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REFERENCE REPOSITORY DESIGN CONCEPT FOR BEDDED SALT

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PREFACE

The purpose of this report is to establish a reference design concept for a repository in bedded salt, to be used as a baseline design for the analysis of pre- and post-sealing performance of deep geologic repositories in this medium. The performance analysis of a deep geologic repository is dependent upon the descriptions, assumptions, and parameters used to characterize it. Only subsurface aspects of such a design are considered here, and only those characteristics of the design relevant to overall repository performance will be considered.

The overall objectives of a deep geologic repository as stated in the draft regulation 10 CFR 60 are that the repository shall be designed so that (1) radiation exposures and releases of radioactive materials comply with all applicable environmental and safety standards, (2) the retrieval option is preserved for a period of 50 years after all waste has been emplaced, (3) the time period for retrieval is comparable to that for emplacement, (4) the in situ environment for the waste package promotes containment of radionuclides for at least 1000 years after decommissioning, and (5) that the repository provide containment of all radionuclides for at least 1000 years after decommissioning.

The achievement of these objectives will depend upon the selection of a suitable site, a complete understanding of the physical processes that occur in a repository, the design of the repository system, and finally, the ability to confidently predict its behavior over a long period of time.

In this report, we discuss the impacts on repository design of the geological and hydrological system, we present a design concept to be used as a basis for future analysis, and finally, we discuss briefly the design process that may be used in the design, exploration, construction, and licensing of a deep geologic nuclear waste repository.

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ABSTRACT

This report presents a reference design concept for the subsurface portions of a nuclear waste repository in bedded salt. General geologic, geotechnical, hydrologic and geochemical data as well as descriptions of the physical systems are provided for use on generic analyses of the pre- and post-sealing performance of repositories in this geologic medium. The design concepts are presented with the waste isolation objectives set forth in the U.S. NRC Draft Regulation 10 CFR 60 in mind.

The geology of bedded salt deposits and the regional and repository horizon stratigraphy are discussed. Structural features of salt beds including discontinuities and dissolution features are presented and their effect on repository performance is discussed.

Seismic hazards and the potential effects of earthquakes on underground repositories are presented. The effect on structural stability and worker safety during construction from hydrocarbon and inorganic gasses is described.

Geohydrologic considerations including regional hydrology, repository scale hydrology and several hydrological failure modes are presented in detail as well as the hydrological considerations that effect repository design. The geotechnical aspects of stress state, rock mechanics, thermal and radiological effects of bedded salt and associated strata are discussed at length. Geochemical reactions affecting both the rock mass properties and waste migration are presented. The physical repository system is described and the types and inventories of nuclear waste to be stored in the reference design are discussed. The structural performance of a repository includes its thermomechanical response and some discussion of scale effects and structural modeling.

Operational phase performance is discussed with respect to operations, ventilation system, shaft conveyances, waste handling and retrieval systems and receival rates of nuclear waste. Support facilities are discussed that are necessary for the operation of an underground facility handling radioactive materials. Operational accident scenarios are presented and very general estimates of radiological accidents during emplacement or retrieval are made based on the nuclear industry and statistics for underground non-metal mines.

Performance analysis of the post sealing period of a nuclear repository is discussed and parameters to be used in such an analysis are presented along with regulatory constraints. Some judgements are made regarding hydrologic failure scenarios.

Finally, the design and licensing process, consistent with the current licensing procedure is described in a format that can be easily understood.

1.0 GEOLOGY OF BEDDED SALT DEPOSITS

1.1 Introduction

The geologic characteristics of bedded salt deposits establish the framework within which a nuclear waste repository in this medium must be designed, constructed and operated. Because of the effects upon salt deposits of slight variations in such geologic parameters as stress, groundwater movement and chemistry, degree of isolation and confinement and characteristics of interbeds, the design and operation of a nuclear waste repository in bedded salt may have to be significantly more sensitive to the geologic environment than the design and operation of a repository in more rigid and/or massive materials such as basalt or granitic rocks.

As shown in Figure 1, bedded salt deposits have been identified in 17 sedimentary basins within the coterminous United States. These occurrences range from relatively minor deposits of impure salt mixed with other rocks as in the Saltville, Virginia, area to regionally extensive, thick, and relatively pure deposits such as those found in the midcontinental Permian Basin and the Michigan Basin of the northeastern United States (Johnson and Gonzales, 1978).

It should be noted that of the very limited number of locations that have been considered in depth as potential higher level nuclear waste disposal sites, two are in bedded salt deposits. These are the Lyons, Kansas (Project Salt Vault) site and the Waste Isolation Pilot Plant (WIPP) Site in southeastern New Mexico. The locations of these two sites are shown in Figure 1. Both the Lyons, Kansas and southeastern New Mexico WIPP sites are located in the Permian Basin salt deposits.

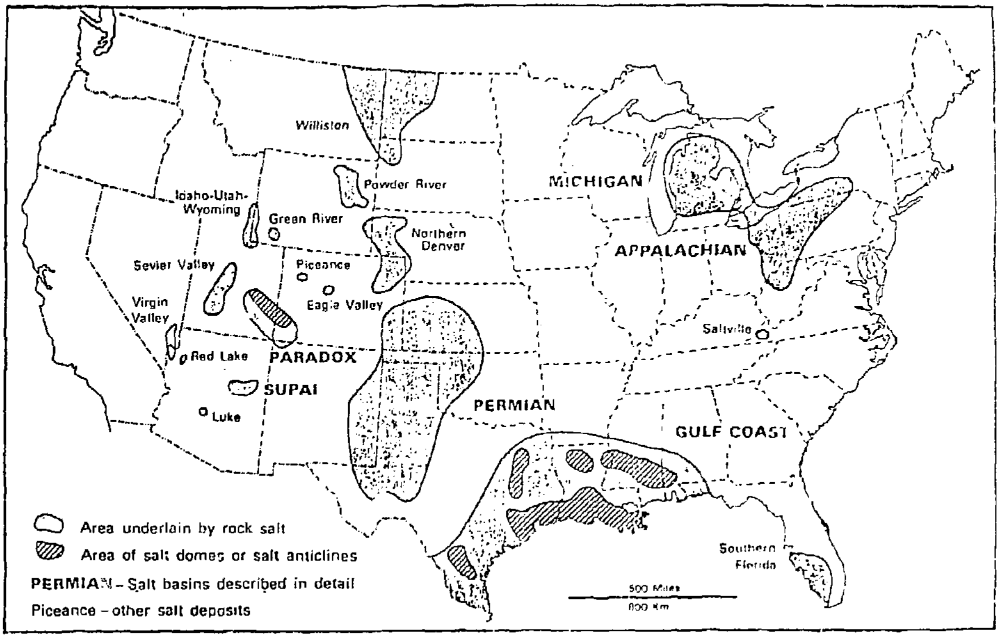


Figure 1: Map showing rock salt deposits in United States.

Geotechnical studies conducted at Lyons, Kansas and at the WIPP site provide a major portion of the information available regarding bedded salt as a potential medium for nuclear waste disposal. Data from the WIPP site is particularly current and is therefore summarized wherever pertinent in this report.

1.2 Regional Stratigraphy of Salt Deposits

Evaporite deposits (including bedded salt) represent unusual although locally important accumulations within marine sedimentary basins that have formed as a result of downwarping of portions of the earth's crust near continental margins. Occasionally, bedded salt deposits may form in lacustrine environments that are entirely of continental origin.

Bedded salt deposits usually differ significantly in composition from deposits that would result if a body of sea water were merely isolated and allowed to evaporate to dryness (Baar, 1977). Rather, evaporite deposits exhibit a cyclical repetition of members representing stages in the restriction of circulation of marine waters into a basin and the concentration of soluble salts by partial evaporation. An idealized evaporite sequence is illustrated in Figure 2, which shows the vertical succession of lithologies. This ideal cycle is commonly interrupted by local clastic deposition.

The vertical lithologic succession is accompanied by a similar lateral zonation of the evaporite deposits in the basin as shown in Figure 3. The deposits form a concentric pattern with the most saline deposits occurring near the center of the basin.

