MASTER

**GEOLOGIC, STRATIGRAPHIC, THERMAL,
AND MECHANICAL FACTORS WHICH INFLUENCE
REPOSITORY DESIGN IN
THE BEDDED SALT ENVIRONMENT**

Prepared for:

**The University of California
Lawrence Livermore Laboratory
Under Subcontract No. 8770703**

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December 1979

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EXECUTIVE SUMMARY

This report describes the geologic, stratigraphic, thermal and mechanical considerations applicable to repository design. The topics discussed in the report include:

- o Tectonic Activity
- o Geologic Structure
- o Stratigraphy
- o Rock Mechanical Properties
- o Hydrologic Properties

The conclusions derived in the report include the following design considerations. The design should:

- o Demonstrate that the integrity of surface structures, shafts, hydrologic seals and canister storage wells will not be threatened by potential seismic events.
- o Assess the long-term risk of crustal uplift or subsidence in the repository area and provide for long-term monitoring of crustal deflection and of groundwater chemistry within the basin.
- o Adjust the shape, layout and structural support of rooms, pillars and shafts to take advantage of the state of regional stress.
- o Limit the allowable thermal load to assure that diapiric flow will not be induced in the repository horizon.
- o Locate the storage rooms in salt beds of adequate thickness to provide the necessary hydrologic sealing, thermal and structural integrity.

- o Allow for rearrangement of corridor, room and pillar geometry to isolate faults, joint patterns and other structures that provide a potential radionuclide escape pathway.
- o Determine the roof and side support requirements in accordance with expected joint characteristics.
- o Allow for sealing of any openwork structures.
- o Demonstrate the capability for local containment of large, short duration water or gas inflows.
- o Minimize induced fracturing around the repository by selecting appropriate excavation methods, opening shapes and sizes.
- o Provide sufficient flexibility in room and accessway location to allow for changes in stratigraphy.
- o Avoid placement of canister containment wells through wet shale and clay bands.
- o Allow for possible failure along known discontinuities.
- o Size rooms and pillars in accordance with the creep properties of salt under long-term thermal and mechanical loading.
- o Demonstrate that room closure will be within acceptable limits.

- o Provide canister spacing such that salt temperatures are held within allowable limits.
- o Provide access to and monitoring of all shaft seals during the operational life of the repository.
- o Provide seals with suitable characteristics to minimize the risk of radionuclide escape over the long term.
- o Assess and allow for the potential escape of radionuclides over the long term via groundwater.

Some of the parameters discussed in the report are more closely associated with site suitability than repository design. These have been included to the extent that they affect the design process.

INTRODUCTION

This report addresses design considerations for high-level waste repositories in bedded salt. In particular, the report describes the geologic, stratigraphic, thermal, and mechanical considerations applicable to repository design. However, it should be recognized that performance of the repository will be governed by the interaction of the engineered features of the repository (waste form, emplacement technique, and repository design) and the hydrogeologic system in which the repository is located. It is assumed for the purpose of this report that the design will be tailored to meet both the requirements imposed by the waste form and the specific site.

In Section 2.0 a general listing is provided of design considerations applicable to all rock types. Section 3.0 consists of a detailed description of the various aspects of geologic structure, stratigraphy, and thermal and mechanical rock properties which impact repository design in salt. For each factor we have listed the relevant parameters, discussed the adequacy of parameter assumptions (i.e., how well does the parameter define what is required?), and given ranges of parameter values we believe are appropriate for use in developing a reference repository. To the extent possible, reference has been made to conditions found to exist at sites where detailed work has been done.

For design purposes, the parameters which must be assessed in greatest detail are those which describe conditions in the emplacement horizon. Attention has been focused on these parameters in this report, although mention has been made of conditions which may prevail in the regional hydrogeologic system and which could be important for the long-term performance of the repository.

Some of the parameters discussed in this report are more closely associated with site suitability than to repository design. Recognizing that there is considerable interaction between site suitability and design, these parameters have been included to the extent that they have some impact on the design process.

2.0 GENERAL DESIGN CONSIDERATIONS FOR REPOSITORIES

2.1 INTRODUCTION

The following list includes most considerations that would have an impact on the design of deep geologic repositories. The relative importance of the various factors vary according to the characteristics of the specific geologic environment.

2.2 TECTONIC ACTIVITY

1. Seismicity
2. Crustal instability (uplift/subsidence)
3. Regional stress
4. Diapirism

2.3 GEOLOGIC STRUCTURE (with emphasis on repository horizon)

1. Complexity (predictability)
2. Bedding (attitude, thickness, contacts)
3. Faults (age, attitude, length, width, permeability)
4. Joints (spacing, orientation, persistence)
5. Mine-induced fractures (density, anisotropy)
6. Primary (sedimentary, igneous) structures

2.4 STRATIGRAPHY (Emphasis on repository horizon)

1. Depth to emplacement horizon
2. Distribution of units (lateral and vertical)
3. Geometry of units
4. Interbeds (uniformity or consistency of units)
5. Mineralogy
6. Petrology

2.5 ROCK MECHANICAL PROPERTIES OF REPOSITORY HORIZON

1. Strength (intact, including discontinuities, and effects of radiolysis and heat)
2. Deformation moduli
3. Creep/Plasticity
4. Density
5. Hydraulic conductivity and porosity
6. Moisture effects/groundwater pressures
7. Formation sealability
8. Ease of mining and maintenance of openings

2.6 ROCK THERMAL PROPERTIES

1. Thermal conductivity
2. Coefficient of thermal expansion
3. Local natural thermal gradient
4. Specific heat

2.7 HYDROLOGIC PROPERTIES

1. Hydraulic conductivity
2. Gradients
3. Porosity
4. Specific storage
5. Dispersivity
6. Retardation factor
7. Geochemical characteristics of the rock
8. Composition of pore fluids

3.0 DESIGN CONSIDERATIONS FOR BEDDED SALT

3.1 INTRODUCTION

The structural design of an underground nuclear waste repository in rock must ensure the stability of the repository during its initial operation phase and throughout its lifespan. It will specify construction procedures which result in minimum disturbance to the rock mass so that decommissioning can proceed effectively. The required design procedure consists of identifying the factors which influence the structural performance of the repository and adopting the best design possible within the limitations of the predictive capabilities of available technology. No generalized design method exists which is applicable to all potential situations.

The design process consists of a mixture of the following elements:

1. Precedent practice, observations, methods, and empirical rules;
2. Stability studies using the results of stress analyses based principally on continuum methods;
3. Analyses using limiting equilibrium techniques applied to specific failure mechanisms.

Past practice may be used initially for a preliminary estimate of design requirements.

Under certain circumstances the design may be based on purely operational considerations. More generally, however, additional studies using theoretical procedures are required.

Owing to the complex nature of most rock masses, these theoretical procedures should always be related to past performance observations. In certain instances where the installation is of critical nature (e.g., nuclear storage facilities) or where past performance observations are limited or non-existent due either to the scale of construction or as a result of a complex geological environment, the design will require the construction of a fully instrumented trial opening.

A variety of stability problems may occur in underground opening design, depending on in situ conditions and the nature of the rock mass. These may be categorized as follows.

1. Instability due to adverse geologic structure. This is more common in hard, brittle rocks which are faulted and jointed and where several sets of discontinuities are steeply inclined. In these cases stability can often be improved by relocation and reorientation of the opening, together with extensive artificial support (rock bolts, etc.), designed according to the nature of the structural discontinuity patterns.
2. Instability due to excessively high rock stress in relation to the rock strength. This occurs commonly either at great depths or at relatively moderate depths where high tectonic stresses and relatively weak rock are present. Changes in the shape of the excavations and repositioning of the excavations relative to each other can be successful in partially overcoming these problems.
3. Instability due to weathering and/or swelling behavior. This is generally associated with relatively poor rock but may also occur in isolated seams within an otherwise sound rock mass.

4. Instability due to excessive groundwater pressure.

Excessive groundwater pressures occur, in general, at the interface of a material of high hydraulic conductivity with another of low conductivity. A common example of such an occurrence is where no provision is made for the drainage of water collecting between a layer of granite and the rock surface.

The basic aim of any underground excavation design is to utilize the rock as the principal structural material, creating as little disturbance as possible during the excavation process and adding as little as possible in the way of concrete or steel support.

The first step in design is to obtain a basic understanding of the existing structural geological conditions. Following an assessment of this information, likely stability problems can be identified by reference to past practice performance using a suitable rock mass classification index. Theoretical design procedures, indexed to past practice and observations and relevant to the particular classes of stability problems encountered, may then be employed to achieve a suitable design.

The design of a repository in salt will be affected by the following factors:

- o Tectonic activity
- o Geologic structure
- o Stratigraphy
- o Rock mechanical properties of the repository horizon
- o Rock thermal properties
- o Hydrologic properties

3.2 TECTONIC ACTIVITY

Tectonic Activity refers to the large-scale disruption of the earth's crust. Tectonic forces can act on large parts of the earth's crust, but the resultant crustal dislocations are generally within well-defined geographic zones. These zones show past or present effects of tectonism by exhibiting one or more of the following: downwarp, uplift, faulting, volcanism, and seismicity.

It is not possible to locate geographic areas devoid of the possibility of tectonic disruption of the repository. Therefore, the risk of tectonic instability must be addressed and accounted for by the design.

The following factors are symptomatic of tectonic activity in a proposed repository site and have an impact on the design of the repository:

- o Seismicity
- o Crustal instability (uplift/subsidence)
- o Regional stress
- o Diapirism

3.2.1 Seismicity

Seismicity encompasses the origin, occurrence and intensity of earthquakes. Earthquakes of sufficient duration and intensity to endanger a repository result from the rapid release of strain energy accumulated within the earth's crust by the action of tectonic forces. Seismic activity is the primary indicator of present tectonic instability in an area and as such must be considered in the design of all facilities for the repository.

Although the risk of seismic disruption to the repository is low (Figure 3.2.1), the local seismic history must be evaluated in order to define the design seismic event and ground response. Maximum vertical and horizontal ground accelerations may then be predicted and, along with event duration, incorporated into the design of surface and underground facilities. Attention must be directed to the structural integrity of storage rooms, canister shafts, shaft linings, backfill, and borehole seals. The surface facilities for handling and temporary storage of canisters must also receive seismic resistant design.

The physical effect of earthquakes in underground workings has had very little systematic study. Most available information is qualitative observation rather than instrumental data. Many of these are newspaper accounts from miners long since dead. The exact mine conditions are unknown, and thus the utility of much of the information is questionable.

Damage from earthquakes may be divided into the following categories:

1. Damage induced in a structure in response to vibration;
2. Damage due to displacement of active faults intersecting the structure.

A review of available information on the effects of earthquakes on underground mines by Peter R. Stevens (1977) has three major conclusions.

