Strength (psi)	Yield* Strength (psi)	Apparent** Elastic Limit (psi)	Modulus of Elasticity (psi x 10 ⁶)
Parallel to Bedding	20 (68)	4200 ± 500	2500 ± 300	1900 ± 300	0.35 ± 0.06
	200 (392)	3900 ± 200	1600 ± 200	1400 ± 100	0.09 ± 0.01
Perpendicular to Bedding	20 (69)	4000 ± 400	2300 ± 300	1700 ± 200	0.36 ± 0.17
	200 (392)	3600 ± 100	1600 ± 100	1500 ± 150	0.11 ± 0.01

Source: Ref. 24

*Yield strength is defined as that stress which results from passing a line through to 0.02 percent strain, parallel to the elastic portion of the stress strain curve.

**Apparent elastic limit is defined as the point at which the rate of deformation is 50 percent greater than the initial rate.

The amount of creep strain (strain under constant load) in a salt core in which a cavity has been excavated has been assessed under various loads (Ref. 25). It was determined that the rate of strain and the total strain at any particular time increased with both temperature and applied load (see Fig. 3.1-2).

R-37990

Source: Ref. 25

Figure 3.1-2 Creep in Salt at Elevated Temperature

While the decrease in compressive strength with increasing temperature may cause the salt to fracture in the heated vicinity of the canister, this is not likely to occur, and it is thought that the increasing plastic behavior will predominate. This is due, in part to the lack of confinement in the upward direction toward the room.

A considerable amount of effort has been expended to develop a realistic creep law for bedded salt, and to define its behavior under applied load and increased temperature. Analytical and laboratory work should be thoroughly compared with in situ behavior to provide adequate verification for design purposes.

An additional problem associated with increased temperature is that of fracturing due to thermal expansion of contained water by increasing the pore pressure in the rock (decrepitation). Samples of bedded salt heated to temperatures of up to 400°C were reported by Bradshaw (Ref. 26). It was found that the salt fractured with considerable violence at temperatures of around 280°C. Table 3.1-2 shows the temperatures at which fracture occurred in bedded salt from several locations. The rate of heating reportedly had little effect on this phenomenon. After consideration of several possible mechanisms, it was concluded that the greatest single cause of fracturing was the pressure generated by expansion of water contained in the salt. It was further concluded by Bradshaw that, to prevent sudden fracture and water release, temperatures of the salt should be kept below 200°C. Jenks (Ref. 22), however, has utilized a 250°C criterion for decrepitation in his calculations of brine migration. Science Applications (Ref. 27) also has recommended a 250°C decrepitation temperature. A repository thermal design criterion that no

TABLE 3.1-2
FRACTURING TEMPERATURE OF BEDDED SALTS

LOCATION	NUMBER OF SAMPLES TESTED	FRACTURING TEMPERATURE (°C)
Hutchinson, Kansas	30	260-320
Lyons, Kansas	8	285-320
Fairport Harbor, Ohio	2	380
Retsof, New York	2	*
Detroit, Michigan	2	290
Cheshire, England	1	250

*Salt did not fracture up to 400° C.

more than 1 percent of the salt volume exceed 250°C was considered. It was stated (Ref. 27) that additional research into the consequences of local effects might eliminate the need for this criterion.

The extent of this decrepitation is linked to the degree of confinement of the salt. Thus, small samples would be expected to shatter completely, while larger samples may spall at the edges. For an unconfined sample, this spalling would continue progressively. For a confined or partially constrained sample, the extent of spalling would be related to the contained vapor pressure and the strength of the rock. It is considered unlikely that sufficient pressure would be generated to cause fracturing to any great depth in the rock; the rock in the vicinity of the canister, however, if heated to a high enough temperature, could fracture around the emplacement hole.

The increased temperatures surrounding a waste canister may also have an indirect effect on rock strength. Pockets of moisture within the salt tend to migrate in the direction of increasing temperatures. This brine migration combined with the increased solubility of the salt at higher temperatures could substantially reduce the strength of the rock near canisters. The high solubility of the chlorides in rock salt implies that the amount of fluid present in the salt will increase at higher temperatures. These effects are discussed at length in Ref. 28. There it is stated that "more than a few percent of fluid would very greatly constrain the thermal and mechanical stresses that could be tolerated for the interval of retrievability." There exists insufficient in situ data to either confirm or deny this potential effect.

3.1.4 Influence of Radiation

Comparatively little information exists on the information of radiation on the strength properties of rock. This pertains to both the allowable stored radiation energy (energy associated with lattice damage through displacement of atoms, which is released when the material is annealed), and the radiochemical effects (which can result in the decomposition of some crystalline solids). There is obviously a requirement for appropriate experimentation in which material is exposed to radiation at the estimated dose and ambient temperatures in the vicinity of the waste. The volume of material subjected to significant radiation dose within the repository will be comparatively small (less than 1.5 ft radius) since the dose rate decreases rapidly with distance from the canister surface. Thus, the radiation effect will be limited to the immediate region of the waste canister and will have little influence on the overall behavior of the rock mass in the vicinity of the depository.

In one experiment (Ref. 29) three limestone samples and one salt specimen were subjected to a radiation dose of 7.6×10^8 R of fast neutrons and gamma radiation at 70°C. At fixed levels of stress, the increase in deformation of irradiated specimens, as compared with the deformation of nonirradiated specimens, ranged from 30 to 240 percent for limestones (with the greatest changes occurring in the more coarsely crystalline specimens), and was 290 percent for rock salt. The compressive strength of the salt was found to decrease by about 45 percent.

The compressive strength, yield strength, apparent elastic limit, modulus of elasticity, and creep of irradiated and nonirradiated bedded salt in directions parallel and perpendicular to the bedding, at 20°C and at 200°C, has been measured (Ref. 24). The results are presented in Figs. 3.1-3, 3.1-4, and 3.1-5. Figure 3.1-3 shows bedded salt stress-strain curves for various irradiation levels up to 5×10^8 R at room temperature. Figure 3.1-4 gives similar results for a 200°C test environments. Figure 3.1-5 shows the effect of radiation on creep in salt. The data in the figures indicates that:

- The compressive strength of salt decreases with high gamma dose
- The modulus of elasticity increases for high gamma dose (the salt becomes more brittle).

The observed changes, however, are relatively small in comparison with the changes caused by the increase in temperature. Very little effect is noted until the radiation dose exceeds 10^8 roentgens, and the volume of salt that will be affected to this degree is quite small and close to the waste canister where the highest temperatures will occur

Figure 3.1-3 Effect of Irradiation on Strength and Deformation of Bedded Salt

Figure 3.1-4 Effect of Irradiation and Temperature on Strength and Deformation of Bedded Salt

initially. The loss in strength due to radiation is not increased with increased temperature. The tendency for the salt to become more brittle with radiation is not conclusively demonstrated, but the effect is far outweighed by the significant softening as the temperature increases. It is therefore concluded that radiation effects on the behavior of the rock around the waste canister are not significant.

The possibility that the density of the salt may change due to irradiation has not been determined.

3.1.5 Melting or Phase Change

Bedded salt usually contains several minor minerals with the halite. While the melting point of halite (800°C) is high enough that it will not melt from the heat around the

a) Force applied parallel to stratification
Constant load of 2500 psi at 20°C

b) Force applied perpendicular to plane of stratification
Constant load of 2500 psi at 20°C

Figure 3.1-5 CREEP IN IRRADIATED SALT

Source: Ref. 24

Figure 3.1-5 Creep in Irradiated Salt

waste canister, the possibility exists that thin layers of the other minerals could melt and possibly induce local structural failure. Carnallite is one such mineral, with a melting point between 160°C and 425°C depending on the mineral phase (Ref. 30). It is, therefore, possible that the heat around the canister may melt any carnallite present. Moreover, Stewart (Ref. 28) has shown that in complex salt systems containing appreciable divalent cations, the melting point may be decreased to as low as 350°C. The importance of local structural failures has not been assessed, but it may be of relevance to waste or fuel package retrieval.

3.2 EFFECT OF ROCK DEFORMATIONS

3.2.1 Thermal Expansion

The prediction of displacements toward the waste canister or into the storage room is an integral part of any non-linear analysis in which the deformation behavior of the rock is temperature dependent. That is, the net strain at a point at any given time is determined from the algebraic addition of the initial elastic strain, the creep strain, and the thermal strain. Depending on the stress conditions, this may result in a net "expansion" or a "contraction". For rock which does not creep, the thermal strains alone would result in less significant rock displacement.

Salt expands as the temperature increases, at a rate that will be a function of the temperature and the state of stress in the rock. Problems that could be caused by thermal expansion include fracturing the salt surrounding the canister, crushing the canister, and storage room floor heave.

If the rock is sufficiently confined during expansion, internal stressing can result in rock fracture. The slow rate of heating and the absence of confinement above the waste package indicate that this will not be a severe problem. Shear or tensile fracture may occur when a high thermal gradient is applied quickly, resulting in surface spalling; nonrecoverable expansion may also occur due to permanent microstructural expansion where the rate of heating is high. It has been determined (Ref. 31) that the rate of temperature rise must be less than $2^{\circ}\text{C}/\text{minute}$ in order to avoid nonrecoverable expansion in igneous rock; no comparable data has been determined for salt. This rate of heating is not likely to be exceeded in the depository. An analysis of the stress state around the waste canister under different conditions of confinement and temperature would provide additional information on the likelihood of rock fracture occurring.