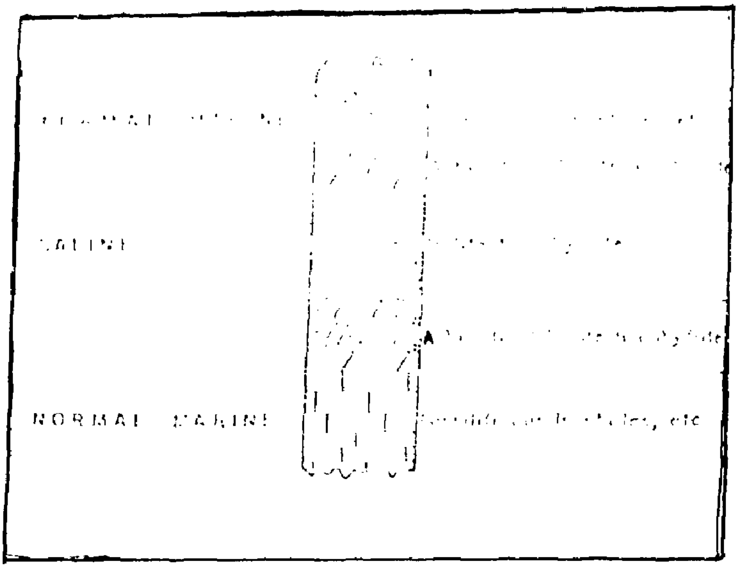


Figure 2: The ideal evaporite sequence, showing a cyclic repetition of stages in restriction of normal marine circulation and concentration of soluble salts (modified from Krumbein and Sloss, 1963).

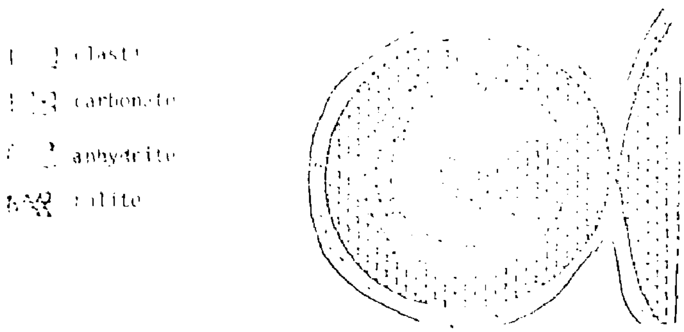


Figure 3: The evaporite basin model. A map view showing the distribution of clastic and evaporite deposits in a restricted marine basin (modified from Krumbein and Sloss, 1963).

Overall basin sedimentation depends upon such geologic factors as relative uplift of adjacent continental areas, basin subsidence, rate of sediment supply, climate, and the types of source rocks available to contribute sediments to the basin. Within a given sedimentary basin, different types of sedimentary deposits or facies may be accumulating simultaneously at different locations. For example, thick deposits of clastic sediments (sands, silts and clays) may be forming as river deltas along the basin margin while biologic activity on shelves and along reefs may result in carbonate deposition offshore. These features are also shown diagramatically in Figure 3.

The resulting sedimentary patterns vary in time and space and, therefore, differing suites of sedimentary rocks are found enclosing the salt-bearing strata from basin to basin. Examples of differences can be observed by comparisons of the composite stratigraphic sections developed for four basins by Dames and Moore, Inc. (1978) as shown in Figure 4.

Salt deposition may be restricted to one stratigraphic unit as in the Supai Basin of eastern Arizona shown in Figure 5, or may occur several times during a basin's history as in the Permian Basin of the U.S. midcontinent as shown diagramatically in Figure 6.

While each of the major salt basins has its own distinctive stratigraphic sequence, a review of the descriptions of the major salt basins provided by Johnson and Gonzales (1978) indicates that three broad groupings may be identified. These groupings are of particular signifi-

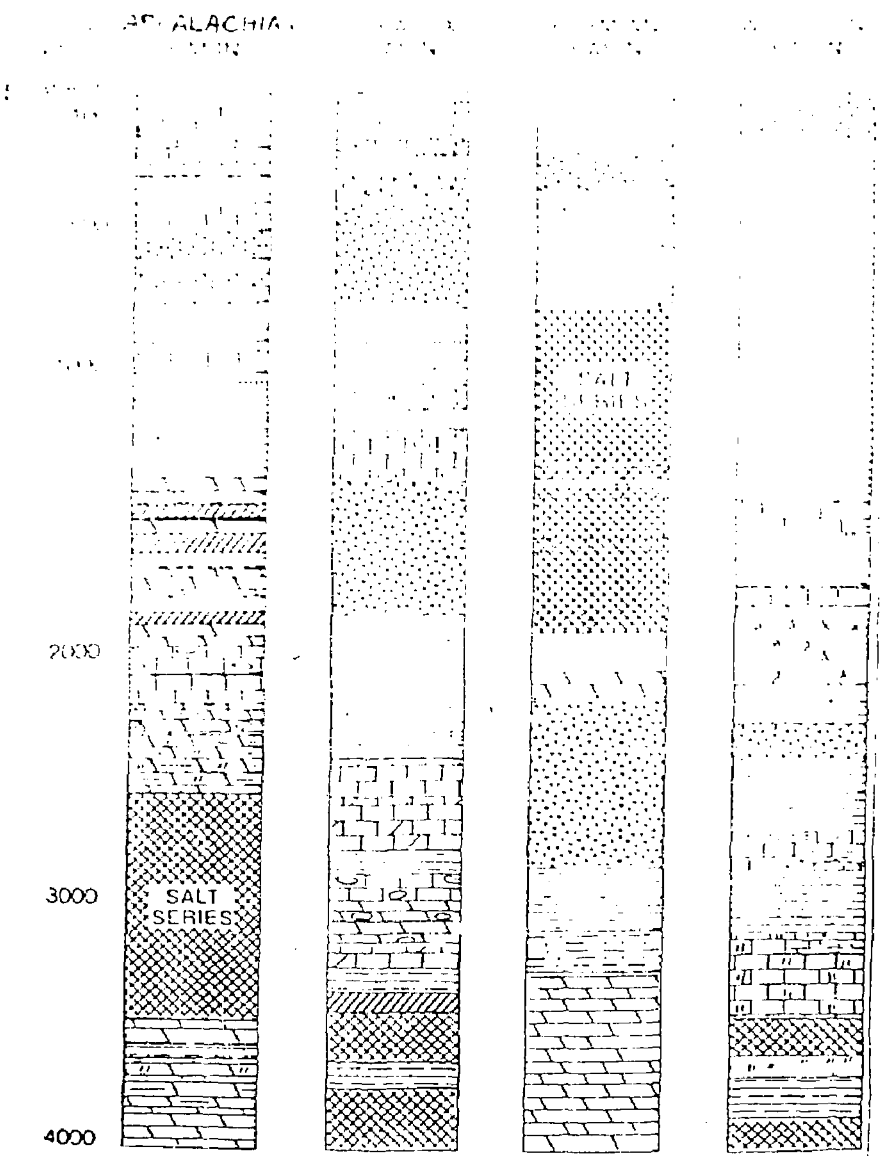


Figure 4 Composite stratigraphic
adapted from Dames and Moore (1978).