1. Severe damage is inevitable when a mine or tunnel intersects a fault along which movement occurs during an earthquake. Possible damage includes offset of the workings of either side of the fault, destruction of

SEISMIC RISK MAP OF THE UNITED STATES

Figure 3.2.1

timbering, collapse of roof and walls of workings and flooding of the mine--all of which which could have disastrous consequences.

2. Mines in the epicentral region of strong earthquakes but not transected by fault movement may suffer severe damage by shaking. Timbering may fail, and collapse of roof or walls and mine shafts or their linings may occur. Flooding of mine workings by the enlargement and interconnection of joints or old fractures is possible.
3. Mines outside of the epicentral region are likely to suffer little or no damage from a strong earthquake. Some spalling of rock, falling of loose or weakened roof pendants, or some shaking are the only effects to be expected and, in many cases, the earthquake is not even noticed in mines so located (Stevens 1977).

A more recent review of seismically-induced damage to underground structures was made by Dowding and Rozan (1978). They included a summary of erosion damage in rock tunnels, attempted to correlate damage with surface acceleration and intensity (modified mercalli), and came to the following conclusions:

1. Total collapse of tunnels was only associated with movement of an intersecting fault, the degree of damage being dependent upon the fault displacement, and the condition of the tunnel.
2. Tunnels dug in rock are safer than shallow tunnels in alluvium, which in turn exhibit considerably less damage than do surface structures.

3. Tunnels in poor condition or poor ground are more susceptible to vibration-induced damage.

The following damage in lined and unlined tunnels resulted from vibration measured or estimated at the surface:

<u>Horizontal Surface Acceleration (Proportion of Gravity)</u>	<u>Damage</u>
<0.19g	None
0.19-0.25g	Few cases of minor damage
0.25g-0.40g	A few cases of minor damage, including loose rock fall and lining collapse
0.4g-0.50g	As above, but no collapses

In order to examine the possible dynamic response of an underground complex, the repository system should be modeled numerically. Initially, the rock medium would be idealized as a linear elastic system, and the response characteristics of any variable will be a function of the frequency of the applied dynamic steady-state disturbance. In any numerical application, the description of the boundary conditions must be handled carefully to ensure that damping effects are accurately modeled. Having determined the response characteristics of any system parameter as a function of excitation frequency, the maximum expected response of the repository complex for the design seismic event may be determined. Such analyses undoubtedly will be idealized, but conservative assumptions can be made to provide an upper bound on the estimate of disturbance to the repository.

Considering the low seismic risk expected in regions of bedded salt in the United States (see Figure 3.2.1) and the attenuation of vibration levels with depth, it is probable that the structural damage to a repository as a result of earthquake loading will be limited to comparatively minor surface effects.

In summary, with respect to potential seismic activity the repository design should:

- o Evaluate potential vertical and horizontal ground accelerations and event duration for both surface and underground repository facilities
- o Demonstrate that the integrity of surface structures, shafts, hydrologic seals and canister storage wells will not be threatened by potential seismic events.
- o Provide dynamic response analysis and appropriate design safeguards to reduce the risk of structural failure in canister handling, transport and storage areas.

3.2.2 Crustal Instability

Crustal instability is used with reference to the structural adjustments arising from both planetary tectonic forces and isostatic compensation. These adjustments range from major mountain building at rates on the order of centimeters per year to the almost imperceptable isostatic adjustment of large stable basins.

Unlike seismicity, the potential effects of crustal instability are limited to the post-decommissioning phase of the repository. It is assumed that site-suitability requirements will result in location of the repository site(s) away from areas of known uplift or subsidence, but the design should allow for longterm monitoring of the repository area to detect any crustal movement. Such movement may create new fractures in the repository horizon and increase the risk of radionuclide escape

to the groundwater system. Monitoring should include precise geodetic surveys of the ground surface within the bedded salt basin and monitoring of the groundwater chemistry in the vicinity of the repository.

In summary, with respect to crustal instability, the design should:

- o Assess the long-term risk of crustal uplift or subsidence in the repository area
- o Provide long-term monitoring of crustal deflection within the basin containing the repository
- o Provide long-term monitoring of groundwater chemistry.

3.2.3 Regional Stress

Regional stress is the in situ stress state of the rock mass prior to any excavation. It is a function of the overburden weight and any tectonically induced stresses.

The pre-existing state of ground stress must be determined before the stress distribution around any manmade excavation can be calculated. Various theoretical attempts to determine the state of stress in virgin ground have been made, but they have been shown to be of limited use as a result of the simplifying assumptions which bear little relevance to the complex geologic processes. Recognizing this fact, recent developments have therefore concentrated on the measurement of in situ stress rather than upon its theoretical determination. A variety of instruments have been developed for this purpose, the most useful of which provide the complete three-dimensional state of stress from a single location and rely on monitoring strain changes induced during stress-release of a region of in situ loaded rock.

The state of stress around an excavation is one of the major factors that affect the stability of the opening. It is determined by the magnitudes and directions of the pre-excavation in situ principal stresses and by the volume of rock removed (excavation ratio). As a general rule, it can be stated that increasing the size of the excavation and the depth below surface will increase the stresses around the excavation.

In bedded salt the measured vertical stresses are generally in fair agreement with the simple prediction which equates vertical stress to the weight of overburden. It should be noted, however, that stresses in unusual geological environments may exhibit significant variations and anisotropy due to tectonically induced regional stresses.

Obert (1962) reports in situ stress measurements in dome salt in Louisiana and indicates a vertical stress field equal to overburden pressure and a ratio of horizontal to vertical stresses of approximate unity. Miller et al. (1977) reported substantial deviations from the hydrostatic condition for stress measurements taken at shallow depth (144 meters) in a halite mine in Cheshire, England. Arnold et al. (1977) showed that in horizontally bedded rock salt at depths in excess of 400 meters the assumption of a hydrostatic stress field was justified. In steeply inclined strata and in salt plugs, large deviations from the hydrostatic stress state may occur at depths even greater than 400 meters.

The avoidance of areas with regional, tectonically induced stress states should alleviate the stability problems associated with unusually high stresses or large-stress anisotropy, but measurements of in situ stress should be made to aid in the design process.

The design should account for regional stress by:

- o Pre-excavation measurement of the in situ stress state of the repository horizon
- o Adjusting room shape and layout to take advantage of the in situ stress
- o Design structural supports and shaft linings to accommodate any excess loads due to regional stress.

3.2.4 Diapirism

Diapirism is the mass upward-flow of salt due to differential pressure and density. The resultant structures are primarily a function of whether or not the salt pierces the overlying strata. In essence, if the salt is contained by the arching of overlying strata, salt anticlines occur; but, should the stress exerted by the rising salt exceed the strength of the arching strata, piercing of the overlying strata by the salt results in the formation of salt domes.

There is a two-fold potential for repository disruption by diapiric processes:

1. The repository horizon may become diapirically mobilized. This may result from natural processes or natural processes aggravated by thermal effects of the waste.
2. Diapiric activity of a salt bed beneath the repository horizon may result in doming and tensional fracturing of the repository sequence. The first may bring the waste directly into the biosphere, while the second may create new pathways for radionuclide escape from the repository.

As with the preceding tectonic factors, avoidance of areas of known diapirism is essential, but the detailed mechanics of diapiric salt flow are not well understood and the design must attempt to minimize the potential for induced diapirism.

It is generally believed that natural diapirism does not present a danger to repository integrity during the required waste containment time span (Gera 1972). However, some authors believe that diapirism resulting from thermal output of waste is a real threat to the repository (Hyder 1977). The design must assure that the thermal loading within the repository will not induce diapiric flow of the repository horizon.

In summary, with respect to diapirism, the design must evaluate and, if necessary, limit the allowable thermal load to assure that diapiric flow will not be induced in the repository horizon.

3.3 GEOLOGIC STRUCTURE OF THE REPOSITORY HORIZON

The selection of a suitable repository site will attempt to exclude geologic structures which have an adverse effect on stability or radionuclide containment. At a specific site, however, there is little hope of detecting all anomalies by surface exploration. Indeed, it would be entirely unnecessary since modifications can be made in repository design during construction to adequately accommodate many such anomalies.

The design alternatives vary somewhat with the feature encountered, although in general the philosophy is to change the geometric layout to minimize the effect of the feature on stability or containment. The aim of the general design should be to minimize excessive stress or deformations around the excavations.

The geologic structural features of interest to repository design are:

- o Structural complexity and predictability
- o Bedding
- o Faults
- o Joints
- o Mine-induced fractures
- o Other features, including sedimentary, solution, and igneous structures.

3.3.1 Structural Complexity and Predictability

Bedded salt in undisturbed sedimentary basins is generally considered to be structurally simple as compared to other deposits of economic interest. However, these other deposits are not required to meet an equivalent set of design standards as applied to a repository and, as the necessary design criteria become more strict, the need for detailed geologic information increases. There is a limit, regardless of initial exploratory effort, in the ability to predict the structural conditions occurring even in a geologically simple environment.

The structural features that would impact on design may be divided into two groups: those that are pervasive features and likely to be identified during a surface drilling or geophysical program (bedding included) and those infrequent structures that are likely to be discovered for the first time during excavation (faults, joints, sedimentary, solution, and igneous structures included). The infrequent category also includes excavation-induced structures, the extent of which will not be known precisely until excavation proceeds.

3.3.2 Bedding

Bedding can be described in terms of thickness, attitude, and nature of the contact between beds. The attitude and thickness of individual salt beds can be determined from exploratory coreholes or rotary boreholes supplemented by downhole geophysical logging. Surface geophysical techniques can also be used to define large-scale bedding thickness and attitude.

Geophysical logging cannot discriminate individual thin beds in any reliable way, and the determination of the detailed stratigraphy, including bed thicknesses and the nature of bedding contacts, will require drilling with core recovery.

Bedding thickness, attitude, and contact nature will affect the location and geometrical layout of a repository. Thickness and attitude will determine repository location, in that thin or steeply dipping bedded salt is unsuitable. Contact nature will affect room stability because slabbing may occur along contact discontinuities.

In summary, the repository design should:

- o Locate the storage rooms in salt beds of adequate thickness to provide the necessary hydrologic sealing, and thermal and structural integrity
- o Locate the storage rooms in generally horizontal beds to avoid steep ramps and bedding at high angles to pillar faces
- o Specify room size, extraction ratio, excavation method, and roof support to minimize the possibilities of roof falls due to buckling and separation along bedding discontinuities.

3.3.3 Faults

Faults are ruptures in the rock mass along which the opposite walls have moved relative to one another. Faults may vary in length (trace) from a few centimeters to several hundred kilometers, and their relative displacements could have the same variability. Most faults have a thickness of a meter or less, but some fault zones may have a width of several hundreds of meters. Gouge or infilling is the material between the two faces of the fault. This material may be the debris resulting from the sliding of one surface upon another or it may be material which has been precipitated from solution or caused by weathering.