Since the depository floor is confined in the horizontal direction, the salt must expand upward toward the storage room and inward around the steel sleeve and canister. One possible problem with salt expansion is that the strength of the steel sleeve or canister might be exceeded and the sleeve or canister crushed, making recovery of the canister difficult.

Another possible problem is that of floor uplift. The floor uplift measured in Project Salt Vault (Ref. 26) was 0.2 ft over a period of about 18 months. Only 16 percent of the total floor uplift was recovered after about 200 days following the power shutoff. Further data on possible floor heave is reported in Volume 4.

3.2.2 Pressure on the Waste Canister/Sleeve

The requirements for canister retrievability for time periods of up to 25 years dictate that a steel encasement sleeve be placed in the drill hole to protect the canister from damage by the surrounding rock. This steel sleeve must therefore be designed to withstand the imposed stresses generated as the temperature in the surrounding rock increases.

Two cases are considered; namely, the sleeve is placed tightly against the wall of the drillhole; and the sleeve is placed with either a space or a backfill material between the sleeve and the wall of the drillhole. In the first case, the sleeve must be designed for the total thermal stress; while in the second case some inward movement of the rock allows stress to dissipate. In addition to the thermal stress, additional stresses may be imposed as a result of changes in the stress state around the depository.

An axisymmetric finite element analysis method has been used to determine estimates of the radial sleeve loading and drillhole closure resulting from thermo/viscoelastic behavior of the salt (Ref. 32). This model allows initial elastic displacements to occur prior to simulating waste placement. It is used to model the two cases noted above. The model is appropriate for the WIPP site repository concept with respect to dimensions and depth below surface.

The thermo/viscoelastic analysis, assuming that the viscous behavior is time and stress dependent only, predicted a maximum drillhole surface pressure of approximately 3,000 psi near the base of the sleeve after six months of heating (5 kW power source) assuming that the drillhole is fixed against radial displacement (see Fig. 3.2-1). With the drillhole surface

Source: Ref. 32

Figure 3.2-1 Radial Stress and Temperature Rise at the Salt/Sleeve Interface

free to move radially, the radial displacement was predicted to be about 1.5 inches after 25 years of heating (see Fig. 3.2-2).

The axisymmetric model represents the drillhole area in detail, but may not accurately model stresses in the pillar. It is appropriate, however, for this particular problem. It also appears that the creep law used in Ref. 32 was based on experimental results at room temperature, and that the thermo-elastic and viscous behavior are decoupled. While decoupling is appropriate, the temperature in the rock will have a significant influence on the creep strains, and it is not clear that this has been properly considered. The results of using a

Source: Ref. 32

Figure 3.2-2 Unconstrained Radial Displacement Around the Canister-Thermo/Viscoelastic Analysis

creep model that is not temperature-dependent will be to underestimate the radial displacements. The effect on the radial stress is not immediately clear.

It is recommended that the work in question be reviewed in much more detail, or that an alternative analysis be conducted. The thermo/viscoelastic method reported in Volume 4 could, with some modifications, be adapted to do this.

The review indicates that high radial stresses may be generated if the steel sleeved is placed tightly against the rock. Among the design alternatives possible is use of a compressible backfill between the sleeve and the rock, to allow inward displacement to occur.

3.2.3 Movement of Canisters

It is possible that the waste canister could sink, rise, or tilt in the salt as it is heated, a result of differences in density between the canister and the salt or anomalies in the stress field. This situation would have a potential for the canister either breaching the repository room, sinking to some depth, or tilting to the point where canister retrieval would be difficult.

A finite element analysis was made (Ref. 32) of long-term upward movement of the waste canister using a coupled thermomechanical formulation for creeping viscous flow and heat transfer. Variable temperature and free expansion of the salt around the canister were assumed. Analyses were performed with the thermal conductivity and viscosity of the salt held constant and varied as functions of temperature.

Results indicated that the canister would initially sink as the surrounding salt begins to heat (see Fig. 3.2-3). A thermal convective cell would then form in the salt at some point, reversing the direction of the canister and causing slight upward movement. Finally, as the thermal power of the canister decays and the salt cools, the canister would again begin to slowly sink.

Reference 32 also indicates that long-term upward movement of canisters induced by a thermally driven convective cell is not of significant magnitude to present a possible breach of the room floor. From Fig. 3.2-3, if the initial downward velocity is held constant at 1.2×10^{-12} m/sec (rather than decreasing as shown), then in 30 years the canister would move 0.04 inches (0.1 cm). Thus, the displacement of the canister over long periods of time does not appear to constitute a problem.

Source: Ref. 32

Figure 3.2-3 Predicted Canister Displacement Rate

A similar analysis is given below without accounting for the buoyancy effects of the surrounding salt. Several simplifying assumptions were made that represented a worse case than would actually occur. These include:

- The salt can be represented as a viscous medium. In actuality, the salt behaves in a plastic manner at high temperatures. The viscous model would allow greater movements of the canister
- The canister surface can be represented by a sphere of the same radius as that of the actual cylinder. This assumption reduces the amount of upward drag forces that would occur along the length of the canister
- The temperature is constant at the maximum temperature to be expected in an actual repository
- The salt is free to expand in all directions, resulting in an assumed density decrease of six percent

between 68°F and 350°F. This results in a less dense salt than actually exists, which would allow greater movement.

Using these assumptions, Stokes' law can be used:

$$v = \frac{2(\rho_c - \rho_s)gr^2}{9\mu} \quad (3.2-1)$$

where

ρ_c = canister density

ρ_s = salt density

g = acceleration of gravity

r = canister radius

μ = viscosity

Strain rate is related to stress and viscosity
(Ref. 33) by

$$\dot{\epsilon} = \sigma/3\mu \quad (3.2-2)$$

where

$\dot{\epsilon}$ = strain rate (in/in/hr)

σ = stress (psi)

and the strain rate is related to temperature in the range 20°C to 200°C (Ref. 35) by:

$$\dot{\epsilon} = 0.39 \times 10^{-37} T^{9.5} \sigma^{3.0} t^{-0.70} \quad (3.2-3)$$

where

T = temperature ($^{\circ}\text{K}$)

t = time (hr)

Simplifying Eq. 3.2-3 by assuming stress and time are constant, yields:

$$\dot{\epsilon} = C_1 T^{9.5} \quad (3.2-4)$$

Combining Eqs. 3.2-2 and 3.2-4 gives

$$\mu = C_2 T^{-9.5} \quad (3.2-5)$$

A low value of salt viscosity at room temperature is assumed to be 1.44×10^{14} lb-sec/ft² (Ref. 35). The maximum temperature of the salt is assumed to be 450 $^{\circ}\text{K}$ (350 $^{\circ}\text{F}$). Then, using Eq. 3.2-5, the viscosity of the salt at 450 $^{\circ}\text{K}$ is found to be 2.88×10^{12} lb-sec/ft².

The density of salt at room temperature is assumed to be 135 lbf/ft³. At 350 $^{\circ}\text{F}$ the density would be six percent less, or 127 lbf/ft³.

Values for the weight and dimensions of a HLW waste canister without overpack at burial are given as (Ref. 36): weight of 3,500 lb; dimensions of 8 in. radius x 10 ft long; volume of 13.96 ft³; and density of 250 lbf/ft³.

Using these values in Eq. 3.2-1, the velocity of the canister is determined to be 4.27×10^{-12} ft/sec.

If the weight of the overpack (1,500 lbs) and a 1/2-inch thick steel sleeve with inside diameter of 20 inches

is considered, then the velocity of the canister would be 7.35×10^{-12} ft/sec.

In 30 years (a potential retrieval time) the canister would therefore sink 0.05 to 0.09 inches. This result is comparable to that previously determined (Ref. 32). Figure 3.2-4 shows the time it would take for the canister to sink 10 feet as a function of maximum temperature in the repository.

Figure 3.2-4 Time to Produce 10 Feet of Canister Displacement at Varying Temperatures

It is possible that the canister could tilt within the salt. This could be initiated by a slight offset from the vertical when the canister is emplaced. Further tilting

would continue due to the density difference, structural weak points in the salt, and the high temperatures. This situation could present problems if the canisters must be located and retrieved, but the magnitude of the movement is unlikely to be greater than that determined for vertical displacement. Problems could develop if canisters are retrieved by over-coring. This method of retrieval must allow sufficient tolerance to accommodate the possible displacement, which may be due to either physical or thermal misalignment.

It has been determined that neither the upward or downward movement due to the density difference between the canister and the salt would be of a significant magnitude. Movement within the retrieval period of 30 years would be less than 0.05 in. according to both studies described. Possible tilting of the canister is probably of the same order of magnitude.

3.2.4 Displacement in the Rock Formation Overlying the Depository

The displacements and stresses that will occur in the rock formations overlying the depository are of interest to assess the ground surface displacement history and to help determine the type of fracturing that may occur over the depository. The total displacements will be determined by subsidence due to creep in the pillars at the depository horizon and by thermal expansion. These strains will generally be in the opposite sense.

The total displacement history will also be a function of the depth of the depository and the area, since the creep rate is a function of stress cubed and will therefore be significantly increased at greater depths.