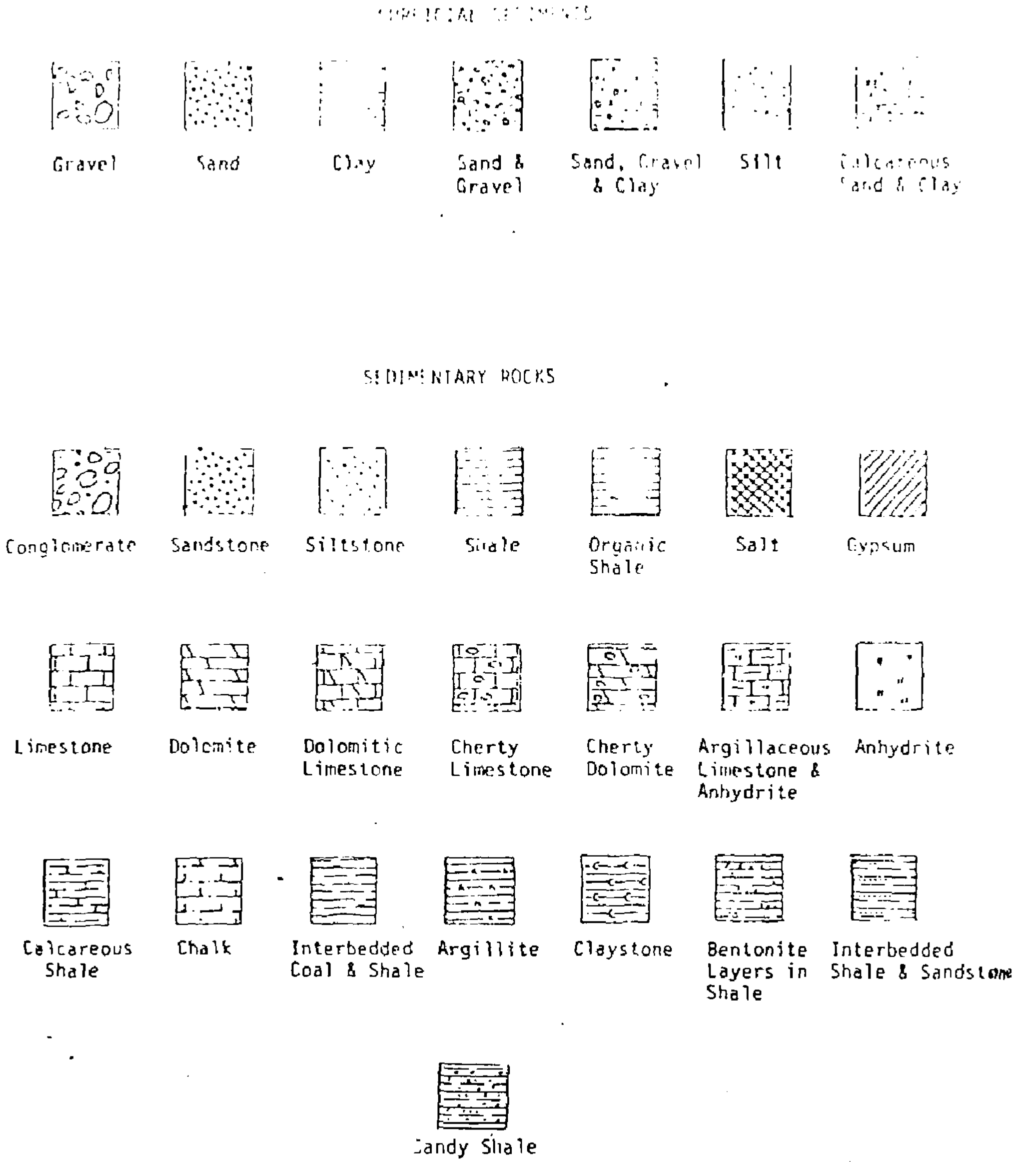


Figure 4 (Continued)

Note: Lithologic symbols from Ridgeway, J.L., 1920, The Preparation of Illustrations for Reports of the United States Geological Survey, Washington, D.C.

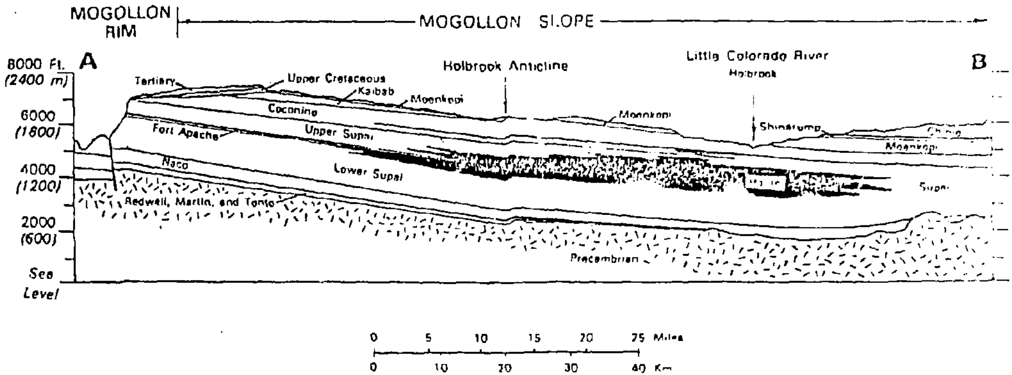


Figure 5: Generalized geologic cross section through Supai salt basin (modified from Brown and Lauth, 1958).

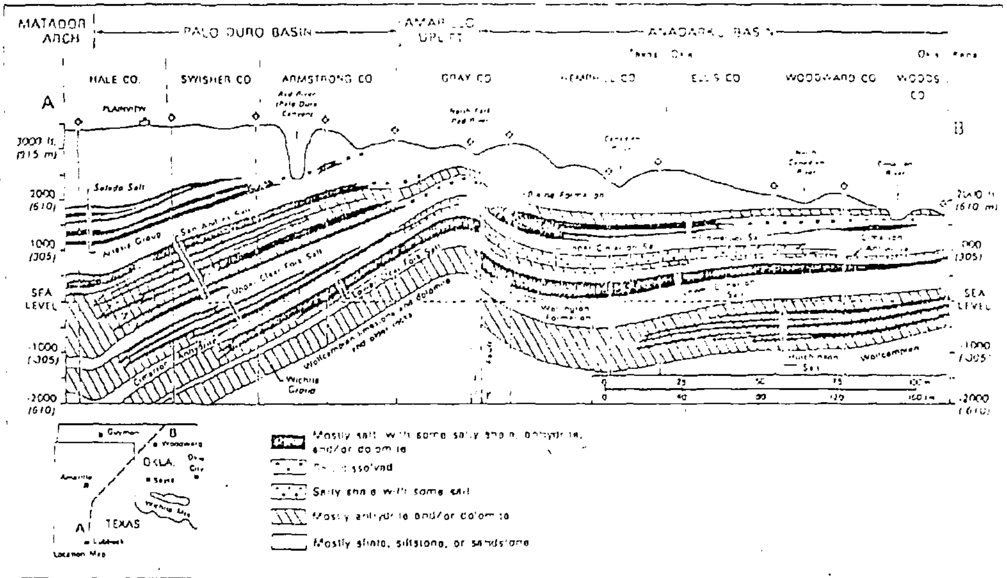


Figure 6 Generalized structural cross section showing Permian salts and associated strata in Texas Panhandle and western Oklahoma (from Johnson, 1976).

cance in developing generic models needed to provide a framework against which detailed performance models can be assessed. The groupings are:

- Basins in which predominantly carbonate sedimentation preceeded and followed deposition of the salt-bearing sequence. Major basins in this category include the Appalachian, Michigan and Paradox basins. The deep, little studied, south Florida Basin may also fall into this category.

- Basins in which clastic sedimentation is predominant. These include the Permian, Williston[1], North Denver, Eagle Valley, Powder River and Supai Basins. The Gulf Coast and Sevier Basins also fall into this category, although carbonates, chalks and marlstones are commonly interbedded with the clastics and therefore, these basins are of somewhat hybrid character.

- Continental basins of Tertiary and Quaternary age in which thick but laterally restricted salt deposits appear to have formed by cyclic filling and evaporation of playa lakes. Examples include the Luke, Red Lake and Virgin Valley Basins located in the arid southwestern United States. These basins occur in the tectonically active Basin and Range province.

1. Salt associated with carbonate rocks occurs at great depth within the Williston Basin.

A detailed stratigraphic section at the southeastern New Mexico (WIPP) site is presented in Figure 7. This section provides a detailed example of bedded salt deposits enclosed by dominantly clastic sedimentary rocks. Figure 8 shows a somewhat more generalized stratigraphic section for the Michigan Basin. In this basin, the salt deposits are largely overlain and underlain by carbonate rocks.

Figures 7 and 8 illustrate the complexities of actual sedimentary sequences associated with bedded salt deposits. Such sequences require simplifying assumptions before near or far field performance models can be constructed. However, such departures from geologic reality can result in serious errors in predicted performance unless the simplifying assumptions are made by a group which includes experienced geologists and engineers skilled in rock mechanics as well as persons experienced in the construction and exercising of numerical models. Determination of appropriate assumptions can best be made when generic or site specific performance models are developed. Representative generic parameters for rocks associated with bedded salt deposits are provided in Tables 6 and 7 in Chapter 7.

It is important to recognize that no single generic sequence of strata can adequately represent the bedded salt environment. Dames and Moore Inc. (1978) sought to resolve this problem by an averaging process. As discussed elsewhere (Carpenter and others, 1980), this resulted in a composite stratigraphic section unlike any actual salt-bearing basin within the coterminous United States and therefore resulted in generic modeling of questionable real value.

EXPLANATION

LITHOLOGIC SYMBOLS

- Sandstone
- Mudstone; siltstone; silty and sandy shale.
- Shale
- Limestone
- Dolomite
- Cherty limestone and dolomite
- Shaly limestone
- Anhydrite (or gypsum)
- Interlaminated anhydrite-calcite
- Halite (rock salt)
- Granitic rocks