The nature of the gouge zone often determines the mechanical and hydrological characteristics of the rock mass. Changes in the stress field, caused either by anthropogenic or tectonic activity, are likely to be reflected in movement along existing faults. The fault will either be a conductor or barrier to groundwater flow, depending on the type of gouge. A breccia type of gouge is usually extremely permeable while a cemented gouge formed from solution precipitates is often relatively impermeable.

Some characteristics of the faulting process need to be described. As the yield strength of a rock is approached, microfracturing begins to occur, causing dilatancy and slight volumetric increase. Joints may form before and during faulting. Movement along faults is often episodic, or discontinuous with respect to time. Major displacements of hundreds or thousands of meters are presumed to occur over time periods of millions of years, with any single episodic increment limited to tens of meters. Some faults exhibit creep behavior, a slow aseismic movement up to several centimeters per year. Thus, while earthquakes are generated by sudden fault displacement, fault movement

can occur without release of noticeable seismic energy. Episodic aseismic creep slip has been documented on faults in California and correlated with experimental rock fracture studies (Byerlee and Brace 1968; Tocher 1960).

Faults in the vicinity of the repository site can be expected to influence the long-term hydrological characteristics of the repository. Under certain conditions, stress changes due to mining can cause movement or dilation of the faults and thereby increase the hydraulic conductivity along the faults. The peak hydraulic conductivity of fault zones in repository rocks has been estimated (Towse 1979) and is presented in Table 3.3.1.

TABLE 3.3.1
Estimated Peak Hydraulic Conductivities
Along Fault Zones

<u>Rock Type</u>	<u>Hydraulic Conductivity(cm/s)</u>
Salt	10 ⁻⁵ to 10 ⁻²
Shale	10 ⁻⁷ to 10 ⁻⁴
Siltstone	10 ⁻⁶ to 10 ⁻³

The existence of faults in the repository area will affect the design and layout of the repository. Even though areas of active fault movement are not likely to be considered as suitable sites for a repository, it is likely that some minor faults will be encountered during excavation. These will probably be high-angle faults that are minor structural adjustments with a low risk of reactivation. These faults will be potential pathways for the escape of radionuclides. The room and pillar layout will have to be adjusted to leave a pillar around the fault sufficiently large to provide for long-term stability of the pillar and to act as a barrier to radionuclide migration from the rooms to the fault.

In summary, the repository design should allow for rearrangement of corridor, room, and pillar geometry to isolate faults within large pillars.

3.3.4 Joints

Most rock masses are broken by relatively smooth fractures known as joints or discontinuities. These weakness planes separate intact rock blocks within a rock mass. The length of these planes (persistence) may be measured in centimeters or even hundreds of meters. The distance between adjacent joints (spacing) may also vary from a few millimeters to several meters.

Joints reflect the response of a particular rock mass to a particular event or event sequence. The properties of the joints such as spacing, persistence and opening will reflect both the mechanical properties of the host rock and the nature of the causative event. The condition of joints at the present time will also reflect the changes in their environment between the time of their formation and the present. Thus, joints formed under tension and originally open may now be tight as a consequence of changes in their stress environment.

Joint sets refer to systems of discontinuities which have approximately the same inclination and orientation. Joint populations are generally described statistically with emphasis on significant groupings. These are discussed below in terms of their orientational relationships.

Within bedded salt masses, the majority of joints parallel the bedding with spacings of 0.3 to 1.0 meters and lengths of 3 meters to an excess of 50 meters. Near-vertical joints occasionally occur, but their length ranges from 0.3 to 10 meters.

Open joints in salt are extremely rare and should not be of significant lateral extent. Joint surfaces tend to be smooth to wavy but not rough (Dames and Moore 1978).

Jointing affects the repository design primarily in the area of rock support and room stabilization and secondarily due to the relationship between joints and permeability. The existence of subhorizontal, pervasive joints may require roof support where spacings and stresses create a potential for roof fall. The existence of two or more joint sets may create blocks in the roof and cause a potential roof stability problem that will affect the design. Practice in evaporite mines is to use rock bolts rather than support sets to control roof fall. The need for roof support will depend on local conditions within the repository and may not be predictable prior to excavation.

It is possible that an abnormally pervasive set of high-angle joints, perhaps created by doming or diapirism beneath the repository, could afford a radionuclide escape pathway. The likelihood of the occurrence of such features may be minimized by limiting the allowable termal load.

In summary, the design process would consider joints and their characteristics as follows:

- o Make allowances for the unpredictability of joint patterns at depth within the repository horizon.
- o Determine the roof (and side) support requirements in accordance with expected joint characteristics
- o Locate and orient the rooms to minimize joint related instability

- o Allow for some flexibility in room location and fracture sealing to isolate joint patterns that provide a potential radionuclide escape pathway.

3.3.5 Other Features, Including Sedimentary, Solution, and Igneous Structures

There are several infrequent structures encountered in bedded salt that may escape detection during preliminary exploration. They are the result of geologic processes at work in the depositional and post-depositional bedded salt environment. The structures of interest are:

- o Breccia pipes/blankets
- o Solution channels
- o Mud plugs
- o Gas pockets
- o Brine pockets and seeps
- o Dikes and sills (igneous intrusions)

Breccia pipes, which are observed in Delaware Basin potash mines, apparently represent ancient solution features, i.e., sinkholes into which blocks of wall and roof rock have fallen. These sinkholes were formed by dissolution of salt, but it is not clear at what depth the dissolution process originated (GEI 1977). There is some evidence that dissolution must also have occurred, and may occur, at the base of or below the Salado formation. Available observations suggests that these features, as encountered in the Delaware Basin, are completely rehealed with secondary or creeped salt.

In the Salina Formation salt, Jacoby (1969) has noted features in salt mines which may represent channels (now filled with crystalline secondary salt) which had been created by post-deposition solution of the salt.

"Mud plugs" appear periodically throughout the potash sequences of the evaporites in the Delaware Basin. These features can be visualized as irregularly-shaped, vertical columns. Though their vertical dimensions are unknown, horizontal dimensions may range up to hundreds of meters. They contain a high percentage of suspended salt crystals within a salty clay matrix.

Gas pockets in the Delaware Basin are reported (unsubstantiated) to contain nitrogen (dead air). Baar (1977) states that other types of gas, including methane and carbon dioxide, may be found in salt deposits. In the Delaware Basin the gas may be under enough pressure to cause "blow-outs" while drilling (Jones, et al., 1973). In one instance, at a depth of 360 meters, the force was enough to blow the brine drilling fluid out of a drill hole.

In salt, pockets of parent liquor are trapped between and within growing crystals. The resulting brine pockets are usually extremely small but occasionally reach tens of meters (Baar, 1977). Baar mentions inflows of brine to German salt mines in excess of 50,000 m³, and in the Delaware Basin inflows of up to 3,800 m³ have been reported.

Brine seeps in potash mines have been observed to originate from clay bands. Normally, ventilation would evaporate the water, leaving "salt flowers" as evidence of the seeps. Brine seeps occasionally produce enough fluid so that ventilation will not evaporate all the water. A standing brine pool several inches deep (approximately 1,300 liters) has been observed. It is generally assumed that this brine is connate water.

A system of narrow, steeply dipping dikes cut the Salado and Castile formations in the Delaware Basin (Jones, et al., 1959; Jones, et al., 1973). In general, the dikes are a few inches to

about a foot thick, although in one potash mine a 5-meter thickness was encountered. The salt is bleached and recrystallized for a distance of from 20 to 30 millimeters from the dike contact. Joints in the dike are salt-filled, and pressurized methane pockets are also present near the contact. Small, 1- to 3-inch thick dikes have been observed in a salt mine in the Salina salt of New York. The salt appears to be undeformed at a distance of 150 millimeters from the dikes. Some dikes are brecciated in the salt but appear undeformed in overlying shale units.

Rehealed breccia pipes found in the Delaware Basin apparently pose no stability problem when encountered in potash mines. However, a major floor cave in a potash mine in the Delaware Basin may have resulted from an intersected breccia pipe (GEI 1977). Ancient solution features such as the channels observed in the the Salina Formation have had no effect on mine stability. These features, however, may afford increased permeability zones and potential radionuclide escape paths and may require sealing.

Mud plugs are an example of structures which may not be found in a surface exploration program for repository in bedded salt. These structures only represent somewhat weaker inclusions in the overall salt matrix. As such, and until in situ test data might prove otherwise, it would not be appropriate to have critical areas of the repository located within or near these features. A reasonable design alternative would be to simply leave the mud plug in place as part of a pillar which was deliberately increased in area. The major consequence of this action would be an increase in repository area. It appears that these features may have dimensions up to several hundred feet across. However, in relation to total repository area, a pillar encompassing such a single feature would represent a low percent increase in the overall area of a repository. Leaving a large pillar will require some minor modification of design layout.

Gas and brine pockets may affect the excavation phase and could be a threat to structural stability and an occupational hazard for workmen. This is especially the case for combustible gas such as methane. The repository design should eliminate the possibility of flooding or fire reaching the active storage sections of the repository.

A reasonable design solution would be to separate the depository into two isolated regions: excavation panels and waste storage/disposal panels. An excavation panel would consist of a region being developed into a given number of storage rooms and associated entries. The excavation panels would have an entry and ventilation system separate from the waste storage areas of the repository. Only at a last stage of the excavation process would physical communication be established between the newly excavated region and the waste storage area of the repository.

Small dikes such as those observed in a mine (Cargill) in the Salina salt in New York State have had no effect on mine structural behavior. It is not known what, if any, impact a 15-meter thick dike which was intersected by a mine in the Delaware Basin (Jones 1977) has had on mine structural behavior.

The mechanical properties of igneous rock and salt differ considerably. Igneous rock is stiffer, stronger, less prone to creep, and has lower thermal conductivity. Therefore, if a storage room is intersected by a dike, some local stability problems might occur. It is also possible that dikes intersecting a repository may provide a pathway for the preferential flow of groundwater and may thus pose a problem for the long-term containment of radionuclides. Until the behavior of the dike/salt combination under depository thermal conditions is better understood, it is advisable to alter design to avoid having dikes within storage rooms.

With respect to sedimentary solution and igneous structures the repository design should:

- o Allow room location flexibility to isolate potentially hazardous structures within large pillars
- o Allow for sealing of any openwork structures (breccia pipes, solution channels, dikes)
- o Design for the local containment of large, short-duration water inflows or potentially explosive gas releases .
- o Isolate the excavation area of the repository from the active storage area.

3.3.6 Mine Induced-Fractures

The excavation of any underground space produces a fracture zone around the resultant opening. The nature of this zone is a function of excavation technique, rock mechanical parameters, and opening shape.