A numerical two-dimensional model for regional analysis of stresses and displacement is presented in Ref. 37 based on the displacement discontinuity method. It incorporates an empirical creep law for the depository horizon which is temperature-dependent and accounts for thermally induced stresses. The assumption was made that the overlying rock formations behave elastically, which is a necessary simplification of real rock behavior. The waste material is modeled as a line heat source. This model has the capability of modeling stresses and displacements near the depository for an array of storage rooms. Direct extension of the method to the study of a full-scale repository at the same level of detail presents difficulties in terms of computer storage and time requirements.

The model was used to review the stresses and displacements associated with a test scale repository consisting of 10 rooms, with a thermal load of 50 kW/acre. Two depths were used, 500 feet and 2,000 feet, and the analyses were made for creep and no-creep situations. For a repository at 2,000 feet, the maximum surface deformations were less than 0.2 ft and occurred as subsidence, at about 35 years after waste emplacement. At 100 years, the effect of thermal strains caused the surface to resume its original position, and after which thermal heave occurred. The limited size of the repository model causes it to underestimate the thermal and subsidence deformations and while the results are of interest, the data cannot be considered as an upper bound.

In order to determine regional effects the analysis was simplified (Ref. 37) by assuming that for long-term simulation the level of detail at the depository horizon could be reduced without influencing the far-field results. The model was therefore reduced to a thermoelastic analysis of a semi-infinite region with the heat sources distributed over a

horizontal planar area. While this is a major simplification, it does allow the regional effects to be examined and is considered appropriate.

An analysis of a HLW repository at a depth of 2,000 feet with an area of $3.6 \times 10^7 \text{ ft}^2$ was reported in Ref. 37, with an initial thermal load of 50 kW/acre. The displacement immediately above the center of the repository was shown to be about 1.6 feet at 100 years and to rise to a peak of about 3.7 feet after 1,000 years. This must be considered as an upper bound on the surface displacement as the model does not consider closure at the depository horizon. This could easily be shown to be comparable to the thermal effects. A more detailed review of this work (Ref. 37) is provided in Appendix A.

An alternative analysis (Ref. 38) has been used to evaluate the long-term response to thermal loading. This thermoelastic analysis compared the displacement for various thermal loadings. The results are shown in Fig. 3.2-5, for a 7,000-ft wide repository at a depth of 2,000 feet. It was concluded that the stratigraphy of the model had little effect on the results. The displacements shown in Fig. 3.2-5 are for various wastes at 1,000 years, at which point the peak values for spent fuel were noted. Values for high-level waste peaked at 200 years. These results compare reasonably well with those predicted by the previous work, although it is not clear whether the effects of creep strain were considered.

No work has been found which relates the predicted stresses with the extent of the rock fracturing, although the existence of tensile stresses is noted (Ref. 38). It is recommended that additional work be performed in this area. Some additional notes on subsidence mechanisms are presented in Appendix B.

Source: Ref. 38

Figure 3.2-5 Comparison of Surface Displacement for Various Thermal Loadings-Spent Fuel and High-Level Waste

3.3 SUMMARY

In this chapter the principal effects of the waste on the rock mass have been reviewed and the important consequences in terms of repository performance have been described. Potentially detrimental effects are:

- Fracture of the salt surrounding the canister. This may increase the quantity of brine available for corrosion of the waste package
- Crush of the waste package by the surrounding salt
- Heave of the storage room floor. This would substantially impede efforts to retrieve the waste canisters

- Movement of the waste package in the salt
- Displacement of the rock formation overlying the depository due to subsidence and thermal expansion. In the long term this could reduce the effectiveness of the repository to contain the waste.

In general, the state of the art in predicting the above effects is well established. However, the following points should be kept in mind:

- Rock property data used for simulation and predictive models should be determined under appropriate loading rates, and the models must be validated against one or more observed in situ cases. Important in this regard are the in situ salt mine experiments currently being carried out at Avery Island by the Department of Energy. Data is being collected on the material properties of the salt surrounding heated canisters. It is expected that these experiments will provide valuable data on corrosion, salt formation stresses, and displacements
- The effect of migration of dense brines on the strength of salt is not well understood. It is not clear, however, how a potential loss of strength near the waste package would adversely affect repository performance
- Although it is possible to estimate the deformations in the rock overlying the depository, it is not certain what the consequences of these deformations will be. The major cause for concern would be fracturing of rock which permitted water to intrude upon the salt formation. No adequate model currently

exists for predicting the degree of fracturing. It should be possible, however, to develop a conservative analysis based upon the extensive information available from mining experience.

The effects on the waste package and the rock mass can be mitigated by several design measures. A reduction in the thermal load and the thermal output per canister would control some of the temperature related effects. The waste canister can also be protected from the rock environment. The necessity for these measures depends in part on the requirements, if any, for retrievability of the waste canisters.

The waste canister, overpack, and the hole liner (steel sleeve) will be exposed to corrosion both from the inside and from the outside. While general surface corrosion effects will occur, they are not likely to be of sufficient magnitude to result in premature failure. Other mechanisms, however, such as pitting and stress-corrosion cracking, may result in rapid local degradation of the waste canister, overpack, and steel sleeve. Fabrication techniques, metallurgy, and surface conditions may contribute to corrosion problems in addition to environment. An excellent discussion of the problems of corrosion is found in Ref. 39. The problem of corrosion from within the waste canister is not considered in this section.

Corrosion in salt formations is common, as evidenced by the damage incurred to equipment in normal salt mining operations. The rate of corrosion will be significantly increased in a waste repository due to the high temperatures, the presence of radiation-produced chemical species, and the increased incidence of water from the migration of brine through the salt layers.

4.1 BRINE MIGRATION

4.1.1 Source of Brine

Brine in salt is found in inclusions ranging in size from 1/16 in. found in negative crystals to brine overflow

from large pockets with a volume in excess of 10^6 ft^3 (Ref. 40). Brine is more commonly found in smaller quantities at grain boundaries and in negative crystals, vugs, and shear zones. A random distribution in size of small brine inclusions was found throughout the salt at Lyons, Kansas (Ref. 26). Typical values of the moisture content for salt from various mines are indicated in Table 4.1-1.

TABLE 4.1-1
MOISTURE CONTENT OF SALT

LOCATION	MOISTURE CONTENT (%)
Detroit, Michigan	1.16**
Carey Salt Co., Kansas	0.048**
Watkins Glen, New York	0.035**
Retsof, New York	0.023**
Lyons Mine, Kansas	0.400*
Hutchinson Mine, Kansas	0.08-0.29*
Wiskey Island, Ohio	0.053**

*Ref. 41

**Ref. 42

No comparable data has been found for the New Mexico mines, but the moisture content is believed to be similar to the lower values quoted in Table 4.1-1. It should be noted that the moisture content of the salt at Lyons, Kansas is approximately one order of magnitude higher than that at several other locations. Thus, much of the investigative work relating to brine migration and corrosion that has been done to date, particularly with reference to Project Salt Vault, will tend to provide upper bound estimates for the problem.

4.1.2 Rate of Brine Migration

One of the results from the Project Salt Vault demonstration (Ref. 26) was the finding that brine-filled cavities tend to migrate toward a heat source. An interpretation of this phenomenon is attributed to the difference in solubilities of salt in brine between the warm and the cold sides of a brine cavity. Under the influence of a temperature gradient, salt ions move from the warm side of the cavity to the cold side where they are redeposited. The net effect is an apparent migration of the cavity in the direction of higher temperatures.

In the Salt Vault project theoretical analyses were performed by Bradshaw that modeled brine migration as a pure diffusion process. An important conclusion from this work was that the cavity migration rate was an increasing function of salt temperature and was directly proportional to the temperature gradient.

Supporting the theoretical studies were laboratory experiments with heated salt crystals containing brine cavities. Cavity positions were measured as a function of time for various crystal temperatures up to 240°C and temperature gradients up to 34°C per cm. These are typical of the values expected in the vicinity of a waste canister. The intent of the laboratory experiments was to validate the diffusion model. Despite test difficulties, the experimental data did agree with the diffusion model for temperatures up to 200°C . This comparison is illustrated in Fig. 4.1-1, which plots the cavity migration rate per unit temperature gradient versus salt temperature. The data points represent the laboratory test results; the dashed line depicts Bradshaw's theoretical model.

Bradshaw used his diffusion model to predict brine inflow rates in the Salt Vault demonstration. The calculations

Source: Ref. 22

Figure 4.1-1 Cavity Migration Rate per Unit Temperature Gradient

utilized estimates of the spatial and temporal temperature distributions around a waste canister (see Fig. 4.1-2) and assumed a 0.5 volume percent water in the salt. This work indicated that peak inflow would occur at about 1 year after emplacement for a "typical" facility (6-in. diameter canister with a 1.6 kW heat source and a 95-ft canister spacing); the peak inflow rate per hole was computed to rank between 200 ml and 1 liter per year. Figure 4.1-3 shows the time dependence of calculated rates. The integrated flow over a 20 to 30 year time period was in the range of 2 to 10 liters.

Measurements of collected condensate during project Salt Vault required corrections for off-gas water removal and

Source: Ref. 22

Figure 4.1-2 Temperature Distribution Around a Waste Canister Used in Ref. 26

inflow between collection periods. Lower and upper bounds on the daily rates measured 0.2 and 3.0 ml/day, approximately the same as calculated.