ERA	SYSTEM	SERIES	FORMATION	APPROX. DEPTH TO CONTACT AT SITE	PRINCIPAL LITHOLOGY	APPROX. THICKNESS (feet)
CENOZOIC	RECENT		Surficial sand	10	BLANKET SAND AND DUNE SAND. SOME ALLUVIUM INCLUDED	0-100
	QUATERNARY	PLEISTOCENE (Kansan?)	Mescalero caliche & Gatuna Fm	40	PALE REDDISH BROWN, FINE GRAINED FRIABLE SANDSTONE, CAPPED BY 5-10 FT HARD WHITE CRYSTALLINE CALICHE (LIMESTONE) CRUST	0-35
MESOZOIC	TRIASSIC	UPPER TRIAS	Santa Rosa Sandstone	50	PALE RED TO GRAY, CROSS-BEDDED, NON-MARINE, MEDIUM TO COARSE GRAINED FRIABLE SANDSTONE. PINCHES OUT ACROSS SITE	0-250
PALEOZOIC	PERMIAN	OCHOAN	Dewey Lake Redbeds	540	UNIFORM DARK RED-BROWN MARINE MUDSTONE AND SILTSTONE WITH INTERBEDDED VERY FINE GRAINED SANDSTONE. THINS WESTWARD	100-550
			Rustler	850	GRAY GYPSIFEROUS ANHYDRITE WITH SILTSTONE INTERBEDS IN UPPER PART; REDDISH-BROWN SILTSTONE OR VERY FINE SILTY SANDSTONE IN LOWER PART. HALITIC NEAR BASE. CONTAINS 2 DOLOMITE MARKERBEDS, MAGENTA (M) IN UPPER PART AND CULEBRA (C) IN LOWER PART. THICKENS EASTWARD DUE TO INCREASING CONTENT OF UNDISSOLVED ROCK SALT	275-425
			Salado (Upper member; McNutt member; Lower member)	[illegible] ZONE; [illegible] ZONE; 2825	MAINLY ROCK SALT (85-90%) WITH MINOR INTERBEDDED ANHYDRITE, POLYHALITE AND CLAYEY TO SILTY CLASTICS. TRACE OF POTASH MINERALS IN MCNUTT ZONE. THE MINOR INTERBEDS ARE THIN AND OCCUR IN COMPLEX ALTERNATING SEQUENCES. THICKEST NON-HALITE BED IS THE COWDEN ANHYDRITE [illegible] FEET THICK. MULTIPLE ANHYDRITE INTERBEDS ARE MOST COMMON IMMEDIATELY BELOW THE COWDEN AND IMMEDIATELY ABOVE BASE OF SALADO	1750-2000
			Castile (Anh. I; Halite I; Anh. II; Halite II; Anh. III)	4075±	THICK MASSIVE UNITS OF FINELY INTERLAMINATED (VARVED) ANHYDRITE-CALCITE ALTERNATING WITH THICK HALITE (ROCK SALT) UNITS CONTAINING THINLY INTERBEDDED ANHYDRITE. TOP ANHYDRITE UNIT LACKS CALCITE INTERLAMINATIONS	1250±
		GUADALUPIAN	DELAWARE MOUNTAIN GROUP: Bell Canyon (Delaware sand)	5100±	MOSTLY LIGHT GRAY FINE GRAINED SANDSTONE WITH VARYING AMOUNT OF SILTY AND SHALY INTERBEDS AND IMPURITIES. CONTAINS CONSIDERABLE LIMESTONE INTERBEDS AND LIME RICH INTERVALS. TOP UNIT IS LAMAR LIMESTONE MEMBER, A PERSISTENT SHALY LIMESTONE OR LIMY SHALE	1000±
			DELAWARE MOUNTAIN GROUP: Cherry Canyon	6200±	MOSTLY GRAY TO BROWN FINE TO VERY FINE GRAINED SANDSTONE SIMILAR TO BRUSHY CANYON, INTERBEDDED WITH SHALE, DOLOMITE AND SOME LIMESTONE	1100±
			DELAWARE MOUNTAIN GROUP: Brushy Canyon	8000±	PREDOMINANTLY FINE GRAINED GRAY TO BROWN SANDSTONE INTERBEDDED WITH MINOR BROWN SHALE AND [illegible]	1800±
		LEONARDIAN	[illegible] (First sand)		[illegible]	[illegible]

REFERENCES:

1. Anderson, 1978
2. Anderson, et al, 1972
3. Brokow, et al, 1972
4. Foster, 1974
5. Griswold, 1977
6. Meyer, 1966
7. Sipes, Williamson and Aycock, 1976

NOTE:

For complete citations, refer to reference list for chapter 4

Halite (rock salt)

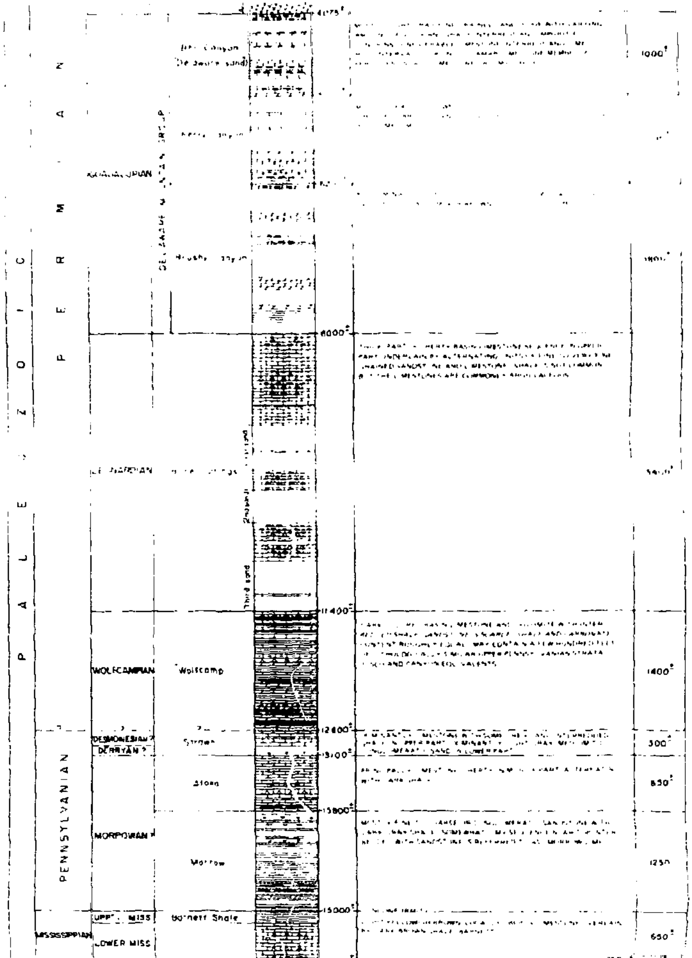
Granitic rocks

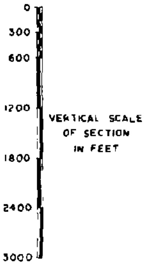
REFERENCES

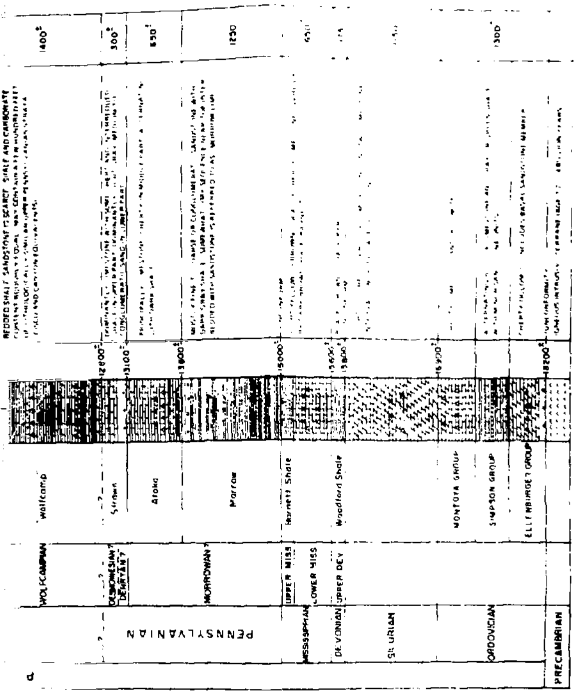
1 Anderson, 1978
2 Anderson, et al, 1972
3 Brokaw, et al, 1972
4 Foster, 1974
5 Griswold, 1977
6 Meyer, 1966
7 Sides, Williamson and Aycock, 1976

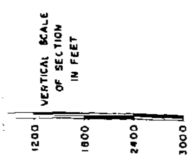
NOTE

For complete citations, refer to reference list for chapter 4









SITE GEOLOGIC COLUMN

SOUTHWESTERN NEW MEXICO (WIPP) SITE

FIG. 7

(From Powers and others 1978)