There is little quantitative predictive information concerning intensity of fracturing around underground openings. Qualitatively, however, mechanical excavation methods produce less primary fracturing than blasting methods. Towse (1979) offers his opinion of the properties of the fracture zone resulting from mechanical excavation:

[Table 3.3.2]...indicates the estimated radius of the anticipated fracture zone around shafts and tunnels. The maximum fracture zone would be in a repository constructed in low strength rock with a high in situ stress field and a poorly placed, nonrigid backfill. The minimum fracture zone would be in a repository in high strength rock with a low stress field with an ideal rigid backfill placed under pressure.

Since permeability within the fracture zones is expected to decrease exponentially from the tunnel or shaft face, the effective conductivity of the fracture zone is computed by multiplying the peak conductivity at the face by a reduced area for the fracture zone. We assumed a reduction factor of 0.20.

An intensely fractured zone is assumed to be formed from mining activities in shale tunnels, but not in salt. All excavations are surrounded by a general fracture zone.

TABLE 3.3.2
FRACTURE ZONES IN SALT REPOSITORIES
(From Towse 1979)

Preferred Values for General Fracture Zones

	Fracture Zone Radius*	Permeability (cm/s)	Porosity
Tunnels	2.7 (R + 0.5)	10^{-4}	10^{-3}
Shaft (in salt)	2.7 (R + 0.5)	10^{-4}	10^{-3}
Shaft (in shale)	1.1 (R + 0.5)	10^{-4}	10^{-3}

*Fracture zone radius is given in meters as a function of shaft or tunnel radius. For example, for a 4 m radius shaft in shale, the width of the fracture zone is estimated at $1.1 (4 + 0.5) = 4.95$ meters. The lower part of the shaft is in salt; it is larger in diameter and is not cased and cemented as is the upper shaft in shale.

The values in Table 3.3.2 are a maximum we expect to be reached in less than 100 y. The creep behavior of salt is such that fractures may heal and reduce hydraulic conductivity to 1 percent of its original value. The expected healing-time value is 50 years with a range of 20 to 200 years. We do not expect fractured shale permeability to change significantly with time.

Mining-induced fractures around shafts and boreholes are potentially high permeability radionuclide pathways and so may pose a serious threat. Unlike limited fracturing around storage rooms, the fracturing around shafts and boreholes intersects the entire geologic column above the repository and creates a possible accessway for groundwater to enter the repository. As a result, the repository design should attempt to eliminate potential radionuclide pathways by minimizing induced fracturing, sealing fractured zones around shafts and boreholes, and isolating or lengthening possible escapeways to increase potential escape time.

The repository design should deal with induced fracturing by:

- o Selecting an excavation method to minimize fracturing
- o Selecting opening shapes and sizes to minimize stress concentration fracturing
- o Sealing all shafts and boreholes
- o Isolating boreholes within pillars.

3.4 STRATIGRAPHY OF THE REPOSITORY HORIZON

The stratigraphy of the repository horizon is the detailed three-dimensional geologic layering of the involved strata. It affects the design by defining the repository material geometry and hence the spatial arrangement of assigned material properties utilized in predicting repository behavior. In short, the repository design responds directly to the stratigraphy, and design flexibility must be in direct proportion to stratigraphic uncertainty.

The aspects of stratigraphy relating to repository design are:

- o Depth to emplacement horizon
- o Distribution and geometry of beds
- o Interbeds
- o Mineralogy and petrology.

3.4.1 Depth to Emplacement Horizon

The stratigraphic depth to emplacement is of prime importance to design consideration concerning room closure and loads exerted on structural members and seals. Depth, allowable closure, and loads will be prime determinators of extraction ratio and pillar design. Project Salt Vault (Bradshaw and McClain 1971) presents a graph relating room behavior, depth, and extraction ratio based on experience in evaporite mines (Figure 3.4.1). To quote from Project Salt Vault:

By use of this figure, the basic criteria for creating waste disposal space, or for mining operations, might be established. For example, if only a negligible amount of structural flow can be tolerated, the maximum allowable pillar load is 2000 psi, and operation to the left of curve A of the figure must be maintained. On the other hand, if some spalling and a few percent closure of the rooms can be tolerated, the pillar load can be increased to 3000 psi, and operation can be anywhere to the left of curve C. In the first case (negligible flow) it may be seen from the figure that the stability criteria cannot be met at depths greater than 2000 feet. It may also be seen that any extraction of salt at depths greater than 3500 feet. It may also be seen that any extraction of salt at depths greater than 3500 feet will produce large structural flows.

The design is affected by depth to the repository horizon in the following ways:

EXPLANATION

- A. Negligible structural flow.
- B. Very small structural flow.
- C. Some spalling possible, small floor heaves, few percent (<5%) change in dimensions.
- D. Possible large floor heaves, roof falls, considerable closure.

after Bradshaw & McClain, 1971

EFFECT OF PERCENT SALT EXTRACTION & DEPTH
ON STRUCTURAL STABILITY OF MINE OPENING

Figure 3.4.1

- o Initial assessment of repository pre-excavation stress conditions
- o Initial assessment of suitable extraction ratio.

3.4.2 Distribution and Geometry of Beds

The detailed lateral and vertical distribution and resultant geometry of the stratigraphic units involved in the repository site will determine the placement and support of rooms, pillars, and accessways.

The mechanical behavior, thermal characteristics, and hydrological characteristics of each unit must be considered and an acceptable design devised to minimize any negative impacts on the repository. The design must allow for even the low level of uncertainty in predicting stratigraphic distribution within the repository site. The design must be sufficiently flexible to allow modification of room location and to permit room abandonment and sealing should severe room-scale problems arise.

Fortunately, unless structural disruption has occurred, the bedded salt environment can be characterized as a classical geologic "layer cake." General practice in evaporite mines in many areas is to use a particular clay band as a marker unit and follow it as a guide for mining operations.

The predictability of stratigraphic variability in the repository should be reasonably good, but the design must not overlook the structural or especially the hydrologic importance of previously unrecognized units encountered during excavation. Such units, particularly if they intertongue the repository sequence and extend laterally into other strata, may provide pathways unaccounted for radionuclide migration.

The design must recognize the stratigraphic distribution of geologic strata within the zone of influence of the repository in the following ways:

- o Provide sufficient design flexibility regarding room and accessway location to allow for changes in stratigraphy.
- o Account for the mechanical, hydrologic, and thermal properties of every recognized unit
- o Provide for sealing and abandonment of areas where unpredicted lateral stratigraphic change has caused major structural or hydrologic problems.

3.4.3 Interbeds

The interbeds of concern within the repository horizon are those with markedly different mechanical, thermal, and hydrologic properties from the host salt layer. These are primarily the clay or shale bands that may be interlayered with the evaporite deposits. These bands will affect the vertical room location and pillar design, the thermal regime within the repository, and the short-term water inflow to the excavation.

The primary design impact of shale interbeds within the repository horizon is on pillar design and room height. Project Salt Vault (Bradshaw and McClain 1971) demonstrated using both modeling and in situ observation that the room closure and attendant pillar spalling was accentuated when the shale partings were located in pillars at the roof and floor interfaces. Apparently these partings act as friction reducers and reduce the effective lateral confinement of the pillars.

Clay and shale bands have a lower thermal conductivity than the host evaporite layers and therefore reduce the rate of heat conduction away from the canister storage areas. The thermal effect of clay bands near the canisters must be included in the design of storage rooms and canister containment wells.

Clay bands are often observed to seep water into an excavation in salt. This appears to be connate water released due to consolidation and drainage of the clay band. In most cases, we have observed that the resultant flow evaporates into the ventilation air before pools are formed; there are infrequent occurrences of standing pools of several hundred liters formed from seep water. Such occurrences will not pose a problem either during excavation or operation of the repository. The location of canister storage wells through clay bands should, however, be avoided.

The repository design should account for clay and shale interbeds in the following ways:

- o Design pillars such that shale partings are not at or near the roof and floor interfaces
- o Allow for additional heating due to the lower thermal conductivity of clay and shale bands
- o Allow for possible wet shale bands in the excavation phase of repository development
- o Avoid placement of canister containment wells through wet shale and clay bands.

3.4.4 Mineralogy and Petrology

The mineralogy of the host evaporite sequence is the group of identified minerals found within each stratigraphic unit, while the petrology involves the origin and resultant geometrical arrangement of the minerals within each rock type. The result is that both mineralogy and petrology (the minerals and their arrangement) govern the mechanical, thermal, and hydrologic behavior of each rock type. Evaporites have been chemically precipitated from hypersaline seawater trapped in a structural depression that was cut off or restricted from the open ocean. The sequence of deposition of evaporites from an evaporating water body and their volumes are controlled by the chemical composition of the water-salt system involved. In seawater, calcite and dolomite are normally deposited first. Then, after further evaporation salts by a factor of three or more, calcium sulfate (gypsum and anhydrite) begins to form. This is followed in turn by halite, polyhalite, and the other less-abundant salts. The solubility of a given salt and, therefore, its deposition is affected by temperature and the presence of other salts in the system. Changes in temperature and salinity during evaporation may cause reversals in the sequence of deposition. Bedded salt is usually a sequence of halite and anhydrite interspersed with thin clay seams which come from non-saline impurities in the original solution.

The halite and anhydrite usually form crystalline intergrowths or repetitive laminae on the order of one to tens of centimeters thick interspersed with clay shales of relatively equal thickness. The design must recognize the variability in mineralogy and petrology both within the repository site and among the data sources utilized in predicting mechanical and thermal behavior.

To take advantage of the thermal properties of salt, the effort should be made to place the canisters in the most homogeneous halite available within the site. If this is not possible, then care should be exercised to ensure the agreement between parametric design assumptions and the mineralogy and petrology of the waste containment horizon.

With respect to repository horizon mineralogy and petrology the design should:

- o Verify the mineralogic and petrologic similarity between the design data base and the repository horizon
- o Place the canister containment holes in the most homogeneous halite available.

3.5 ROCK MECHANICAL PROPERTIES OF THE REPOSITORY HORIZON

The rock mechanical properties are the predictive parameters used in design of the underground openings. The selection of value ranges and geometries depends on a knowledge of the geologic situation as outlined in the preceding sections.

The rock mechanical properties of interest in the design phase of a repository are as follows:

- o Strength
- o Deformation modulus
- o Creep and plasticity
- o Density
- o Hydraulic conductivity and porosity
- o Moisture
- o Response to seismic loading
- o Formation sealability
- o Ease of mining and maintaining opening.