Reference 22 utilized the Salt Vault laboratory brine migration data to estimate the brine inflow rate for a series of hypothetical waste canister systems. In computing brine inflows, a more conservative (higher) estimate of the migration

Source: Ref. 26

Figure 4.1-3 Brine Cavity Migration Rates for a Six Inch Diameter Waste Canister

rate per unit temperature gradient was used -- the solid curve appearing in Fig. 4.1-1 -- that exceeds Bradshaw's theoretical curve at higher temperatures. Reference 22 also accounted for salt fracture (decrepitation) at temperatures above 250°C , a mechanism assumed to release brine to the canister region at a radius greater than the actual emplacement hole.

Jenk's results for 2-kW and 5-kW canisters were in the range of 15 to 50 liters total inflow at 50 years, somewhat higher than Bradshaw's values for the same time period, as expected from the conservative model. An exact comparison between the Bradshaw's and Jenks' results is difficult because

the configurations and thermal power assumed by the two researchers were not the same. The Jenks interpretation of the Salt Vault data does appear to represent, however, the best estimate available for brine migration rates.

The work of Anthony and Cline (Ref. 43) has raised a question whether reverse migration of vapor liquid-droplets down a temperature gradient is possible. This phenomenon could act to transport radioactive products away from the waste region into the salt formation. However, in the opinion of Baar (Ref. 40) bi-phase reverse migration of droplets is still unproven.

While data on migration of brine has been principally derived from single NaCl crystal experiments, a real bedded salt structure consists of aggregates of small crystals. There is no direct information on movement of brine inclusions at crystal boundaries, and it is currently not clear whether migration rates are decreased or enhanced at such boundaries. OWI has initiated such studies (Ref. 1) in the laboratory on small samples of compressed salt. In addition in situ underground tests at Avery Island with electrical heaters are planned to obtain brine migration data in a more realistic environment (Ref. 8).

4.2 MECHANISMS OF CORROSION

4.2.1 Causes of Corrosion

Corrosion of the waste canister, overpack, and hole liner can occur when moisture and corrosive chemical products are present around the emplacement hole, especially at elevated temperatures. These conditions are present when brine inclusions migrate toward the canister.

The physical chemistry of brines at high temperatures in the vicinity of the waste is complex. It is of interest to know whether a vapor phase can form, because the presence of a vapor phase is likely to enhance corrosion of the canister. Phase diagrams and vapor pressure curves are available for a number of brine systems of different composition (see Ref. 28). The state of the art in this area, however, is not sufficiently well developed, nor is the temperature and pressure environment well enough known, to be able to determine which phases exist. Stewart in Ref. 28 has inferred that trapped brines reaching the waste region may not release H_2O as steam, but in fact are hygroscopic and remove H_2O from the air. Further study of these phenomena is warranted.

Water vapor, if formed in the vicinity of the waste package, is likely to rise due to diffusion or buoyance effects. As it reaches a cooler area away from the waste it may condense on either the salt or the canister sleeve. Field tests in Project Salt Vault indicated that water did condense on the upper, cooler regions above the waste containers, and corrosion of metal was more severe in this area (Ref. 26).

Corrosion may be either chemical or electrochemical. Chemical corrosion will occur, for example, as a result of the interaction of stainless steel with hydrochloric acid or chlorine gas. Electrochemical corrosion involving a single metal would occur due to small potential differences arising from minor variations in composition, surface finish, deposits or inclusions, and stress. Corrosive penetration results in pitting and roughening. High salinity promotes electrochemical corrosion. It has been stated (Ref. 22) that both hydrogen and hydroxyl ions will be formed by dissolution reactions of irradiated salt. An excess of hydrogen ions increases the corrosion rate, while an excess of hydroxyl ions depresses the corrosion rate by forming a neutral metal hydroxide coating.

Gaseous oxygen dissolved in water will promote corrosion. At the temperatures expected near the canister (230°F or greater) the amount of dissolved oxygen is negligible. Factors stimulating corrosion that can be controlled are:

- Nonuniformity in the metal
- Use of dissimilar metals
- Increased stress in the metal.

Thus, polished surfaces resist corrosion much better than rough surfaces, and variations in surface finish may have a greater influence than ordinary variations in chemical composition. An initial rust layer may accelerate or inhibit corrosion and pitting after emplacement.

The effect of corrosion on a metal under stress can be much more severe than under ordinary conditions. This may be fatigue stress, or internal stress due to local overheating. The latter may occur if the waste glass-matrix is melted in place in the canister, or by welding of joints in the case of the steel hole liner which may be placed in sections.

With stainless steels such as type 304 containing nickel and chromium, corrosion resistance can be seriously impaired by welding or improper heat treatment, and the metal becomes susceptible to intercrystalline corrosion. These steels resist corrosion by forming a self-repairing oxide film, but halide ions may penetrate this film causing severe pitting or stress-corrosion cracking.

For metals exposed to brine, corrosion is a minimum when there is a pH value of about 8.5. Unfortunately, actual brines have value of pH in the vicinity of 5 to 6 and become even more acidic as the temperature increases. Control of

corrosion by attempting to adjust the local pH near a canister is thus a possible, but unlikely method.

The most satisfactory method of inhibiting corrosion would be to provide a protective coating to the steel in order to prevent contact with the corrosive fluid or vapor. This may include a metal sheath (lead, nickel, or copper), a ceramic coating, or a protective paint.

4.2.2 Corrosion Resistance of Steels

Some experimental work has been done to evaluate the corrosion resistance of steels (Ref. 26) which were exposed to various salt chemicals for 30 days at temperatures of 300°C (572°F) and 500°C (932°F) (more than the maximum expected temperature). The steels evaluated were stainless steel (types 304L and 310), Hastelloy C, Haynes Alloy No. 25, Ti-45A, and carbon steel. Corrosive agents were mixtures of salt, magnesium chloride, calcium sulphate (anhydrite), and water. The data indicated that:

- Corrosion rates for the alloy steels were about five times less than that for carbon steel
- Corrosion rates generally increased by 25 percent from 300°C to 500°C
- Corrosion rates for alloy steels ranged from 0.1 to 0.8 mils/year (less than one-thousandth of an inch per year)
- Mixtures of salt and magnesium chloride were the most corrosive.

It was concluded from this study that type 304L stainless steel is the most satisfactory material.

Using a corrosion rate one order of magnitude greater than that observed experimentally (i.e., one hundredth of an inch per year), a protective sleeve one-inch thick could reasonably be expected to provide protection for the period over which retrievability may be considered. This rate of corrosion is roughly the same as the upper bound computed in Ref. 22 and discussed earlier in Section 2.3.2.

In Project Salt Vault, the surface of the simulated canister and heaters was maintained at temperatures well above the boiling point of brine. These components were superficially in good condition, but showed extensive stress corrosion cracking to a depth of one-half of the wall thickness in a 6-mm case of 304L stainless steel. Much more severe was the corrosion of the stainless steel conduit feeding the heating elements. The worse corrosion was at a position surmised to be where condensation of the steam was occurring. However, the 304L stainless steel lower tier sections were essentially unaffected, although they were spotted with evaporated salt from the bursting brine cavities. The canisters made of carbon steel were very rusty on the outside, but showed no sign of penetration.

A number of thermocouple failures occurred during Project Salt Vault as a result of scaling and corrosion of the 304L stainless steel sheet. When the large heaters (304L stainless steel) were removed from the structure, they were also heavily scaled, with the greatest corrosion occurring on those heaters exposed to the highest temperatures (Ref. 26).

4.3 SUMMARY

The migration of brine inclusions is a potentially serious problem in salt repositories containing HLW. Its

consequences are, principally, enhanced corrosion of canisters or sleeves and the generation of hydrogen gas. Considerable data on this subject does exist, much of which was obtained from Project Salt Vault. The ability to calculate the thermal environment of a waste canister is also well developed. However, there are remaining major uncertainties in predicting migration rates. One is the wide variation in brine content at different locations; another is the effect of crystal boundaries. Currently planned laboratory and in situ experiments may help to clarify the brine migration picture. It must be emphasized that brine influx is less of a problem for canisters of spent fuel and military waste, due mainly to the smaller thermal gradients and lower temperatures near the canisters. This conclusion is based on typical values of thermal output per canister as given in Section 2.1.

Corrosion of steel canisters or sleeves by brine at elevated temperatures is an area in which there is some confidence because of the available test data. It is desirable, however, that corrosion experiments be conducted with simulated brine that matches the composition of actual brines, or is bounded by a worst case composition. The best methods of reducing corrosion problems to ensure retrievability have not been systematically investigated; they include coatings of various types, air gaps, and use of very thick sleeves.

The generation of H_2 as a hazard has been dismissed in the literature. It has been concluded that both the possibility for formation of an explosive mixture with air near the canister or in the room, and the buildup of pressure near the canister can be counteracted by appropriate design or operating methods. While it is likely that the above conclusion is true, insufficient data is at hand to prove those assertions in a realistic environment, nor have the requisite countermeasures been defined.