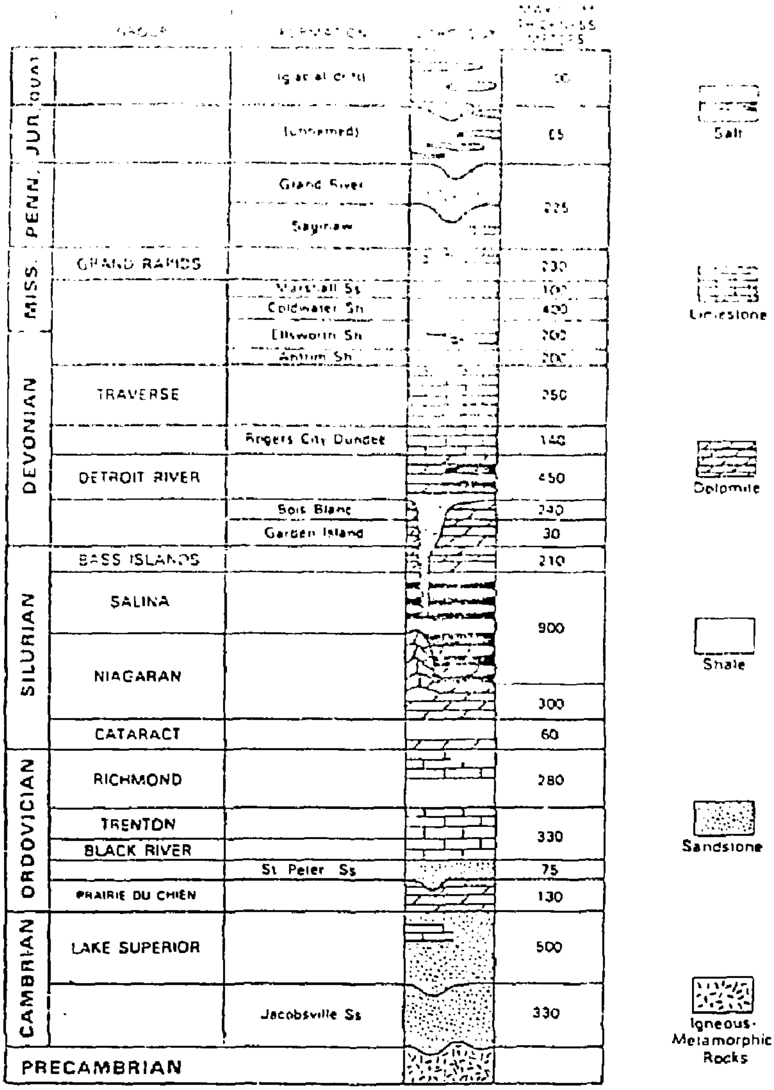


FIG. 8 Stratigraphic succession in Michigan Basin (after Michigan Geological Society, 1964).

A more realistic approach would be to model actual stratigraphic sequences such as those shown in Figures 7 and 8. The effects of lithologic variations in the rocks above and below the repository layer would then appear in the model output permitting an assessment of the impacts of such variations on repository performance. A range of expected values would be developed against which a site-specific performance model could be tested. Also, any stratigraphic sequences unacceptable on a general basis could be identified permitting the exclusion of potential sites in such sequences early in the characterization process.

The formation of thick, pure salt deposits requires the long persistence of a set of unusual geologic conditions. Fluctuations in salinity resulting from changes in water supply and climate, invasion of the basin by clastic sediments from nearby continental sources, all can interrupt the deposition of halite (rock salt) beds. As a result, massive halite deposits of sufficient thickness and lateral extent to be potentially suitable as sites for nuclear waste repositories are limited.

Wagoner and Steinborn (1979) indicated that a minimum thickness of about 60m (200 feet) is necessary for a safe repository based on the thermal properties of salt measured by Bradshaw and McClain (1971).

Figure 9 is a reproduction from Johnson and Gonzales (1976) of a detailed stratigraphic section through the salt-bearing Salina Group as present in the northeastern Michigan Basin. As shown in Figure 9, the salt is interbedded with shale, limestone, dolomite and anhydrite in

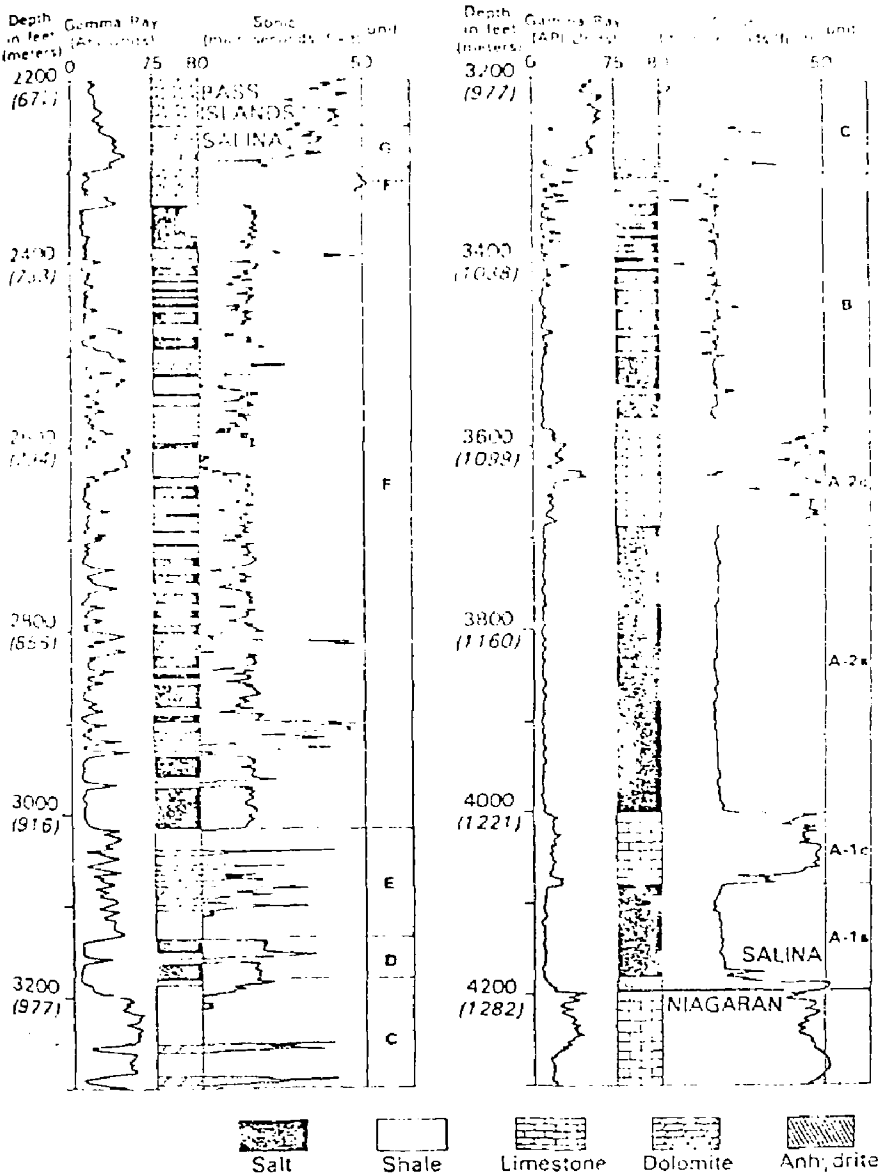


Figure 9 Lithology and mechanical logs of Salina Group near northeast margin of Michigan basin. Logs from Shell Oil Co., Sheldon-State-Wellington No. 1-34, sec. 34, T. 32 N., R. 5 E., Alpena County. Lithology interpreted from mechanical logs and sample log. From Johnson and Gonzales (1976).

varying proportions. Review of data compiled by Johnson and Gonzales (1978) indicates that similar associations characterize salt-bearing sequences generally, although the relative proportions vary. Relatively rapid lateral, as well as vertical variations may be observed.

Redfield (1967) has described rapid lateral changes from anhydrite and gypsum to carbonate rocks (mainly dolomite) with a further lateral gradation downdip[1] from the carbonate facies to siltstone. At the site investigated, the lateral shift from evaporites to carbonates was essentially complete within a distance of 4500 feet (1.4 km.).

Occasionally, nearly complete evaporation will occur in a salt basin leading to the formation of potash deposits, which are assemblages of complex potassium and magnesium salts. These potash deposits overlie or are interbedded with the common salt[2]. Commercially exploitable potash deposits occur in the Permian and Paradox Basins. Potash salts are rare in other United States salt basins (Johnson and Gonzales, 1978).

Powers and others (1978) have published a detailed log of exploratory well ERDA-9 cored through potential repository horizons at the WIPP site. Interested readers are referred to Figure 4.3-3B in their report for details.

1. For definitions of geological terms, see AGI glossary.
2. For a thorough discussion of the formation of potash deposits, see Baar (1977).

Although the strata surrounding the repository horizon are of primary importance in assessing more regional aspects of a nuclear waste repository such as waste migration, the characteristics of these strata will also influence repository design, construction and performance modeling. Examples of such influences and their impacts include:

- The distribution and characteristics of rocks which must be penetrated by shafts and tunnels in order to reach the repository horizon will strongly influence shaft sinking procedures and costs and could have important long-term effects on shaft maintainance and durability. The thermal and mechanical properties of these rocks must be determined and included in performance models.

- The locations of aquifers with respect to the repository horizon, the characteristics of recharge and discharge areas, and factors influencing hydraulic heads will determine potentials for groundwater inflow to an operating repository and likely create areas where grouting, thickened shaft linings or special seals will be necessary. Perturbations in groundwater flow as a result of the repository's thermal field will have to be established. Alternative designs may be necessary to assure that the selected configuration has the least effect that may be efficiently achieved.

- Facies relationships with particular reference to materials which interfinger with the repository horizon. The presence of interbeds in hydraulic continuity with permeable strata updip could provide important short-circuits leading to unanticipated groundwater entry problems during repository operations and result in rapid filling following decomissioning. Such facies relationships will be important to consider during near-field modeling.