3.5.1 Strength

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 mechanical properties are usually determined by laboratory testing of comparatively small samples. On this scale, the strength is usually observed to decrease with the increase in specimen size because of structural flaws. A constant strength is achieved in specimens which are sufficiently large to approximate the flaw distribution in the rock mass. This maximum size will vary with rock type and structure. Decreases in strength with a decrease in specimen size may also be caused by disturbances during sample preparation and should be considered in interpreting laboratory test results.

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., macroscale features such as joints and faults) must be determined separately, and these features, together with the rock material, constitute the 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 macrodeformations 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 with resulting 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. For the design of a repository in salt, the approach must be modified to account for the nonlinear and time-dependent deformation of salt (creep) and the additional effects of the significantly increased temperatures in the rock around the waste canister. Thus linear modeling approximations for a repository in salt are not valid under any circumstances.

Only 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 large confining pressure, which may be difficult or impossible to simulate in a 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 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 and must account for changing stress conditions.

The repository conditions likely to affect the long-term rock behavior are increased rock temperatures and radiation doses. 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 a reduction in strength results from an increase in temperature, although the magnitude of the effect is different for different rock types.

Laboratory tests have been conducted (Gunter and Parker 1961) 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, i.e., parallel or perpendicular to the bedding planes. This conclusion may not be true, however, with samples from different salt deposits or strata. From stress-strain curves determined for bedded salt, it is apparent that there is more strain per unit of stress in the 200°C test, and the salt exhibits marked inelastic behavior. The values of elastic modulus, compressive strength, yield strength, and apparent elastic limit that were derived from this data are shown in Table 3.5.1. It is noted that the apparent decrease in compressive strength is quite small, i.e., the rock exhibits strain without failure. The yield strength and the apparent elastic limit are used to indicate the marked nonlinear deformation of the salt at elevated temperature.

TABLE 3.5.1

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: Gunter and Parker, 1961

*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.

Comparatively little information exists on the influence of radiation on the strength properties of rock. This applies 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 crystal-line 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 doses within the repository will be comparatively small (less than a 0.5-meter 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 repository.

Some measurements of 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, have been made at 20°C and at 200°C (Gunter and Parker 1961). The data indicate that the compressive strength of bedded salt decreases and the modulus of elasticity increases with high gamma dose, but very little effect is noted until the radiation dose exceeds 10^8 roentgens.

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, and the effect is far outweighed by the significant softening as the temperature increases. The evidence tends to the conclusion that radiation effects on the behavior of the rock around the waste canister are not significant.

The design of a repository in bedded salt must:

- o Utilize strength values obtained from representative samples of repository material
- o Account kinematically for possible failure along known discontinuities
- o Account for the thermal effect on bedded salt strength.

3.5.2 Deformation Modulus

Linear elastic modeling is not appropriate for long-term repository design, but the immediate elastic response of rock salt is of interest, particularly with regard to the generation of thermal stresses caused by thermal expansion. Wawersik et al. (1977) tested rock salt samples from Carlsbad, New Mexico, sampled

at depths between 300 and 850 meters. The elastic response obtained from the testing indicated Young's modulus values between 1.6×10^7 and 2.3×10^7 kPa and Poisson's ratio values between 0.24 and 0.27. Gnirk, et al. (1975) report values of Young's modulus of approximately 1.9×10^6 psi (1.3×10^7 kPa) and Poisson's ratio of 0.28 for Carlsbad rock salt. Dames and Moore (1978) report value ranges of several moduli calculated for overburden depths of 600 meters. These are Young's modulus 2.4×10^6 to 6.9×10^6 kPa, bulk modulus 4.0×10^6 to 7.7×10^6 kPa, and shear modulus 8.6×10^5 to 1.7×10^6 kPa.

In summary, the design should account for the short-term elastic response of the salt surrounding the waste canisters to preclude the chance of localized failure or abnormal pressures on the canisters.

3.5.3 Creep and Plasticity

The mechanical response of an underground nuclear repository located in salt will be primarily influenced by the viscoplastic nature of the material in its response to applied loading. The thermal loading imparted by heat generating waste, together with effects induced by geological structures such as clay bands, can exert a significant influence on the performance of the salt pillars.

Much effort has been exerted by many researchers to establish mathematical relationships between creep strain and the the ambient stress and temperature in particular situations. These factors, together with the elapsed time, are the main influences on the amount of time-dependent formation of rock around a storage cavern.

The most crucial aspect of the development of predictive capability is the appropriate selection of a law describing material behavior (constitutive equations). However, adequate models exist only for the simplest material behavior. For materials such as salt, which exhibit time-dependent deformation and strength characteristics, no single-model type has been accepted as adequate by all workers in the field of rock mechanics. Depository structural stability is highly dependent upon the creep characteristics of the material.

In experiments for Project Salt Vault (Bradshaw and McClaine 1971), creep experiments were done on small scale model pillars for different confining pressures and temperatures. The duration of most of these tests was about 1,000 hours. The equation describing the creep of these models was found to be:

$$E = 1.3 \exp(-37/T) \exp(9.5/\sigma) \exp(3.0/t) \exp(0.30)$$

where

E = strain

T = temperature °K

σ = average pillar stress (psi)

t = time (hours)

The power law equation presented above was based on experiments in which the deformation of specimens was recorded for a particular set of stress and temperature conditions. The deformations were measured along the same axis as the applied load.

Creep flow of salt due to plasticity is influenced by three factors: load, time, and heat. A reduction in one factor can be offset by an increase in the remaining factors. The repository design must:

- o Size pillars to reduce loading to account for thermal effect and required repository lifetime

- o Provide room designs to keep room closure within allowable limits
- o Design support structures and shaft linings in response to the plastic nature of salt
- o Provide canister spacing such that salt temperature is held within allowable limits.

3.5.4 Density

The most important consideration in relation to rock mass density is the buoyant force exerted on an embedded container of waste when temperatures in the immediate vicinity of the canisters are sufficient to melt the rock or to cause plastic behavior. Under these circumstances, there will be a tendency for the waste canister to migrate upwards or downwards, depending on the relative densities of the waste package and the molten repository rock. In the case where retrieval of canisters is an objective, this type of behavior is not desirable, and the design requirement is to ensure that temperatures in the vicinity of the canisters do not result in complete loss of shear strength in the adjacent rock. The temperatures should be limited to values which will enable the rock to develop sufficient shear stress to maintain the waste canisters in their correct location.

According to Lotze, et al., (1957) and Robertson (1962), the average values of density at normal temperature of salt minerals are as follows.

<u>Material</u>	<u>Density (g/cm³)</u>
Carnalite	1.60
Sylvite	1.98
Kainite	2.10
Halite	2.16
Gypsum	2.31
Anhydrite	2.90

(In engineering calculations in Germany, the average density of rock salt is taken as approximately 2.20 g/cm³; Baar 1972).

Gussow (1968) has compiled data on salt density versus the temperature, as shown in Figure 3.5.1. The possibility that the density of the salt may change due to irradiation has not been determined.

In summary, the design should space the waste canisters to keep the adjacent salt temperatures below the threshold value where density-initiated movement may occur.

3.5.5 Moisture Effects

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

- o Erosion of softer materials by flowing water
- o Dissolution of the more soluble minerals
- o Expansion or contraction due to wetting and drying.

The most noticeable effect would be deterioration of rock surfaces; the contribution to deterioration of a repository in bedded salt is expected to be insignificant. However, the effect of an increase in temperature on bedded salt with some moisture content may be much greater, as discussed below.

SALT DENSITY AS A FUNCTION OF TEMPERATURE Figure 3.5.1

after Gussow, 1968

Samples of bedded salt heated to temperatures up to 400°C were reported by Bradshaw and McClain (1971). It was found that the salt fractured with considerable violence (decrepitated) at temperatures of around 280°C. Table 3.5.3 shows the temperatures at which fractures 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 and McClain (1971) that, to prevent sudden fracture and water release, salt temperatures should be kept below 200°C. Jenks (1972), however, has utilized a 250°C criterion for decrepitation in his calculations of brine migration. Science Applications, Inc., (1976) recommends a repository thermal design criterion that no more than 1 percent of the salt volume in a unit cell exceed 250°C. It was stated (SAI 1976) that additional research into the consequences of local effects might eliminate the need for this criterion.

TABLE 3.5.3
Fracturing Temperature of Bedded Salts
(from SAI 1976)

<u>Location</u>	<u>Number of Samples Tested</u>	<u>Fracturing Temperature (°C)</u>
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

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. This spalling would continue progressively for an unconfined sample. 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, could fracture around the emplacement hole if heated to a high enough temperature.

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 reduce the strength of the rock near canisters. These effects are discussed at length by Stewart (1978), who 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 exist insufficient in situ data to either confirm or deny this potential effect.

In summary, the design should space the canisters to keep salt temperatures below an acceptable decrepitation limit (200-250°C).

3.5.6 Formation Sealability

Shafts and boreholes are direct connection between the repository and the biosphere, and they will require sealing prior to decommissioning. Fault zones, and perhaps certain heavily fissured zones around storage rooms, may also need sealing in order to reduce the induced permeability.

Shafts and boreholes will also need sealing during the operational life of the repository, and the sealing will be of aquifer formations traversed by the shafts or boreholes.

Repository Operation.

Three types of shaft seals for the operational life of the depository are identified.

- o Sealing of the rock formation around the shaft
- o Placing a shaft lining
- o Sealing the interface between the shaft lining and the rock formation.

All three types of seal are installed as part of the shaft construction and must function as designed for an indefinite period beyond the decommissioning of the repository. The lining or sealing around the shaft is required to permit safe construction and performs at least four important functions:

- o Control water or gas inflow from aquifers or other porous zones
- o Support zones of weak or fractured rock
- o Provide anchorage for shaft hardware
- o Provide the foundation for what may become an integral part of the ultimate backfill system for long-term isolation of the repository.

Requirements determined by radionuclide escape modeling may dictate that guidelines for sealing the shaft would be more comprehensive than those that would be applied in conventional mining practice.

Post-Decommissioning.

The procedures to be adopted at the time the repository is decommissioned include final shaft sealing. This will most likely be accomplished by either plugging the shaft at selected intervals, by complete backfilling or by some combination of these two methods. At that time, additional requirements may be indicated to either reinforce or otherwise modify the seal between the lining and the rock formation.

In evaporite mines (e.g., a repository), the presence of water at high pressure around operating shafts can lead to particularly serious stability problems. Apart from the possibility of flooding caused by very large inflows, unsaturated water readily dissolves salt, and the shaft provides a natural pathway for water to enter the salt horizon. The stability problem caused by salt dissolution is exemplified by experience with a shaft in a salt dome of the Five Islands area of Louisiana. This shaft collapsed after water had dissolved the salt support away from the shaft lining. The magnitude of the permeability of both the lining-rock contact and the excavation-disturbed rock have a considerable effect on how much water reaches the salt formation.

Shaft Lining.