5.1 SUMMARY

In a salt repository there will be thermal, radiolytic, chemical, and physical interactions between the buried waste in the form of HLW or spent fuel and the geologic medium. Local interactions could take place in the immediate vicinity of the waste package and influence the design or operation of the repository. These include:

- Gamma radiation from the waste package can be absorbed directly by the salt and result in the accumulation of stored energy
- Gamma radiation can be absorbed in brine pockets, leading to the production of hydrogen gas and various oxidizing chemical species
- The thermal output from the waste package causes elevated temperatures and temperature gradients in the vicinity of the burial hole, both of which contribute to the migration of brine pockets toward the waste heat source
- The elevated temperatures near the waste package may cause decrepitation of brine inclusions. This will accelerate the movement of brine towards the waste package
- Chemical species in the brine, particularly hydrochloric acid from hydrolysis of magnesium chloride, can corrode metallic components of the waste package such as steel sleeves or waste canisters. As a consequence:

Hydrogen gas is evolved as a product of the corrosion process, which along with HCl can migrate upwards to the storage room

The waste matrix is more rapidly exposed to the salt/brine environment and subsequent to corrosion may combine in complex and as yet unknown ways with the salt/brine medium

- The thermal output from the waste creates thermal stresses and enhances creep in the salt surrounding the waste package, with translation or tilting of canisters a possible result.

Interactions in the storage room and pillars that could influence the design or operation of the repository are:

- Increased temperatures can cause buckling of the storage room floor and rock falls from the storage room ceiling
- Increased temperatures may lead to unacceptable closure rates for the storage room and could result in pillar failure
- The rate and degree of subsidence may be increased due to the higher temperatures in the depository region.

Far-field interactions include displacements in the rock overlying the depository caused by thermal expansion and subsidence.

It is very important that unresolved waste/rock interactions, which pertain only to the operating phase of the

repository, not be confused with the issues of long-term confinement of wastes. Only a few of the interactions described could have a significant effect on the integrity of the repository following decommissioning. Appropriate design measures can reduce potential effects. Those effects directly related to long-term risk are:

- Chemical and radiolytic reactions between the dense brines and the waste matrix (or spent fuel elements) following penetration of the protective steel sleeve and metal canister. This could result in an increase in the predicted leaching rate or transport properties of the waste form
- Structural failure of the depository excavation which could prevent proper decommissioning and lead to fracturing of the rock layers surrounding the depository. This can be prevented by appropriate repository design, as discussed in detail in Volume 4
- Thermal expansion and subsidence which could fracture the rock layers overlying the depository as well as increase the zone of fractured rock immediately adjacent to the storage room openings. These effects can be lessened by reducing the repository thermal load and by properly backfilling the depository, as discussed in Volume 5.

It must be noted that the steel sleeve and canister are not considered to be long-term containment barriers. Therefore, long-term risk does not depend on maintaining their integrity. In the past, Department of Energy plans have relied on the geologic medium to contain the wastes.

5.2 CONCLUSIONS

Based on the current study, the following conclusions can be drawn:

- Temperature and gamma-ray dose distributions can be adequately predicted by current analytical techniques, if the necessary parameters are known
- The formation of radiolysis products has little effect on the corrosion of the waste package compared to hydrolysis products
- Stored energy in the rock formation from gamma-ray irradiation does not present a hazard when salt temperatures exceed 150°C (when annealing processes dominate)
- Sinking of the waste package is likely to be negligible
- Decrepitation of brine inclusions can easily be controlled by keeping the temperatures in salt below 250°C
- Any gaseous products such as HCl and H₂ released into the storage rooms will be adequately diluted and carried away by the ventilating air
- Buildup of gas pressure around the waste package is unlikely to occur. Due to the shallow depth of burial, thermal stress effects should provide sufficient gas permeability to dissipate any pressure
- Brine migration will be significantly less for canisters of spent fuel and military waste than for commercial HLW. This is due mainly to the smaller thermal gradients and lower temperatures near the waste package.

5.3 RECOMMENDATIONS

Based upon a study of the literature, certain areas have been identified as being potentially significant to the issues of retrievability, safety or containment. For some of the areas hazards are merely suspected, but insufficient data exist to either verify or deny their importance. It is recommended that the following areas receive additional attention:

- The relatively unstudied physical chemistry of dense brines containing many constituents in contact with canisters, sleeves, or waste forms. A wide variety of undesirable effects could be produced, including reduced melting points and rock strength, enhanced corrosion, and accelerated dissolution of the waste matrix
- Explosions due to the formation (via radiolysis) of unstable species such as perchlorates and chlorates
- Release of stored energy (deposited in salt by gamma radiation) for the case of buried spent fuel elements when salt temperatures are below annealing levels
- The formation of an explosive H_2 , O_2 mixture either in proximity to the waste canister or by diffusion and buoyancy effects in an unventilated storage room
- Determination of the process that limits the corrosion rate of the waste package, either the brine influx rate or the brine/metal chemical reaction rate
- Formation of a critical assembly of actinides at times after canister dissolution. This is highly speculative

- Formation of volatile chemical compounds at times after canister dissolution when fission products combine with chlorides and other active species in the brine
- Fracturing of the rock overlying the depository due to thermal expansion or subsidence.

APPENDIX A

NUMERICAL METHODS TO DETERMINE STRESSES AND DISPLACEMENTS ABOVE THE DEPOSITORY ZONE

A.1 INTRODUCTION

A technique is needed to predict stresses and displacements induced by the placement of heat emitting nuclear waste in underground excavations in salt and other rock formations. A finite element program has been used to study stress and deformation locally around a repository room and results are reported in Volume 4. However, this program probably cannot be economically applied to evaluate a whole repository.

An alternative approach (Ref. 37) describes a computer program, SALT2, designed to numerically model in two dimensions the regional temperature, displacement, and stress distributions around a repository. The SALT2 program appears to be a significant advance beyond the original SALT program (Ref. 26). Presented briefly in Ref. 37 are displacement results obtained from a three-dimensional thermoelastic analysis which ignored excavations and creep. Two previous papers are reviewed below to set the discussion of the SALT2 approach in perspective.

A.2 PREVIOUS WORK

The first paper (Ref. 26) described a three-dimensional analysis to examine the effect of point heat sources placed in

an infinite elastic medium with displacement discontinuity elements between the roof and floor along the mining plane. The analysis allows for creep, including the effect of temperature, in the salt pillars at the mining plane. Program SALT, developed from this analysis, is for two-dimensional plane strain only, and was used to model the Project Salt Vault observations. After many trials, a set of parameters was obtained which provided a reasonable match with the observed distribution of convergence through the study area over the time span modeled.

Factors affecting the applicability of SALT include:

- The effect of the ground surface on temperatures and stress is ignored
- The material (salt and rock) above and below the mining plane is assumed to be homogeneous and elastic. Creep occurs only at the mining plane
- The analysis is for two-dimensional plane strain
- Horizontal stresses in pillars are not explicitly calculated. The effect of lateral confinement on vertical creep rate is allowed for by a postulated formula.

The first is probably not too serious for the Project Salt Vault example where the length of the heated zone was only one-quarter of the depth below ground surface. For a full scale repository the effect of the ground surface must be included. The assumption of homogeneous elastic material above and below the mining plane is an essential feature of the program. Detailed modeling including creep deformation in the floor where the highest temperatures occur is not possible.

The authors applied program SALT to a longitudinal section of the Project Salt Vault layout. The layout is not very suitable for two-dimensional analysis, so the parameters obtained must be considered indicative only. The formula allowing for the effect of lateral confinement in pillars appears reasonable, provided field data is available to determine the empirical parameters.

The second paper (Ref. 42) describes a three-dimensional version of program SALT which was also applied to the Project Salt Vault observations. The assumptions are as before, except that the mining plane is now modeled by square grid elements, and complex mining layouts can be modeled. This model was restricted to normal stresses and convergence only, which is sufficient for modeling mining on a single plane remote from ground surface effects. The calibration against observations led to changes in some of the salt creep parameters compared to the two-dimensional ones.

A.3 PROGRAM SALT2

A.3.1 Present Form

For this program a semi-infinite half space of homogeneous elastic material is assumed (i.e., ground surface included). The waste material is modeled as a line heat source of declining intensity, placed below the excavated level. At the excavated level, displacement discontinuity elements (imaginary thin slits) are used to satisfy the boundary condition that the traction on the roof and floor in the mined portions of the level must be zero. The pillars, remnants between the roof and floor, are allowed to creep depending on the stress and temperature history at each location. At each time step

the magnitude of the displacement discontinuities (normal and shear) which must satisfy these boundary conditions are calculated. From these and the temperature changes due to the heat sources, the total stresses and displacements throughout the semi-infinite body can be determined.

The inclusion of ground surface with its effect on stress and temperature makes this program a significant improvement on the earlier SALT, for the modeling of a full scale repository. The results presented show clearly the value of program SALT2 for studying the effect of depth, placement rate, etc., on pillar and abutment stresses and surface subsidence. The effect of heat output intensity could also be studied. SALT2 should also be suitable for two-dimensional studies of repositories on more than one excavation level if this is required.

Some investigation is warranted into the significance of assuming elastic material above and below the mining plane. The assumption is important, as it simplifies the whole problem enormously. It should be examined critically in a situation where a large repository generates appreciable temperature rises and nonhydrostatic biaxial stresses, to see where the assumption of no creep is reasonable. The program is clearly appropriate for broad rather than detailed studies and cannot be extended to provide a more detailed study.