- Non-salt strata interbedded with the saline deposits will possess different thermal and mechanical properties. Their distribution can lead to zones of tension and/or compression in strata within and surrounding the repository workings. These conditions can in turn lead to fracturing and shearing of the rock mass compromising repository integrity. Near-field models must have the capability of identifying such zones if realistic performance estimates are to be made.

- The potential exists for natural breeches in aquicludes and intercommunication of aquifers in the block immediately enclosing the repository. Such unanticipated intercommunications could be missed during site characterization studies because of the recognized need to minimize vertical penetrations and then be encountered during repository development. Large water inflows and possible structural stability problems could result.

- Lateral stratigraphic variations will determine locations favorable or unfavorable for placing seals and introduce 3-dimensional effects into performance models.

- *Potentials exist for adverse impacts on repository facilities* unrelated to the repository horizon itself. As an example, dissolution of a salt bed overlying the repository sequence could cause shaft failures and induce subsidence adversely affecting surface facilities. Such effects must be evaluated by performance models with particular reference to the long-term, post decommissioning potential.

The repository design and performance modeling processes must recognize the effects of strata surrounding the repository site in the following ways:

- Provide sufficient design flexibility regarding room and accessway location to allow for lateral variations in rock properties.

- Account for the mechanical, hydrologic, and thermal properties, and the natural variability of every recognized unit.

- Provide for sealing and abandonment of areas where unpredicted lateral stratigraphic change has caused major structural or hydrologic problems.

1.3 Stratigraphy of the Repository Horizon

A nuclear waste repository in bedded salt would be planned to be located in a thick, uniform halite (rock salt) deposit. However, apparently massive salt units may contain thin interbeds of clay, shale, anhydrite or potash salts. These interbeds may not be detected by conventional geophysical logging of boreholes, but could be identified in continuous cores or exploratory excavations (GAI, 1979a).

The primary design impact of these 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 room closure and attendant pillar spalling was accentuated when 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 pillar (GAI, 1979a). Near-field performance models must have the capabilities to evaluate such effects.

Clay and shale beds have lower thermal conductivities than the host evaporite layers and, therefore, reduce the rate of heat conduction away from the canister storage areas. The thermal effect of clay and shale beds near the canisters must be included in the design of storage rooms and canister containment wells and considered during near-field performance modeling.

Clay and shale beds are often observed to seep water into an excavation in salt. This appears to be connate water released by consolidation and drainage of the clay bed. In most cases, it has been 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 seeping water. Such occurrences are not expected to cause significant problems during repository development. However, effects upon emplacement operations should receive attention unless it can be clearly demonstrated that the presence of minor amounts of water will not lead to contamination and local waste migration. For instance, the effects of water seeping from clays or shales encountered in canister holes should be thoroughly evaluated during proof testing prior to repository licensing.

Many shales that contain abundant clay minerals will deteriorate on exposure to air and heat. The mechanism is partial hydration or dehydration induced by the air circulating through mine ventilation systems resulting in shrinkage or expansion of clay minerals resulting in turn in a breakdown of the rock structure. Some shales swell on exposure to air, either by creep or as a result of rehydration of clay minerals facilitated by relief of rock stresses which prior to excavation of the opening were sufficient to prevent entry of water into the clay mineral crystal lattice. Clay minerals will also dehydrate partially or completely at elevated temperatures.

The repository design should account for interbeds within the repository horizon in the following ways:

- Design pillars such that shale partings are not at or near the roof and floor interfaces.

- Allow for additional heating due to the lower thermal conductivity of clay and shale bands.

- Allow for possible wet shale bands in the excavation phase of repository development.

- Avoid placement of canister containment wells through wet shale and clay bands, or compensate for the presence of these materials during repository operations.

- Evaluate variations in thermal/mechanical response as a result of the presence of any anhydrite or potash interbeds.

As noted previously, near-field performance models must have the capabilities to assess these problems.

Obviously, the potentials for all these problems depend upon site conditions.

2.0 STRUCTURAL FEATURES

2.1 Introduction

Under structural features we summarize those effects upon bedded salt deposits and associated strata that result from such geologic processes as tectonism and deformation resulting from salt dissolution and discuss their potential effects upon a nuclear waste repository in bedded salt. A related phenomenon, the potential effects of future seismic activity, will be discussed in a separate chapter.

It should be noted that the selection of a suitable repository site will be a process that will attempt to exclude geologic structures which have an adverse effect on stability or radionuclide containment. However, there is little hope of detecting all anomalies by site exploration, and therefore, the design process must include allowances for anomalies that are discovered during repository development.

Structural features of importance to repository design and performance modeling are:

- Structural complexity and predictability.
- Salt flowage structures such as salt anticlines and diapirs.
- Discontinuities such as bedding, joints and faults.
- Mine-induced fractures.
- Dissolution structures such as breccia pipes and blankets.
- Other associated sedimentary and igneous features.

2.2 Structural Complexity and Predictability

Bedded salt basins are generally considered to be structurally simple. Descriptions provided by Johnson and Gonzales (1978) indicate that the bedrock sequences typically dip toward the center of the sedimentary basins with inclinations of 1 degree or less. Broad folds and old faults that pass upward into local, but often sharp, folds are seen in some basins.

More intense deformation has affected the southeastern portion of the Appalachian Basin, the northeastern portion of the Paradox Basin, and several lesser basins such as the Sevier Valley, Eagle Valley and the Idaho-Utah-Wyoming border areas (Johnson and Gonzales, 1978).

Because of the greater potential for faulting and fracturing, disruption of aquicludes and difficulty in constructing the repository totally within a favorable stratigraphic horizon, areas of strong deformation are not likely to provide sites suitable for a nuclear waste repository. It should be noted that a regional dip of as little as 1 degree, or approximately 92 feet per mile (17m per km) could result in a difference in elevation of the repository horizon of as much as 230 ft. (70m) within a 2000 acre repository (assuming a configuration of 2 miles by about 1.5 mi.). While lesser elevation changes would accompany flatter regional dips, it is evident that the repository design must contemplate storage levels at different elevations within the repository in order to follow a favorable horizon. Otherwise, the workings could too closely approach the margins of the salt horizon.

The presence of thick salt beds may profoundly affect the type of deformation which occurs in the salt itself and in rocks lying above the salt. Under favorable conditions, even slight tilting of the beds will be sufficient to initiate long-term viscous flow of salt. As a result, deformation in rocks overlying salt deposits will be decoupled from deformation in rocks beneath the salt. Structures in rocks overlying salt deposits may be expected to be generated in response to salt flow while structures in rocks beneath the salt will closely reflect regional tectonic forces.

In addition, structures above salt beds affected by active or past dissolutioning can be expected to exhibit karst or collapse features or to have internal irregularity and chaotic structure brought about by uneven subsidence or upward stopping following removal of significant thicknesses of salt at depth.

Powers and others (1978) have described structural features at the southeastern New Mexico (WIPP) site. These are summarized here for illustrative purposes in conjunction with discussions of structural features which must be considered during repository design and performance modeling. The discussion presented by Powers and others focuses separately on geologic structures in rocks beneath the Late Permian (Ochoan) salt-bearing rocks and those overlying these beds.