The technology of shaft lining design is fairly well-established. The main issues that must be addressed are the likely modes of failure (which relate in part to the construction method) and the external loads applied to the lining.

Failure may occur either through buckling or shear. Buckling can be induced by the self-weight of the lining, particularly if the design incorporates a flexible material such as bitumen between the liner and the rock. Shear failure may be induced by either water or ground pressures.

External loads may be imposed on the lining by either water or gas pressure or by deformations of the surrounding rock. Deformation occurs in all rock types after excavations are made, but would be greater in salt due to its creep properties. If the lining is placed too quickly, before the initial relaxation has occurred in the rock, loads on the lining may be excessive. This is normally not a problem with conventional shaft sinking practice. For salt, a delay of 1-1/2 to 4 days should limit the load to less than half of the overburden pressure. (Excessive delays may, in certain circumstances, lead to spalling or the development of a fracture zone.)

It is considered desirable to line shafts for their full depth. At depths of 1,000 meters, excessive pressures on the lining may be reduced by placing a compressible material such as polyurethane or bitumen between the lining and the salt. This technique may also be suitable to accommodate shearing displacement between the rock formation and the shaft liner that may be caused by subsidence or thermal uplift of the whole repository area in the long term.

The shaft liner can be made relatively impermeable by using watertight concrete and by sealing the joints in the liner. Normal industry practice would be to provide drain holes to prevent excess water pressure building up behind the liner. A water ring is then used to collect any seepage water at a lower elevation. Should seepage occur, additional grouting would be required. Typical leakage rates experienced by the salt mining industry are generally less than 250 gpm. However, large flows are handled by providing sumps (lined to prevent salt dissolution) and adequate pumping capacity. The design should also determine pumping requirements and allow for the treatment and disposal of water containing radionuclides that collect in the sumps.

Borehole Seals.

Boreholes that may have to be sealed can be classified into one of the following three categories:

- o Abandoned boreholes for which no record of location exists
- o Abandoned boreholes for which the location is recorded
- o New boreholes that will be drilled for specific purposes at a proposed repository site.

The potential for radioactive release is increased in proportion to the number of boreholes that penetrate the depository and, in particular, by the number of boreholes that cannot be located and whose condition is therefore unknown.

It has been estimated (Herndon and Smith 1976) that a search of available records should disclose up to 90 percent of the boreholes in an area. At the Webb Storage Field in Grant County, Oklahoma, 25 oil wells abandoned in the late 1920's were located from record searches. At the Lyons Gas Storage Field in Lyons, Kansas, aerial photographs proved most successful in locating old drill sites.

It may be possible to make an estimate of the number, type, and distribution of undetected abandoned holes by considering the following:

- o The type of drilling that has been previously carried out in the area, e.g., water, gas/oil, mineral exploration
- o The observed density and pattern of drilling for known boreholes.

The presence of boreholes and voids in close proximity to the repository may be detectable using remote sensing methods such as radar or other geophysical techniques.

A minimum number of exploratory holes should be drilled to obtain the necessary design data. The depth of the holes would be sufficient to penetrate from between 200 to 300 meters below the depository layer. Some of the boreholes may have to be drilled to depths far beyond the repository horizon to make sure that the repository does not lie above or in the vicinity of economic natural resources. The diameter of the holes would probably not exceed 15 centimeters. Maximum protection and improved ability to seal the holes would be obtained by sealing as soon as the holes are abandoned.

Several general statements can be made about borehole seal design. The seal must effectively bond to the surrounding medium despite possible unfavorable conditions of temperature and chemical environment (mineralized groundwater, for example). Both the seal material and the seal/rock bond should have good mechanical strength. The seal should be at least as impermeable as the environment in which it is placed and be resistant to the erosion and leaching effects of possible water flow, either vertically through the borehole or from aquifer zones.

The basic seal design parameters include the strength of the seal material, the bond strength with the formation, the porosity and permeability of the seal, and its resistance to chemical and thermal breakdown.

Seal Strength.

The seal should set up quickly to minimize contamination from drilling mud, etc., and this may dictate the use of a high, early-strength cement. While the ultimate strength should be

sufficient to resist squeezing pressures in viscoelastic materials such as salt, which may be in the range of 12 to 20 MPa depending on depth below surface, this factor is probably less important than the quality of the seal-to-rock bond. Certainly the significance of strength variations within the seal itself would be reduced by sealing the hole for its full length.

Seal-Formation Bond.

The bond between the seal and the borehole wall must be tight, without voids. It may be required to bond either to the formational rock or to steel casing or to both, and the bond will be affected by the roughness and the degree of contamination of the wall. Use of expansive cements, to offset natural shrinkage may provide an improved bond. Bond strengths have been reported (Eilers 1973) for seals made against a contaminated surface, and subsequently flushed with a variety of agents. The importance of the cleaning process is demonstrated by the range in the data, and mud acids were demonstrated to be the most effective cleaning agent.

<u>Sealant</u>	MPa	
	Bond Strength (psi)	
	<u>Salt</u>	<u>Sandstone</u>
Cement Grout	5.0-7.1	0.7-8.3
Chemical Grout	3.9-11.2	1.0-19.3

Bond strengths will vary with the stratigraphy, and it may be necessary to employ different sealing materials for different formations. The bond strength for cement seals inside steel casing will tend to be lower. Values of 1.7 to 5.8 MPa have been reported (Boa 1978). Bond strengths must be sufficient to withstand the anticipated hydraulic pressures that may be developed. The acceptable limits will depend in part on the length of the sealed zone in the borehole.

The strength of the bond is particularly important where the seal is between an aquifer formation and the borehole/shaft wall. Any percolation of water from the aquifer could in time reach a salt formation and cause dissolution of the salt, enlargement of the hole, possible collapse of the hole, and finally a direct connection between the aquifer and the repository.

Sealing Materials.

A wide variety of materials can be injected into a rock formation in the process of grouting, but long experience (Garrett et al. 1961) has confirmed that satisfactory results are obtained with cement. It can be forced into fine cracks, and its capacity to bond with surrounding rock is good. Where large fissures or voids are encountered, sand may be added as a filler. The use of the term "cement" include normal portland cement, aluminous cement and other specialized products.

In criteria cases, particularly in salt where the rock mass has numerous microfissures of extremely small width ($<1\text{mm}$), it may not be possible to seal effectively with cement. In such situations chemical sealants are used. Chemical sealants are water-thin grouts that can penetrate into thin cracks and seal them. The grouts may be either silicate gels, insoluble silicate salts, or organic grouts. Silicate gels are usually preferred, since insoluble silicate gels may not achieve adequate penetration before setting and the long-term stability of organic grouts is not known. Some research on the long-term stability of the chemical sealants when subject to thermal and mechanical loading will be necessary before using them in a repository.

Silicate gels may be acid or basic. The acid gels are not affected by sodium chloride (salt), but gel rapidly in limestone. The basic gels set up quickly in the presence of salt water and would therefore not be suitable for a repository in bedded salt-water. The gelation time can be controlled to suit the in situ conditions.

Weak chemical grouts are desirable for deep-rock penetration and will withstand high water pressures. They have limited bond strength in open fractures and should generally be followed with a cement grout to produce a strong seal. Typical laboratory test data (Eilers 1973) indicate that available silicate gels can withstand hydraulic pressures of up to 27 MPa.

Experience with grouting (Garrett et al. 1961) indicates that in hard rock the grouting pressure must be at least two and one-half times the static water pressure and that the zone around a shaft liner or shaft plug should be grouted to a minimum depth of at least 6 to 7 meters.

Permeability and Porosity.

Hydraulic conductivity for typical seal materials (Eilers, 1973) from laboratory tests on small samples aged for 3 days are of the order of 5×10^{-9} cm/sec to 2×10^{-10} cm/sec.

Hydraulic conductivity measurements on cement samples cored from the AEC No. 1 well at Lyons, Kansas (Eilers 1974), indicate values of 7×10^{-9} cm/sec to 1×10^{-9} cm/sec, slightly higher than the laboratory test values. There is no information available, however, on the long-term degradation and possible increase in permeability of cement or chemical grouts.

Similar hydraulic conductivity values are reported for three cement grouts (Rennick et al. 1977) ranging from 4×10^{-9} cm/sec to 1.4×10^{-10} cm/sec. The lower value was determined for an expansive cement. These data suggest that the permeability of the seal is likely to be as good as the formational material. It is therefore the tightness and permeability of the seal/rock bond that is likely to provide a significant hydraulic pathway, particularly as long-term changes occur.

Little data are available on porosity, but reported values (Rennick et al. 1977) range from 17.4 percent for an expansive cement to 31.3 percent, and values of up to 43 percent have been reported (Boa 1978) at a pressure of 8.3 MPa.

Thermal Expansion.

If a good bond is achieved between the seal material and the rock, the seal material should be designed so that the thermal expansion of the placed seal matches that of the formation rock in which it is contained. Failure to do this would possibly lead to cracking in the seal.

The data available, particularly concerning the long-term effects of the environment on the performance of a borehole seal, are not considered adequate to make satisfactory judgments on longterm seal performance. The uncertainty of current borehole sealing methods, particularly long-term performance, indicates that sealed boreholes should be tested and monitored.

In summary, with respect to formation sealability, the repository design should:

- o Provide access to and monitoring of all shaft seals during the operational life of the repository
- o Monitor borehole seals
- o Provide seals of suitable permeability to minimize the risk of radionuclide escape
- o Provide seals of suitable strength to minimize the risk of radionuclide escape

- o Provide seals with proper bonding, elastic and thermal characteristics to minimize the risk of radionuclide escape.

3.5.7 Ease of Excavation and Maintenance of Openings

The excavation process will contribute to fracturing around the underground opening. This will decrease stability and increase permeability, therefore requiring both increased support and hydrologic sealing. The excavation method should be designed to minimize this fracturing.

In general, the two available excavation techniques are the drill and blast method and machine excavation. Both are used in evaporite mines, but the machine method results in less overbreak and closer control of opening dimensions. The proven ability of machine excavation to cut both salt and shale should make it the preferred method for repository excavation.

Maintaining openings in bedded salt is often a problem at depths below 600 meters or where shale partings create roof fall or pillar slabbing problems.

Rock bolting is the most common method of support used in salt mines on either a regular or an as-required basis. Expansion shell bolts of varying lengths are generally used, but in areas of bad ground or where long-term stable openings are required, cement or resin-grouted bolts are sometimes used. Significant ground control problems can occur when shale seams are very close to the mine roof.

Rock reinforcement may be installed either in some form of regular pattern where ground conditions are reasonably consistent or as is deemed necessary by mine operators. Pattern bolting is generally preferred, particularly in bedded deposits.

Rational design criteria for support in rock exhibiting strong creep characteristics are not available. The experience gained in evaporite mining should allow sufficient empirical design criteria for the excavation phase, but detailed numerical modeling should be applied to predict long-term support requirements under the thermal loads present in a repository.