A.3.2 Possible Development of SALT2

The authors of Ref. 37 state that direct extension of the method to study a full-scale repository presents practical difficulties as far as computer storage and time are concerned. It is not known to what level the program has been developed for the solution of large problems, so there may be room for

improvement in this direction. For example, the test scale repository studied used about 80 discontinuity elements and 20 time steps of one year, followed by 20 time steps of 10 years. Creep calculations require the stress and temperature history of each element to be stored. For large problems this would best be stored out of core. In this way a larger problem could be analyzed.

If examination of temperature and stress conditions outside the excavation level shows a significant zone where creep should be occurring, then a modified version of SALT2 with a pattern of inclined creeping discontinuities throughout the zone may be worth developing. Each discontinuity element would have to model the creep for its representative portion of the total creeping zone. Hopefully this would not be necessary.

Modification of SALT2 to include bedding plane discontinuities on which slip or separation could occur would be possible. Some trial runs including bedding planes probably are warranted to see whether any waste placement sequence could lead to slip or separation. A recommended simpler approach would be to check normal and shear stresses at imaginary bedding plane locations to see whether slip or separation would have occurred if a bedding plane discontinuity had been included in the model.

Development of a three-dimensional version to model creep on one or more excavation planes with given sequences of mining and placement on each plane should in principle be possible. This could be based on portions of program NFOLD, developed by the University of Minnesota for stress analysis of mining on multiple planes with a free ground surface, and SALT2. Limitations on problem size in terms of number of elements and number of time steps will certainly be encountered.

Development of a three-dimensional model should not be commenced until considerable experience has been obtained with the two-dimensional one.

Further study of additional work completed (Refs. 44 and 45) should be made to review broad modeling of repositories. It is expected that detailed finite element studies of a typical room and pillar will form the basis for designing a special displacement discontinuity element which can broadly represent the behavior of a portion of a repository level, including a room and pillar.

A.4 CONCLUSIONS

It is concluded that program SALT2, or something similar, is the most promising method for broad studies of stresses and displacement induced by an underground nuclear waste repository. The main simplifying feature and limitation in SALT2 is the assumption of homogeneous elastic material above and below the excavation plane(s). Investigation is warranted to see whether the temperatures and biaxial stresses in the salt outside the excavation plane(s) make this assumption satisfactory.

The finite element program used in Volume 4 to evaluate stresses above and below the depository layer should be reviewed, to determine whether special "depository level elements" could be included to broadly model the excavation level. The rest of the salt would then be modeled with ordinary viscoelastic elements. This would be more expensive to run because it would be analyzing for creep in a larger number of elements, but it would eliminate any doubts about whether creep occurs outside the excavation level.

APPENDIX B

REPOSITORY SUBSIDENCE POTENTIAL

B.1 INTRODUCTION

Preliminary studies of the stresses and deformation behavior of salt in the immediate vicinity of a depository room have been completed (see Volume 4). The problem of determining stresses and deformations in the strata surrounding the depository also demands consideration for several reasons. Of primary importance is an assessment of the potential for fracturing of the strata overlying the depository, which could lead to an increase in hydrologic communication between the depository and overlying strata. Both subsidence and uplift have been postulated as surface expressions of deformations around the repository, and surface displacements must be considered in the design of surface structures; also, monitoring of the displacements will assist in evaluating below-surface conditions. Finally, it must be assured that repository shafts will not be adversely affected by movements in the strata surrounding the repository.

In the following discussion, results of past experience will first be evaluated for their applicability to a nuclear waste repository. Then further attention will be given to those facets of the problem which are peculiar to a repository.

B.2 APPLICABILITY OF PREVIOUS EXPERIENCE

Extensive worldwide mining of essentially horizontally lying coal seams has led to the accumulation of a considerable body of knowledge concerning the behavior of the strata overlying such tabular excavations.

Many mines have been located below water sources including aquifers, rivers, lakes, and the ocean. Thus, data has been gathered as to the conditions necessary to ensure little or no hydrologic connection between the mine and the water source. The thickness of the seam, thickness of low permeability beds above the seam, vertical distance to an aquifer, percent extraction and use of stowing all affect the extent of disturbance above the seam. However, it has been concluded (Ref. 46) that in coal-bearing sediments the zone of fracturing or increased permeability extends from about 120 feet to 200 feet above the seam. Many coal mines extract almost 100 percent of the coal; for mines in which substantial pillars are left (as will occur in the repository), it is suggested that fracturing would extend only a few meters above the seam.

Empirical relations have been fitted to data to describe the shape of the surface subsidence profile. Thus, predictive capabilities of such parameters as maximum subsidence and maximum extensional strain are available for specific areas. Generally, the maximum surface subsidence (S_m) is expressed by:

$$S_m = AW \quad (B.2-1)$$

where W is the seam thickness and A is the influence factor. The value of this factor depends on the geology of the location and the amount of support left after mining. It has been

determined (Ref. 47) that the influence factor generally assumes a range of values from 0.9 for caving (no support) to 0.5 for complete stowing (backfilling). The influence factor has been more specifically defined (Ref. 48) as being composed of the product of two factors, f and q , where f is a depth factor and q is a stowing factor. The factor f varies with the depth of the seam, being 0.7 at 50 meters and 1 at about 500 meters. The factor q varies as shown below:

0.85 to 0.90 for caving
0.45 to 0.55 for pneumatic stowing
0.20 to 0.35 for hydraulic stowing

Maximum extensional strain E_m can be determined using direct calculation formulae such as:

$$E_m = S_m/h \quad (B.2-2)$$

where h is the depth of the seam below the surface. Values of E_m can also be obtained using empirically derived profile functions which duplicate the shape of the subsidence profile. One such function is (Ref. 48):

$$S = (S_m/2) \left(1 - \operatorname{erf} \left[\sqrt{\pi} x/B \right] \right) \quad (B.2-3)$$

where x is distance, with zero being at the inflexion point of the subsidence curve and B is the critical radius, or distance from $x = 0$ to where maximum subsidence S_m occurs. Expressed as an equation

$$B = 2h \cot \gamma \quad (B.2-4)$$

where γ is the limit angle (see Fig. B.2-1 for terminology). Table B.2-1 presents some data on subsidence characteristics over coal seams in several regions of the world.

Figure B.2-1 Subsidence Terminology

TABLE B.2-1
SUBSIDENCE PROFILE CHARACTERISTICS
FROM VARIOUS COUNTRIES

Location	Position of Ribside d/h	Critical Width W_c/h	Maximum Extension $E_m/S_m/h$	Position of E_m x_E/h	Angle of Break β	Limit Angle γ
Great Britain	0.14	1.5	0.66	0.10-0.14	90°	55°
Northern France	0.00	1.4	0.80	0.18	80°	55°
Saar region, Germany	0.17	1.0	0.65	0.25	88°	60°
Ruhr region, Germany	0.05	1.6	0.80	0.30	75°	50°
Hungary	0.10	1.0		0.30	80°	60°
Poland	0.05	1.0	1.2	0.15		
Bulgaria	0.06	0.95	1.3	0.21	82°	50°
Donbass, U.S.S.R.	0.10	0.9	1.2	0.16	87°	

Adapted from Ref. 47

For definition of terms, see Fig. B.2-1

*All positions normalized by dividing by h .

Determination of the potential for fracture of strata overlying the repository would be aided by a knowledge of the strain in these strata. Methods of predicting strain are reviewed in Appendix A. It would be useful to be able to apply the empirical formulae describing surface movements to horizons

below the surface. It has been suggested that empirical formulae for surface subsidence profiles cannot be applied directly to horizons below the surface (Ref. 48). In particular, these authors presented results of an elastic analysis and field studies to show that the critical radius (B, as defined above) is constant to a depth equal to 4/5 of the overburden thickness. Using the profile function defined above, it can be shown that the maximum tensile surface strain is given by

$$E_m = 0.6 S_m/B \quad (B.2-5)$$

where $B = 2h \cot \gamma$. A direct application of the profile function to horizons below the surface would require B to vary with h. It is clear that keeping B constant would lead to significant differences in strain magnitudes at considerable depth.

The applicability of coal mining subsidence experience to a nuclear waste repository depends on the geologic and structural similarities of the two. Bedding dip, rock type and the presence of bedding plane discontinuities all affect subsidence characteristics. Geologically, bedded salt and coal seams are similar in that they are both in relatively flat-lying sedimentary formations containing some similar rock types. It is believed that this very general similarity justifies the use of coal field experience in describing general subsidence characteristics over a repository, provided that thermal effects are ignored. The use of the same general characterizations in various coal regions throughout the world tends to substantiate this opinion.

There are, however, several differences between the repository and coal mines including: heat generation, larger pillar size and the pillar material properties. Because salt

creeps, greater subsidence would be expected than if the pillar material (such as coal) does not exhibit significant creep behavior. Heat generated by the waste has two effects on the magnitude of subsidence:

- Salt exhibits a greater tendency to creep at high temperatures and thus higher temperatures would cause increased subsidence over long time periods
- Both the repository layer and the strata surrounding the depository will tend to expand; thermal expansion would tend to cause negative subsidence or uplift.

Finally, the extraction ratio of 20 percent to 30 percent expected for a depository is much lower than would be used in a coal mine, and thus, subsidence figures from coal mines tend to be very conservative.

B.3 ANALYSIS OF SUBSIDENCE

B.3.1 Subsidence Assessment

Because of the special problems associated with subsidence over a depository, some analysis must be performed to supplement data already available. In this section some of the pertinent aspects of subsidence analysis will be discussed, as related to surface movements, formation of fractures and shaft stability.