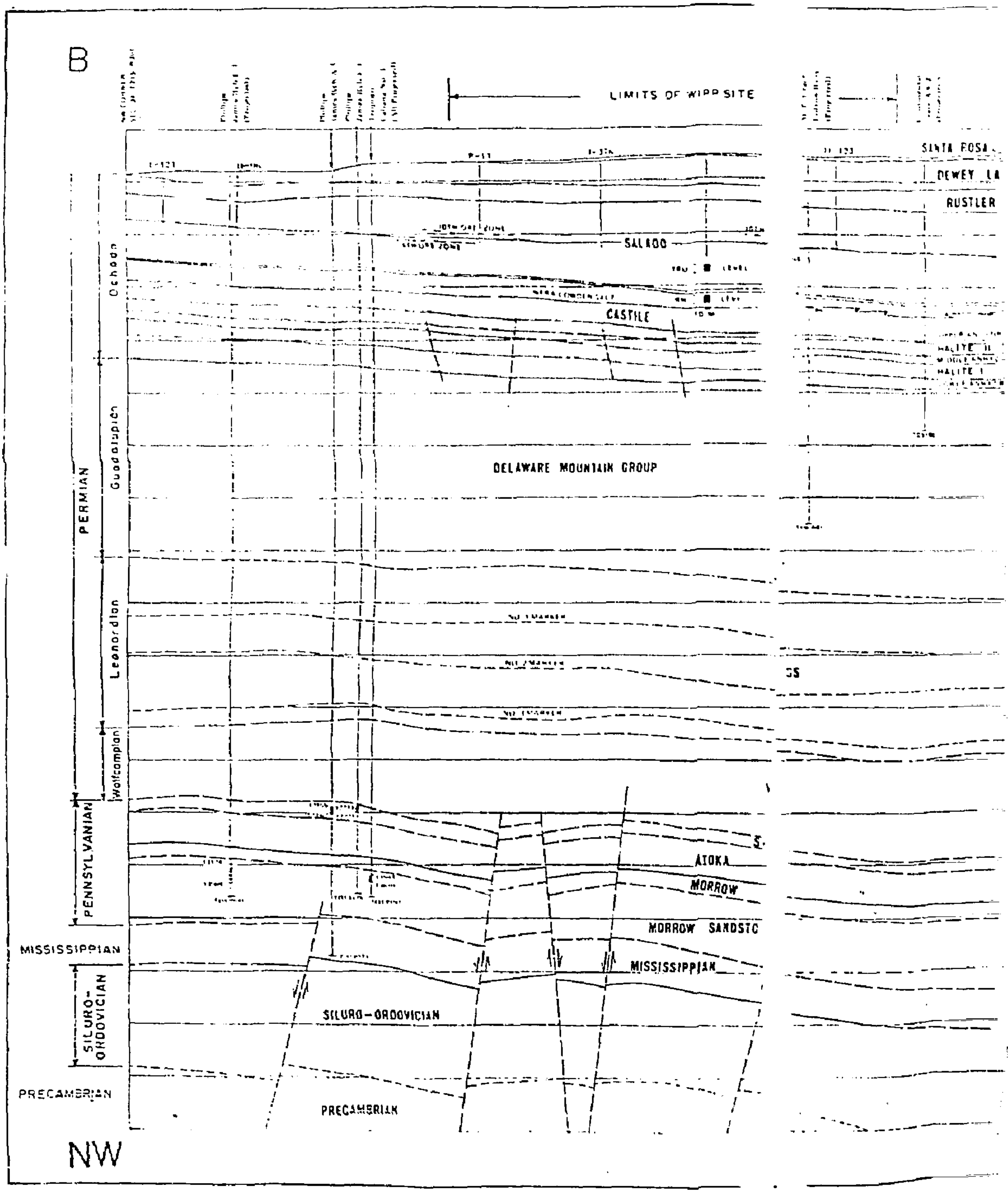
In general, structure contour maps developed from well records for horizons beneath the salt deposits at the WIPP site show a gradual regional dip toward the southeast to east reflecting the general downwarn of the Delaware sub-basin of the Permian Basin. Gradients on all pre-Permian strata are similar in direction decreasing from about 150 feet per mile in early Paleozoic strata to about 100 feet per mile at the top of the Pennsylvanian (Powers and others, 1978).

High resolution geophysical surveys run at the WIPP site as part of characterization studies reveal the presence of minor faulting and secondary warping (swells and saddles) in the Paleozoic strata below the evaporite beds. The data indicate changing structural patterns with time; in general, significant faulting is restricted to beds older than early Permian in age. Some apparent local faults in beds immediately beneath the salt-bearing strata could not be detected in deeper units suggesting a shallow-seated origin for these features (Powers and others, 1978).

Figure 10 presents a geological cross-section at the WIPP site.[1] The magnitudes of minor faulting in older rocks and local warping of Permian and younger beds can be observed in Figure 10.

Within the salt sequence beneath the WIPP site, deformation of the salt beds has locally modified the areal homoclinal structure. The easterly homoclinal dip of 50-100 feet per mile is modified by broad northwesterly trending ridges and saddles with crest to trough separations of 2 to 3 miles and a total structural relief of up to 400 feet (Powers and others, 1978). Also, as described by Powers and others

1. Section B-B' shown in Figure 10 was selected because it depicts more structural features than Section A-A'. Interested readers are referred to Powers and other (1978) for Section A-A'.


B
LIMITS OF WIPP SITE
SANTA ROSA
DEWEY LA
RUSTLER
SALADO
CASTILE
DELAWARE MOUNTAIN GROUP
ATOKA
MORROW
MORROW SANDSTC
MISSISSIPPIAN
SILURO-ORDOVICIAN
PRECAMBRIAN
PERMIAN
Ochoan
Guadalupian
Leonardian
Wolfcampian
PENNSYLVANIAN
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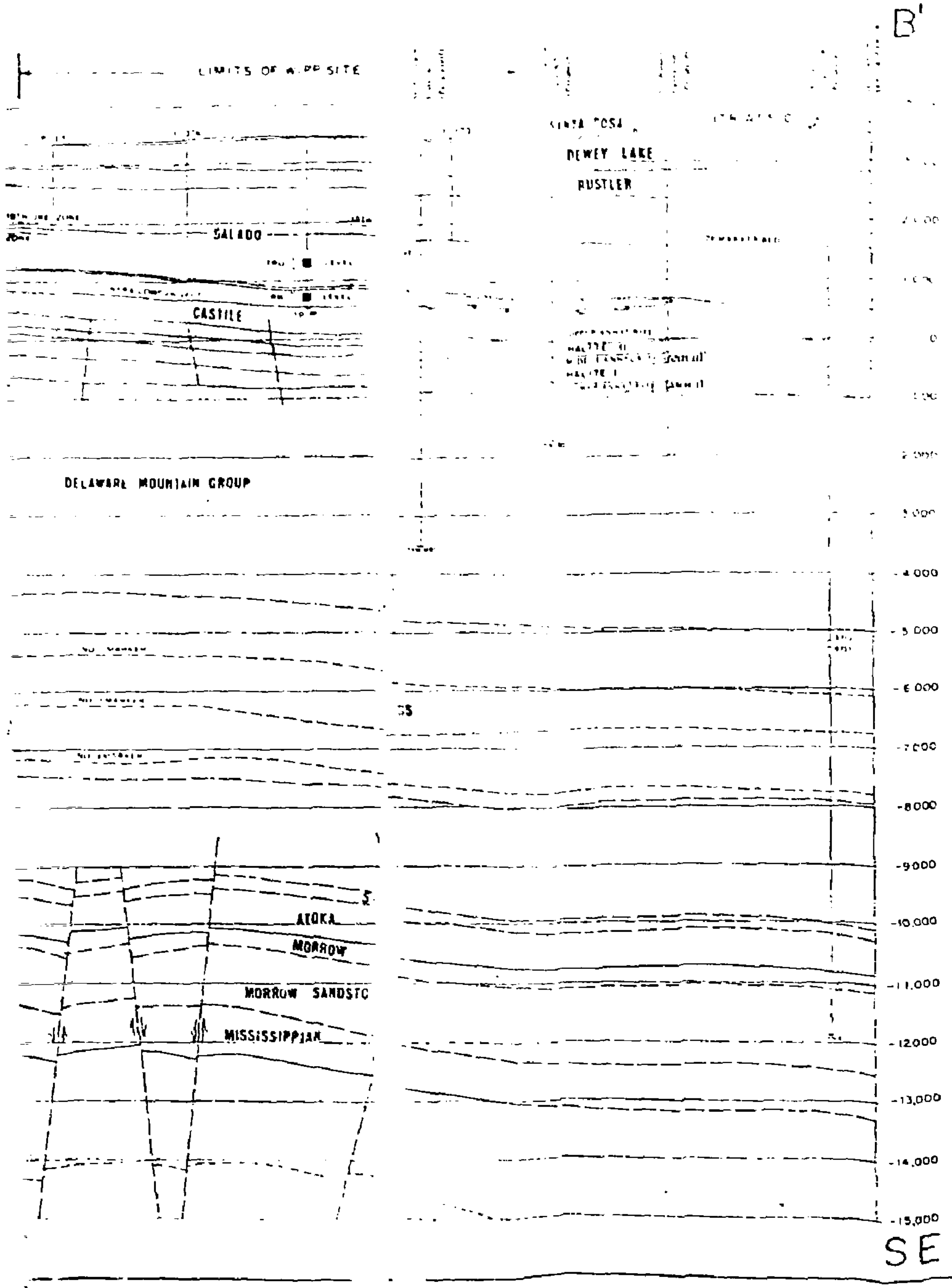