In summary, the design should:

- o Use the excavation method that provides the least fracturing of unexcavated rock (probably machine excavation)
- o Provide short-term rock support where necessary, especially where shale partings are present directly above the excavation roof
- o Provide sufficient support to minimize room closure due to thermal loadings
- o Provide room and pillar shape, dimension, location, and orientation that reduce the need for artificial support.

3.6 THERMAL PROPERTIES OF THE REPOSITORY HORIZON

In addition to the influence of high temperatures on the mechanical properties of rock masses (reduced strength, increased ductility), thermal stresses will be induced as a result of the expansion of the rock mass in a relatively confined environment. The nature of the thermal stress distribution will depend upon the geometrical layout of the underground repository, the magnitude and distribution of the developed temperatures, and the thermal and mechanical properties of the rock.

The temperature distribution within the repository will depend upon the distribution and heat generation of each of the high-level waste canisters, together with the thermal properties of the medium. The convective effects of circulating air (prior to backfilling) and circulating gas and/or water (after backfilling) may also have a significant impact. Heat balance may be significantly altered by phase changes such as water to steam.

For any given distribution of temperature within a repository zone, the thermal stresses developed will depend on the coefficient of thermal expansion and on the parameters describing the stress-strain response of the rock mass. These thermal and mechanical properties of the rock will be dependent upon the temperature and hence a non-linear numerical analysis will be required. In addition, the thermal conductivity values will depend upon the conditions of the rock mass, and an iterative solution procedure between the heat flow analysis and the thermal stress analysis may be required. Such a procedure will ultimately be instrumental in defining maximum permissible temperatures which can be tolerated in the zone of the repository. One of the primary concerns of thermal loading is the potential areal ground heave and formational fracturing which might occur above the repository.

Values of the mechanical and thermal properties of salt and other sedimentary rocks are presented in Table 3.6.1. 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 3.6.1

Thermal Properties of Various Minerals and Rocks

Mineral Rock	Thermal Conductivity (Watt/cm°C)	Melting Point (°C)	Linear Thermal Expansion Coefficient (%/°C)	Specific Heat (Cal/gm°C)
Halite	5.01x10 ⁻² (a) 5.35x10 ⁻² (a)	800 (d)	4.2x10 ⁻³ (b)	0.10 (c) 0.22 (a)
Polyhalite	1.55x10 ⁻² (b)	880 (d)		
Sylvite	6.94x10 ⁻² (b) 4.94x10 ⁻² (b)	770 (d)	3.7x10 ⁻³ (b)	
Anhydrite	5.40x10 ⁻² (b) 4.99x10 ⁻² (b) 5.61x10 ⁻² (b)			
Shale	1.62x10 ⁻² (45°C) (b) 1.17x10 ⁻² -3.51x10 ⁻² (c) 2/38x10 ⁻² (b)	1100 (c)	8x10 ⁻⁴ (c)	0.16 (c)

Sources: (a) Ratigan, 1976 (c) PBOD, Inc., 1976
(b) Clark, 1966 (d) Brokaw et al., 1972

The thermal conductivity of salt appears to be quite sensitive to temperature (Birch and Clark 1940). The thermal conductivity of a single halite crystal decreases across a range of approximately 13×10^{-3} to 5×10^{-3} cal/cm-sec-°C as temperature increases from 0 to 400°C.

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 salt 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.

Coefficients of linear thermal expansion are also given in Table 3.6.1, and it is noted that the linear thermal expansion coefficient for salt is approximately five times greater than that for shale. Values for linear thermal expansion coefficients are generally quoted for a specific temperature range.

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 affect 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.

Prior to decommissioning or backfilling, the flow of ventilating air through the emplacement rooms will provide a considerable heat sink, removing significant amounts of 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 (Ratigan and Van Sambeck 1978) 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 midplane are reduced for almost 300 years.

The principal advantage of ventilation is 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 long-term problems caused by thermal expansion and uplift. This conclusion is predicated upon a 5-year ventilation period for HLW and a 25-year ventilation period for spent fuel.

In summary, the design must account for the thermal properties of the repository horizon by adjusting the canister spacing to keep the thermal load below critical levels both during the operational life (ventilated case) and after decommissioning (unventilated case) of the repository. Critical thermal loads will be those rock temperatures that endanger the structural integrity of the repository.

3.7 HYDROLOGIC PROPERTIES OF THE REPOSITORY HORIZON

Hydrologic properties of the repository horizon are necessary in assessing four processes that are of importance to the design of a repository in bedded salt. They are:

- o Water Inflow. Inflow to the bedded salt repository will be extremely low unless connection is provided to overlying aquifers by faulty borehole or shaft seals. During operation no special designs to handle normal inflow will probably be needed. An exception to this

could arise if significant packets of gas and/or brine are encountered during excavation. After decommissioning, the rate of inflow to the repository determines resaturation and repressurization time.

- o Natural Groundwater Flow. Hydrologic properties of the repository will determine the naturally occurring groundwater flow, if potential for nuclide release via the natural flow may be assessed from knowledge of the groundwater regime.
- o Man-made or Man-induced Groundwater Flow. Hydrologic properties determine potential flow and nuclide release through the shaft seal, backfill, boreholes, fractures (induced by mining) etc. The design should try to minimize or eliminate these potential pathways.
- o Long-Term Changes to Groundwater Flow. Hydrologic parameters are necessary to determine the effects of long-term salt dissolution, climate change, faulting and tectonic activity upon waste containment.

It is important that due consideration be given to these processes during the design of the repository. The hydrologic properties of a repository may be characterized by the following:

- o Hydraulic conductivity
- o Hydraulic gradients
- o Porosity
- o Specific storage
- o Dispersivity
- o Retardation factor
- o Geochemical characteristics
- o Composition of pore fluids

3.7.1 Hydraulic Conductivity

Hydraulic conductivity (often called permeability) is a proportionality constant relating the Darcy velocity of a fluid (acutally the volume flux rate) to the hydraulic gradient as defined by:

$$q_i = -K_i \delta h / \delta x_i \quad 3.7-1$$

where:

q_i = Darcy velocity (flux rate) in i direction

K_i = hydraulic conductivity in i direction

$\delta h / \delta x_i$ = hydraulic gradient in i direction

The above equation indicates that hydraulic conductivity is a directional property of porous media. In layered sedimentary rocks including bedded salt, the hydraulic conductivity in the horizontal direction can be several orders of magnitude greater than that in the vertical direction.

Hydraulic conductivity is a measure of the ability of a porous media to transmit fluid of a particular density and viscosity. It is often convenient to separate out the fluid properties from the porous media properties. This is accomplished by expressing hydraulic conductivity as:

$$K = \frac{k \rho g}{\mu} \quad 3.7-2$$

where:

K = hydraulic conductivity

k = intrinsic permeability

ρ = fluid density

g = gravitational acceleration

μ = fluid viscosity

Bedded salt deposits are usually found in sequence with limestone, dolomite, and anhydrite which can isolate them from percolating waters by acting as seals. Bedded salts commonly contain impurities and thin shale seams. These shale seams form the major permeable pathways in bedded salt. Because they are horizontally bedded they contribute to a high horizontal to vertical anisotropy in bedded salt. Most brine-seeps in productive mines occur along these seams. They are thought to be the result of pressure release and usually continue only for a short time.

Permeability tests have been made on laboratory samples of both bedded and dome salts. Gloyna and Reynolds (1961) concluded that if flow occurs in a rock salt specimen, it must occur through fractures or intercrystalline planes and not through the salt crystals. They measured intrinsic permeabilities for dome salt from effectively zero to $1.5 \times 10^{-9} \text{ cm}^2$ and for bedded salt from effectively zero to $2.3 \times 10^{-13} \text{ cm}^2$ (10^{-5} cm^2 is approximately equal to 1 cm/sec for pure water at 20°C). These values were increased using a non-reactive fluid (helium or kerosene). Permeabilities decreased with increased stress and also with time. Many of the fractures which transmitted fluid initially were thought to be caused by stress relaxation when the samples were removed from their in-situ environment. These fractures start to close with increased pressure and continue to do so over time. Bedded salt was found less permeable than dome salt which Gloyna and Reynolds attribute to the larger amount of impurities present in the bedded salt. Permeabilities measured using brine were highly variable but averaged only 32 percent of the nonreactive fluid permeabilities. Porosities varied from 1.71 percent in the dome salt to 0.59 percent in the bedded salt. Katz and Coats (1968) report intrinsic permeabilities of rock salt from effectively zero to

10^{-9} cm² and porosities from 0.6 to 2.0 percent. It seems possible that overburden pressure will cause permeability channels in salt to heal resulting in little if any permeability.

Determination of horizontal and vertical hydraulic conductivity (or permeability) of the bedded salt will be critical to design. The hydraulic conductivity of the bedded salt will directly effect such design factors as pillar dimensions around boreholes or structural discontinuities, location of repository with respect to other mines, boreholes, or structural discontinuities, and others.

3.7.2 Gradients

Gradients define the magnitude and direction of the driving force(s) causing fluid flow. Such flow causes repository resaturation and repressurization and results in nuclide transport.

The magnitude and direction of all gradients is an important factor in repository design. It can influence the location of the repository within the host rock, the thermal output of the repository and other design considerations.

Gradients may either be naturally occurring, that is they exist whether the repository is there or not, or they may be induced by the repository. A number of different gradients can be acting upon a fluid with their cumulative effect determining fluid flow.

Gradients are usually determined by measuring fluid parameters. Most often fluid pressure is used to determine gradient but such factors as temperature and density are also important.

In bedded salt environments, naturally occurring gradients and those induced by the repository will be difficult to measure because extremely low permeabilities and the general lack of significant amounts of pore fluid will cause measuring devices (i.e., piezometers) to respond poorly. Estimates of hydraulic gradient can be made based upon measured heads in aquifers (if any) overlying and underlying the repository host rock. Such estimates can result in substantial errors if other gradients are acting on the fluid.

3.7.2.1 Hydraulic Gradient

Hydraulic gradient is the rate of change in hydraulic head. In the absence of other gradients it causes fluid flow as shown in Equation 3.7-1. Hydraulic gradient will probably be the major force causing fluid flow in most situations.

3.7.2.2 Density Gradient

Differences in fluid density within a porous media can result in gradients which act in addition to the hydraulic gradient. These density gradients result from fluid density variations caused by salinity or temperature and may act in the direction of the hydraulic gradient or oppose it. In the repository host rock the major cause of any density gradients would be the high temperatures produced by the waste. Repository design should consider the potential effects of density gradients. Of primary consideration would be the thermal output of the repository as determined by canister thermal output and spacing.