Pertinent parameters affecting surface displacements are the heat output at the depository level and whether or not the rooms are ventilated, size of pillars, and properties of

the backfill (when it was placed and stiffness of the material). During the operational phase, rising temperatures will tend to produce surface uplift from thermal expansion and surface subsidence from accelerated creep deformation. It is not clear which effect will predominate, although results indicate that for a depository at a 2,000-ft depth the creep deformations would be larger and lead initially to surface subsidence (Ref. 37). After decommissioning and backfilling, the pillars will continue to deform, transferring load to the backfill. This process will lead to a reduction in convergence at the repository layer and eventually all creep closure will cease. After this time, it is possible that the thermal expansion of the rock will produce some uplift.

This problem has not been subject to detailed investigation, although the thermal creep deformations at the depository level during the operational phase of the repository have been assessed. Surface movements over long times have been examined (Ref. 37) but the potential for creep closure at the repository level was ignored. As a first-order approximation, the results of these two methods of investigation could be algebraically added to obtain a net surface displacement. In the long term, after the backfill has been fully loaded, conditions would approach those determined by ignoring creep. The surface displacement/time curve would tend to parallel that predicted by ignoring creep but at a different magnitude. It is therefore necessary to define, for the purposes of a first-order approximation, an average value of subsidence at the repository level.

B.3.2 Fracture Processes

Of primary concern is the potential for fracturing of the strata overlying the depository. Because of the method of support in the depository there are two areas of maximum fracture potential: the pillars and roof of the individual rooms,

and the abutments at the boundaries of the depository. As mentioned, stresses and deformations have been computed for the rock around a room in the central area of the depository during repository operation (Volume 4). Explicit strength criteria have not been included in such analyses but some estimates, based on field experience, could be made of the potential for fracturing based on the present results. The stress and deformation state will be different at the boundary abutments of the repository and analyses to estimate magnitudes have not been done. Determination of stress and deformation in the abutment region presents some practical modeling difficulties. In particular, geometric symmetry conditions used to limit the size of a model of a region in the center of the depository do not apply to the abutment areas; thus, computer models must necessarily be larger. It may be necessary to eliminate some detail, as in the representation of the pillars, so that a model of reasonable size could be constructed. A thermal analysis of the abutment areas, which is necessary input to this model, is given in Volume 4.

It is believed that some order of magnitude estimates might be possible by using the results of analysis of the room in the center of the depository. If these results indicate subsidence will occur, they could be assumed to represent the maximum subsidence which will occur anywhere over the depository. Once a value of maximum subsidence has been determined, values of maximum tensile strain could be estimated using empirical subsidence theory developed for coal mines.

B.3.3 Shaft Stability

It is, of course, necessary to maintain adequate shaft stability during the operational phase of the repository. Thus, shafts must be located so that the disruptive effects of subsidence will not hinder shaft operation. In mining practice

this is sometimes accomplished by designing a shaft pillar of sufficient dimensions that the shaft will not be within the angle of draw. The angle of draw (or distance to the limit of subsidence effects) has not been defined for the repository. This type of information would be obtained as part of the results of a study, as outlined above, of the stresses and deformations of the abutment area of the repository.

B.4 CONCLUSIONS

Studies of the rock movements in the strata surrounding the depository are necessary in order to assess the potential for fracturing of the strata, surface displacements and shaft stability. Techniques for predicting subsidence in coal mines were reviewed. A brief summary of coal mine subsidence data from various parts of the world indicates that subsidence though characteristics and empirical predictive techniques are similar in flat-lying sedimentary formations. It is therefore felt that, for a first-order approximation, empirical coal field subsidence descriptive techniques would be applicable to predicting effects of subsidence over a depository in bedded salt. Because both thermal expansion and creep convergence will occur around and within the depository, it is not clear whether the net surface movements will lead initially to subsidence or uplift. Pertinent parameters and techniques for resolving this question are discussed. Over the center of the depository is is concluded that results of work already done could be extrapolated to obtain a first-order approximation of surface movement. Similarly, some data exists which would be of use in discussion of the extent of fracturing around rooms in the repository. However, over the boundaries of the repository, where subsidence theory indicates a great potential for fracturing, no analyses of stresses and displacements are

available. Data from an analysis of rock movements over abutments would be of further use in determining the size of shaft pillars.

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GLOSSARY

Abutment: a surface or mass provided to withstand thrust; as in the end supports of an arch. The outer limits of the depository or the shaft pillars are examples of abutments.

Alteration: any change in the mineralogic composition of a rock brought about by physical or chemical means.

Anhydrite: a mineral consisting of anhydrous calcium sulfate.

Apparent Elastic Limit: that stress at which the rate of deformation is 50 percent greater than the initial rate of deformation.

Applied Deviatoric Loading: the net stress experienced by an element of rock under triaxial loading conditions, equal to the difference between the applied normal stress and the confining pressure.

Aquiclude: a zone which will store water but does not transmit significant amounts.

Aquifer: zone below the surface of the earth which will store water and also produce substantial amounts (as through a well).

Argillaceous: term applied to all rocks composed predominantly of clay minerals such as slate, shale, etc.

Artesian: refers to groundwater under sufficient hydrostatic pressure to rise above the aquifer containing it when unconfined.

Auger: a rock drill in which the cuttings are continuously, mechanically removed from the hole bottom without the use of fluids.

Backfill: sand, crushed rock, or other material used to fill voids in underground openings.

Bedded: refers to rocks resulting from consolidated sediments and exhibiting planes of separation between depositional units.

Benching: a process by which an excavation is enlarged by drilling and blasting vertical holes in the floor.

Bentonite: a soft, plastic, porous rock consisting largely of colloidal silica and composed essentially of montmorillonite clay minerals.

Biaxial Stress: a state of stress in which one of the principal stresses is zero.

Bitumen: natural inflammable substances composed principally of a mixture of hydrocarbons -- i.e., petroleum, asphalt, etc.

Blasting: the operation of breaking rock by boring a hole, inserting an explosive charge, and detonating the charge.

Blind Drilling: drilling of a large diameter hole without the use of a small, predrilled pilot hole.

Borehole: a hole drilled into soil or rock to obtain geologic and hydrologic information.

Breasting: process of enlarging an excavation by drilling horizontal holes in the roof parallel to the excavation.

Breccia Pipe: zone of angular fragmented rock.

Bulkhead: a tight partition of wood, rock, or concrete used to seal underground openings.

Burn Cut: a technique used in blasting underground where the cut holes are drilled parallel to the excavation, one or more holes being left unloaded.

Cable Tool Drill: a drilling machine based on the percussive principle in which the rock at the bottom of the hole is broken up by the drill bit chipping the rock with a series of repeated blows.

Calyx Drilling: a method of rotary core drilling using a toothed, hardened steel cutting bit.

Caving: fracturing of the rock overlying an underground excavation as it collapses into the excavation.

Clastic Rock: a consolidated sedimentary rock composed of broken fragments that are derived from preexisting rocks and that have been transported individually for some distance from their place of origin.

Closure: reduction in dimension of an underground excavation through deformation.

Cohesion: the cohesion of a rock or soil is that part of the shear strength which does not depend upon inter-particle pressure.

Compressive Strength: the load per unit area at which an element of rock will fail, or rupture.

Confining Pressure: a pressure applied perpendicular to the major direction of loading.

Constitutive Equations: equations relating stress to strain whose character depends upon the physical properties of the material under consideration.

Continuous Mining: a mining method where a mining machine mechanically breaks the rock and loads it onto either conveyor belts or haulage truck in one operation.

Contour Blasting: shaping the walls of an excavation by special blasting.

Convergence: see closure.

Core: cylindrical sample of rock obtained by drilling.

Creep: slow deformation in rock that results from the application of constant stress.

Cushion Blasting: a method of blasting in which the hole is substantially larger in diameter than the cartridge.

Cut-and-Fill: a method of underground mining whereby ore is removed overhead in a series of horizontal slices or cuts, working from a lower to an upper level, each cut being sequentially backfilled.

Decrepitation: the breaking up of a mineral, usually violently, when heated.

Depository: a subterranean cavern excavated in a deep geologic medium for the disposal of nuclear waste.

Deviator Stress: the difference between the major principal stress and the minor principal stress.

Dike: a tabular body of igneous rock that cuts across the structure of adjacent rocks, usually resulting from igneous intrusion.

Dilation: the volume expansion of a fracture during shearing processes.

Dip: the angle at which a planar feature is inclined to the horizontal.

Dip Direction: the bearing of the maximum dip line of a planar feature.

Discontinuity: a fracture, fault or other change in rock mass.

Dolomite: a common rock-forming mineral, $\text{CaMg}(\text{CO}_3)_2$.

Downcast: the shaft through which fresh air is forced into the mine.

Drilling Mud: a viscous fluid containing bentonite or equivalent materials used in drilling rock to improve efficiency, reduce damage to in situ rock, and control subsurface gas and water pressures.

Effective Porosity: the portion of the pore space in a saturated permeable material in which flow of water takes place.

Effective Stress: the difference between the rock stress and the pore water pressure.

Elastic Modulus: the slope of a line describing the recoverable strain as a linear function of stress.