3.7.2.3 Osmotic Gradient

Some earth materials such as shale and clay behave as natural semipermeable membranes which retard or prevent passage of charged ionic species. Osmotic gradients can occur where two

is an osmotic pressure difference. The amount of osmotic pressure developed depends, of course, on the salinity and it can be as much as 50 bars if the same solution is 25°C on one side and 80°C on the other side of the membrane.

3.7.2.4 Threshold Gradient

Some evidence indicates that in certain types of porous media no flow will occur until a minimum threshold gradient is reached. Clays in particular, have been observed to display threshold gradients. It is possible that bedded salts which contain a significant clay or shale content could also exhibit threshold gradients. If so, hydraulic gradients would have to be sufficient to overcome the threshold gradient before any flow could occur.

3.7.3 Porosity

Porosity is the ratio of the volume of the voids in the rock to the total volume. Primary porosity is formed when the material is deposited and consolidated. Secondary porosity forms after the rock is deposited and results from such phenomena as joints, fractures, solution or faults.

The term effective porosity is often defined as the ratio of void through which fluid flows (interconnected voids) to the total volume. In terms of solute transport it is defined as the porosity value which when divided into the Darcy velocity gives the true average flow velocity of fluid through a porous medium. The two definitions above are not necessarily equivalent, particularly in fractured media where a large proportion of the fluid can be carried by a very small proportion of the voids.

The total porosity of the host rock is of little significance to repository design. Of major significance however, is the porosity of the material used to backfill the repository after the waste canisters are emplaced. The time to resaturate the repository after abandonment will vary directly with the amount of pore space available in the backfill. Therefore, a high porosity backfill could be advantageous if it meets other design criteria (i.e., strength).

Effective porosity is used here with reference to the definition applicable to solute transport as given above. Effective porosity of the bedded salt directly affects the time for solute transport. Since many of the design features of the repository might be based upon the probable time for nuclides to travel through the bedded salt, effective porosity does have a significant effect upon design. An example is the design pillars around exploratory boreholes or structural discontinuities and the location of the repository (areally and vertically) with respect to other mines, boreholes, or structural discontinuities.

No values of effective porosity in bedded salt have been located. As mentioned in Section 3.7.1, porosities have been measured in both dome salt and bedded salt core samples. Gloyna and Reynolds (1961) report porosities varied from 1.71 percent in dome salt to 0.59 percent in bedded salt. Katz and Coats (1968) report porosities in rock salt from 0.6 to 2.0 percent. These values represent total porosity and not effective porosity. Also, the use of these measured values as total porosities of the rock mass is extremely questionable because of the stress release experienced by the core samples. It is quite possible that in-situ stresses cause salt to heal resulting in little if any porosity.

aqueous phases having different salt concentrations are separated by a semipermeable membrane. At constant temperature, a greater net transfer of water will occur from the less saline solution through the membrane into the more saline solution. This will cause the pressure to increase in the more saline solution and decrease in the less saline solution, if the two solutions are confined. Osmotic pressure is the hydrostatic pressure difference across the membrane which results from a greater net transfer of water from the less saline side to the more saline side of the membrane. Alternatively, the pressure that must be applied to the more saline side of the membrane to cause the passage of water to be the same in both directions, is equal to the osmotic pressure. An equation to express the relations between osmotic pressure and solution activity, derived from the thermodynamic arguments, is:

$$\pi = \frac{RT}{V_{H_2O}^0} \ln \frac{\alpha_{H_2O}^I}{\alpha_{H_2O}^{II}}$$

where:

π = osmotic pressure

R = the gas constant

T = absolute temperature

$V_{H_2O}^0$ = the mean molar volume of H_2O , and

$\alpha_{H_2O}^I + \alpha_{H_2O}^{II}$ = the activities of water in solutions I and II, respectively.

Theoretically, a halite saturated seawater solution against pure H_2O ($\alpha_{H_2O} = 1.0$) would be about 500 bars.

If a temperature difference exists across the membrane, an additional factor is introduced. If the two solutions have the same salinity but are at different temperatures, the chemical potential of H_2O will be equal across the membrane when there

3.7.4 Specific Storage

The specific storage is the volume of fluid taken into or released from storage in a unit volume of porous media per unit change in hydraulic head. It is related to the compressibility of the rock matrix and the pore fluid. For porous media with high permeability the relationship can be expressed as (Domenico and Mifflin 1965):

$$S_S = \beta n \gamma_L + \alpha \gamma_L$$

where:

β = compressibility of liquid (water)

n = total porosity

γ_L = unit weight of liquid (water)

α = compressibility of porous media matrix

The applicability of this equation to media with low permeability is very uncertain.

Specific storage is not a critical factor in repository design. It is significant only when transient pressure response in the repository host rock is considered such as during depressurization (mining) and repressurization (post-decommissioning).

3.7.5 Dispersivity

Dispersion describes the spreading of a tracer when introduced into a flow domain and includes both mechanical and dispersion and molecular diffusion. Mechanical dispersion results from the movement of the fluid through the porous media and is the dominant process at high velocities. Molecular diffusion results from the physiochemical properties of the fluid and is dominant at low velocities (Reddell and Sunada 1970).

Dispersivity, which is a characteristic length property of the porous medium, is much larger when determined in the field than when determined in the laboratory (Cherry et al. 1975). The size of dispersivity is related to the size or scale of heterogeneities within the flow system. At the microscopic (laboratory) scale, dispersivity is the consequence of the tortuosity of the media pore space, velocity gradients in the pore spaces and variations in pore space dimensions. At the macroscopic (field) scale it is primarily due to the divergence of flow paths resulting from heterogeneities in aquifer properties, particularly hydraulic conductivity.

Dispersivity is not of major concern in repository design. It pertains primarily to the extent and rate of spread of any nuclide plume. However, consideration of dispersion in repository design may aid in locating the repository so as to minimize impacts of nuclide release.

3.7.6 Retardation Factor

Adsorption and other chemical processes can cause retardation of nuclides. The degree to which they are retarded depends upon the nuclide species, the geochemical character of the rock, and the composition of the pore fluid.

A retardation factor is used to relate the average pore velocity of fluid to that of a nuclide species. For instance, a retardation factor of 1,000 indicates that the average velocity of the nuclide is 1,000 times slower than that of the pore fluid. Retardation factors can vary from 1 to about 10,000 depending upon the situation. In bedded salts the retardation factor for all nuclide species will probably be near or equal to one due to the saline composition of the pore fluids. Thus, retardation may not really be a factor in the host rock.

Artificial means of increasing retardation are possible as for instance, encasing the canisters in a clay which provides good retardation characteristics. However, any design relying upon nuclide retardation must take into account the saline environment and the resulting potential for contamination of the retardant substance by brine, thus making it inoperative.

3.7.7 Geochemical Characteristics of the Rock

The geochemical and petrographic composition of bedded salt determine the composition of pore fluid and influence the chemical reactions between the rock and the nuclides carried by the fluid. In addition, the geochemical character of bedded salt may control the formation of osmotic or density gradients.

Probably the most important geochemical characteristic of bedded salt is its high solubility in freshwater, about 360,000 mg/l. The term dissolution front is used to describe the zone of active solution of the salt. This zone requires circulation of fresh groundwater because salt saturated groundwater may actually act as a barrier to further solution. One mechanism for solution collapse features is the change of anhydrite (CaSO_4) to gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). There is a 30 to 58 percent increase in volume creating pressures between 300 to 10,000 psi. One uplift analyzed in the field gave 35 to 42 percent volume increase and 2,000 psi uplift pressure (Brune 1965). Buckling of beds during hydration will cause cracking and open waterways for subsurface solution. This uplift seems to be restricted to moderate depths around 500 feet. At greater depth in the area investigated, rock overburden pressure was sufficient to reasonably contain the expansion pressures.

Solution features are not restricted to the presently active dissolution front or zone. Hydration, solution and the related overlying slumping and subsidence may have occurred during a variety of erosion cycles in the past. Dissolution, which is not restricted to a single front, may be active along a series of zones. Buried solution features may be healed by recrystallization of salt or by plastic flow into the void areas. They also may be partially open with the subsiding formation forming a cap that seals the salt from circulating water.

Some operating salt mines have experienced water inflows, sometimes relatively large, attributed to connection with aquifers resulting from poor shaft seals, leaky boreholes, or fractures caused by mining. These inflows may increase with time and may eventually dissolve large volumes of salt forming breccia pipes and other solution and collapse features.

3.7.8 Composition of Pore Fluids

Generally very little fluid exists in bedded salt with the result that most salt mines are very dry. Often the only evidence of fluid inflow are deposits of salt formed by evaporation of brine at locations where shale seams intersect the mine.

Within the salt body itself, large pockets of brine may exist separate from that found within the shale seams. Some mines have experienced brine inflow of up to 100,000 gallons when they drilled into such a pocket. This may be connate water or water that was trapped when the salt healed a flaw. Small bubbles of brine may be included within the salt crystals as in the Hutchinson salt of Kansas. Pockets of gas also exist within salt bodies. Both the brine inclusions and the gas may be under great pressure.

The brine is in saturated equilibrium with the rock salt and thus has little potential for further dissolution. Increased temperatures near the repository could raise solubilities and result in some additional dissolution. However, the brine would quickly reach equilibrium and upon a decrease in temperatures with time, salts would precipitate out of the brine.

A typical analysis of brine from a mine in bedded salt is shown on Table 3.7.1. Total dissolved solids content of the brine is over 500,000 mg/l which exceeds the solubility limits of halite (approximately 360,000 to 390,000 mg/l depending upon temperature). This is caused by the presence of other evaporites such as sylvite, polyhalite, kieserite, and carnalite which can have extremely high solubilities.

TABLE 3.7.1
REPRESENTATIVE CHEMICAL ANALYSIS OF BRINE
(SAMPLE FROM A BEDDED SALT MINE IN NEW MEXICO)

<u>Constituent</u>	<u>Concentration</u>
Alkalinity (ppm)	465
Chloride (ppm)	208,000
Specific Conductivity (mhos/cm)	1.38×10^{-2}
Nitrate (ppm)	7.9
Nitrite (ppm)	92
pH	6.15
Total Dissolved Solids (ppm)	512,000
Sulfate (ppm)	18,405
Calcium (ppm)	487
Magnesium (ppm)	41,150
Potassium (ppm)	28,250
Sodium (ppm)	28,250
Total Hardness (ppm)	175,000
Carbonate (ppm)	0
Bicarbonate (ppm)	465
Fluoride (ppm)	0.39
Specific Gravity	1.229

In summary, hydrologic parameters or characteristics of a repository and its surroundings will determine the long-term waste containment capabilities of the repository. According to these characteristics, it may be necessary to increase or change the containment capabilities of parts of a repository or to change the design of subsystems in order to meet containment objectives.

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