Evaporite: a non-clastic sedimentary rock composed of minerals produced from a water body that became concentrated by evaporation.

Extraction Ratio: the ratio of the area or volume mined to the total area or volume.

Face: the solid surface of unbroken rock at the advancing end of an excavation in progress.

Fault: a fracture or fracture zone along which displacement of the sides relative to one another has occurred.

Fissile: term applied to bedding consisting of thin laminations.

Forced Convection: heat transfer as a result of the forced passage of a fluid over a heated surface.

Friction Angle: a measure of the shear force necessary to overcome the shear resistance of a rock due to inter-particle pressure.

Free or Natural Convection: the motion of a fluid due to density changes arising from heating.

Full Face Blasting: excavating the entire face of the advancing excavation in a single phase operation.

Geophone: a detector, placed on or in the ground, which responds to ground motion at the point of its location.

Grout: a thin paste (usually cement) used to fill fractures underground either to increase structural support or decrease permeability.

Halite: rock salt, NaCl.

Head: height to which a fluid will rise above a base elevation due to the pressure in the fluid.

Headframe: the shaft hoisting frame and associated equipment at the top of a shaft.

Horizon: a particular stratigraphic level in the geologic column.

Hydrostatic Pressure: a condition wherein the pressure is equal in all directions.

Hygroscopic: readily taking up and retaining moisture.

Interbed: a bed of one kind of rock material occurring between or alternating with beds of another kind.

Invariant: a mathematic combination of stress (or strains) acting on an infinitesimal particle that is not directionally dependent and has a constant value.

Joint: fracture in rock along which no movement has occurred.

Kneading and Static Compaction: alternative standard methods of compacting soil samples for testing and quality control in soil construction.

Limiting Equilibrium Technique. an analysis method which determines the minimum strength parameters necessary for stability of a structure by analyzing the structure at the moment of failure.

Lithology: the physical characteristics of a rock.

Logging: the recording of information obtained from drilling.

Longwall: a method of underground mining whereby virtually all of a rock seam is extracted and the roof is allowed to cave uniformly behind an advancing mining front.

Massive Rock: competent rock that has a homogeneous structure over wide areas free from minor joints, layering, or similar features.

Mixed Convection: heat transfer when the processes of free and forced convection are comparable.

Mylonite: a fine grained laminated rock formed by the grinding of rock and fault surfaces during movement along the fault.

Negative Crystal: a hollow opening shaped like a crystal presumably formed by the solution of a previously existing crystal.

Normal Stiffness: a measure of the deformation characteristics of a joint in a rock, defined as the increase in normal stress force that results from each unit increment of normal displacement.

Normal Stress: the component of stress perpendicular to a given plane, either tensile or compressive.

Octahedral Shearing Strain: the shear strains associated with the octahedral shearing stress.

Octahedral Shearing Stress: the shear stress across a plane equally inclined to the principal stress axis, which is a function of the second invariant of the principal stress deviations; used as a yield criterion for plastic materials.

Open Stopping: a method of mining in which the walls and/or roof of the stopes are supported by rock pillars.

Overburden: rock or soil that overlies a potential excavation.

Packer: a device lowered into a borehole that can be made to expand to produce a watertight joint against the sides of the borehole.

Parting: a thin layer of material dividing mineral veins or beds.

Peak Strength: the maximum stress that can be applied to a rock in compression before it fails.

Percussive Drill: see cable tool drill.

Permeability: a measure of the capacity of a rock for transmitting a particular fluid. Also referred to as the hydraulic conductivity. The term permeability is often used in a different sense to describe the capacity of rock for transmitting fluid independent of fluid density and viscosity. The former definition was used in these volumes.

Piezometer: a device for measuring in situ water pressure.

Pillar: a vertical column of rock left in an underground excavation, usually to support the roof.

Plastic: behavior in which a material is capable of deforming indefinitely and permanently under a constant stress.

Plug: a zone of normally impervious material placed in an excavation so as to prevent the flow of water.

Pneumatic Backfilling: placing fill with a high velocity air stream.

Poisson's Ratio: the ratio of lateral expansion to the associated longitudinal contraction in a material under stress.

Polyhalite: a mineral, $K_2MgCa_2(SO_4)_4 \cdot 2H_2O$.

Pore Pressure: the stress transmitted through the fluid that fills the voids between particles of rock.

Porosity: the ratio of the volume of voids in a rock or soil to its total volume.

Pozzolan: siliceous tuff, ash, or other material used in cement which when mixed with lime hardens under water.

Presplitting: used in blasting to form a fracture plane around the perimeter of an excavation.

Principal Stress: the stress acting on an infinitesimal particle can be resolved into three orthogonal planes on each of which the stress is uniquely normal and the shear stress is zero. These stresses are called the major, intermediate and minor principal stresses.

Raise Roring: the process of drilling large diameter holes between different mine levels by enlarging a pilot hole with a full-face drill bit.

Repository: the entire region, subterranean and surface, which will be owned by the Federal government for the purpose of HLW disposal.

Ripping: the act of breaking rock or soil by a steel toothed machine.

Room and Pillar: a method of underground mining in relatively flat lying deposits whereby a grid of rooms separated by rock pillars is excavated.

Rotary Drill: a drilling machine that rotates a drill bit attached to a rigid string of rods.

Rotary/Percussive Drill: a drilling machine which combines percussive drilling with bit rotation.

Scaling: the scraping down of loose rock from the roof or walls of an excavation.

Sedimentary: formed by the deposition of sediment.

Shaft: an excavation of limited area compared to its depth which provides access to underground mines and is used for hoisting men and materials or for ventilation.

Shaft Collar: the junction of a mine shaft and the ground surface.

Shear Stiffness: a measure of the deformation characteristics of a joint in rock, defined as the increase in shear stress force that is required to produce each unit increment of shear displacement.

Shear Strength: the amount of shear stress that can be sustained without failure.

Shear Stress: any of the tangential components of the stress tensor.

Shear Zone: a zone in which in situ shearing has occurred on a large scale so that the rock is visibly crushed.

Shotcrete: cement sprayed on tunnel walls as a thin lining to increase the structural stability of the opening and to decrease the loss of moisture from the rock.

Sill: an igneous intrusive body of rock emplaced parallel to the bedding or schistosity of the intruded rock.

Slickenside: polished and striated surface resulting from frictional forces during movement along a fault plane.

Smooth Blasting: technique used in blasting to form a smooth wall during excavation by initiating the perimeter charges after the main charges are fired.

Spall: to break off in layers parallel to the surface.

Static Compaction: see kneading compaction.

Strain Hardening: material behavior whereby each additional increment of strain requires an additional increment of differential stress.

Stand-up Time: the length of time that an excavation will remain stable without support.

Stope: an underground excavation from which ore is extracted.

Stopping: a masonry or brick wall built across old mine workings used to control the ventilating air.

Strain: linear or volumetric deformation resulting from an applied stress; expressed as a percentage or fraction of the original length or volume.

Stratigraphy: the arrangement of strata as to geographic position and chronologic order of sequence.

Stress: the applied force divided by the area over which it is applied.

Strike: the direction or bearing of a horizontal line in a structural plane such as a fault, joint, or bedding plane.

Subsidence: the lowering of a part of the earth's surface, often due to the collapse of an underground opening or removal of fluids such as water, oil, etc.

Sump: a surface excavation or diked area to hold water, drilling mud, sludge, and discharged matter from drilling.

Sylvite: a white or colorless isometric mineral, KCl .

Tailings: fine ground rock, formed as a waste product from ore beneficiation processes.

Tangential Stress: shear stress.

Tectonic: pertaining to the deformation of the earth's crust. Usually associated with earthquakes and volcanic activity.

Tensile Strength: the maximum amount of stress which can be applied to a rock in tension.

Tensile Stress: a normal stress that tends to cause separation across the plane on which it acts.

Tension: stress that tends to pull a body apart.

Trackless Mine: a mine in which rail haulage is not used. In these mines, rubber tired vehicles or conveyor belts are used for haulage and transport.

Triaxial Strength: the strength of a piece of rock which is confined either by an external force or by adjacent rock.

Triaxial Stress Conditions: a situation in which none of the principal stresses is zero.

Tuff: a rock formed of small volcanic fragments.

Ultimate Strength: the maximum differential stress that can be sustained before failure.

Undercut: a technique used in underground blasting where a machine cut is made along floor level to provide a free face to which the rock can break.

Uniaxial Strength: the strength of a piece of rock loaded in one direction only and unconfined in all other directions.

Upcast: a shaft through which exhaust mine air is removed from the mine.

Viscoelastic: behavior of material where an applied stress produces some recoverable and some nonrecoverable deformation.

Void Ratio: the ratio of the volume of voids to the volume of solids in a material.

Volumetric Strain: the net change in volume resulting from an applied stress.

Vug: any opening in a rock, from the size of a small pea upwards.

Wedge Cut: a technique used in blasting where the central cut holes are drilled so as to break out a wedge-shaped section.

Yield Strength: the maximum stress which can be applied to a material before the material ceases to behave elastically.

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16. ABSTRACT (200 words or less) This report describes the important effects resulting from interaction between radioactive waste and the rock in a nuclear waste repository. The state-of-the art in predicting waste/rock interactions is summarized. Where possible, independent numerical calculations have been performed. Recommendations are made pointing out areas which require additional research.					
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