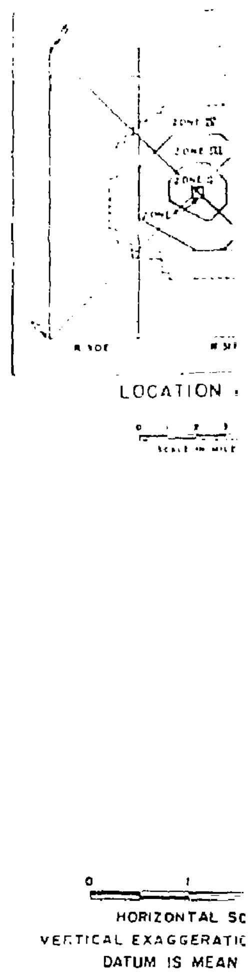

Figure 10 Site geol
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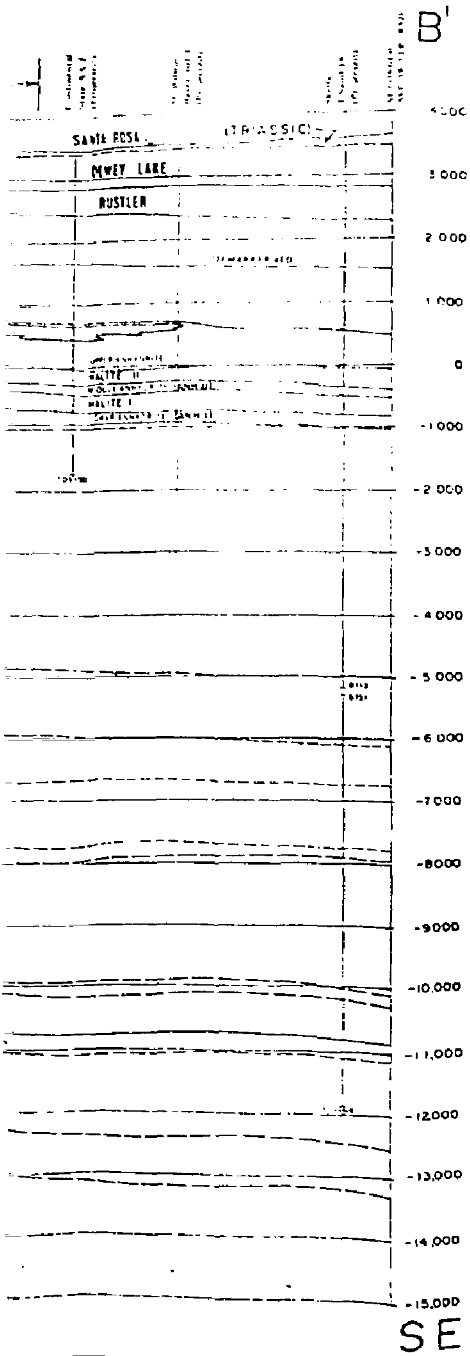


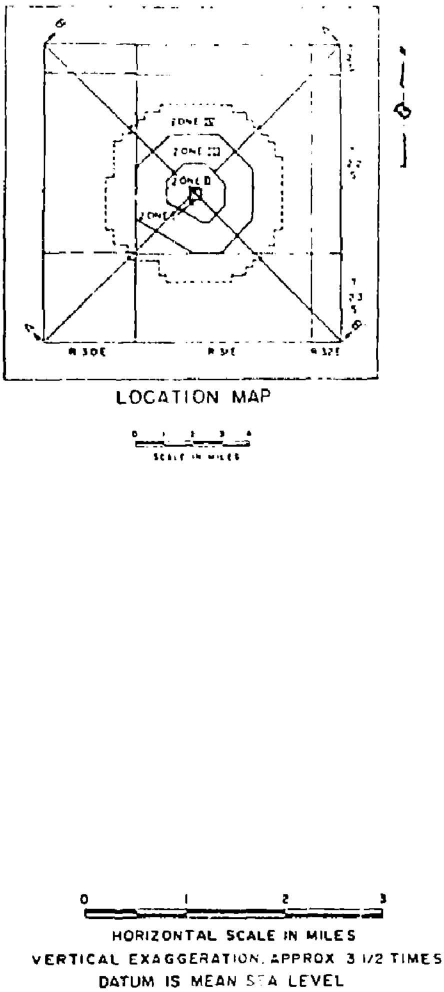


Figure 10 Site geologic section B-B' southeastern New Mexico (WIPP) site.

(1978), more intense deformation has affected the salt sequence north and east of the WIPP site where flowing salt has piled up against limestone deposits of the El Capitan reef, an ancient barrier reef that nearly encircled the Delaware Basin during late Permian time.

Shallow structures at the WIPP site include local dip changes believed to be the result of partial removal of salt from the upper part of the Ochoan series by dissolutioning and some irregularities resulting from periodic erosion of beds during the long period of geologic time following the end of Permian time (Powers and others, 1978). Powers and others (1978) state that salt dissolution beneath the WIPP site has not resulted in the development of highly irregular subsidence structures in overlying strata.

The principal impacts of structural features of these types on repository design and performance models are on aquifer properties, particularly on the locations and gradients of highly permeable zones created by salt dissolution and brecciation of overlying strata. As noted previously, regional dips must be considered in the design of subsurface features and will also influence regional hydrology.

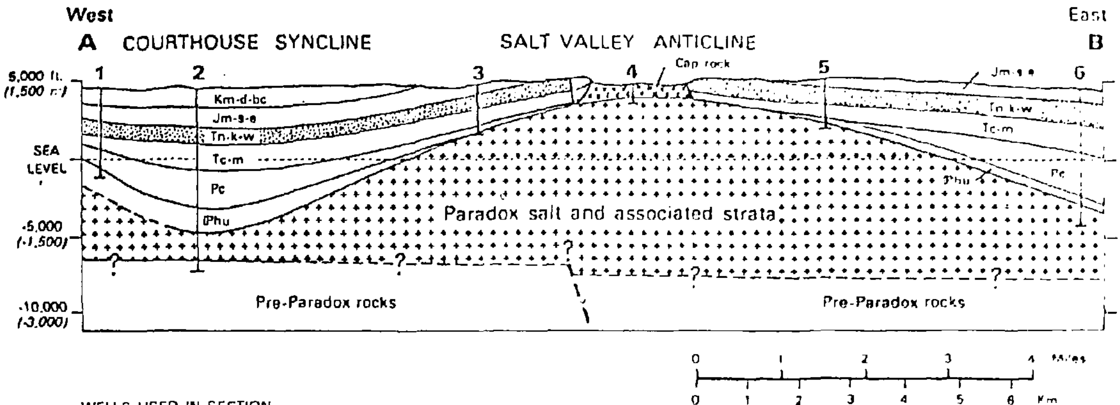
Although not reported as present at the WIPP site, the presence of karst terrain or significant subsidence features would seriously impact the waste isolation capability of a site in bedded salt. The detection of these features should be a major effort during early phases of site screening and characterization as their presence would call into question the integrity of a proposed site unless it could be clearly demonstrated that sufficient unaffected material was present above the repository horizon to assure waste isolation.

2.3 Salt Flowage Structures

With increasing deformation, bedded salt deposits will flow plastically, thinning outward from the axes of synclinal depressions and thickening in the cores of anticlinal folds. The resulting structures, referred to as salt anticlines, are particularly well developed in the deformed portion of the Paradox Basin (Hite and Lohman, 1973) and have also been identified in the southern Appalachian Basin (Frey, 1973), the Delaware Basin (Powers and others, 1978) and in several other basins as well. A generalized cross section through a salt anticline in the Paradox Basin is shown in Figure 11.

Because of the greater thicknesses of salt available, salt anticlines in the Paradox Basin have been considered as potential nuclear waste disposal sites (Hite and Lohman, 1973). Such structures are intermediate between undeformed bedded salt deposits and salt domes, and therefore, would share geotechnical characteristics with both.

The presence of salt anticlines in a salt basin is proof of past tectonic activity although possibly of very minor extent. Therefore, in order to assure safe nuclear waste isolation in such basins, absence of geologically young tectonic activity must be established. Long-term monitoring of geodetic networks, analysis of geomorphic patterns and distribution of young strata (late Tertiary and Quarternary) are methods



WELLS USED IN SECTION

1. Equity, Donahue No. 1
2. Texaco, McKinnon No. 1
3. Continental, Gov't.—Hall No. 1
4. Western Allies
5. Pure, Salt Valley No. 1
6. Union, Devils Garden—USA No. 1

Km-d-bc	Mancos-Dakota-Buro Canyon
Jm-s-e	Morrison-Summerville-Entrada
Tn-k-w	Navajo-Kayenta-Wingate
Tc-m	Chinle-Moenkopi
Pc	Cutler
Phu	Hermosa (Upper Member)

Figure 11 Cross section through Salt Valley in Grand County, Utah.

whereby this may be accomplished. Also, the impossibility of renewed movements as a result of thermal effects must be demonstrated (Hyder, 1977).

Powers and others (1978) have described salt flowage structures in the vicinity of the southeastern New Mexico (WIPP) site. In addition to the local ridges and saddles previously described, a domal structure with about 500 feet of structural relief was identified several miles northeast of the proposed site. A test boring, ERDA-6, was drilled near this feature and encountered brine under artesian pressure. Core analysis indicates that the dome formed as a result of mobilization of the deepest major salt bed in the salt bearing sequence and is regarded as a portion of the belt of intensely deformed salt found near the El Capitan reef (Powers and others, 1978).

Powers and others (1978) reported that artesian brine flow was also encountered in a hydrocarbon exploration well in the Los Medanos gas field area located several miles southwest of the WIPP site. This occurrence is associated with a domal feature although no salt-cored anticline of the type encountered in ERDA-6 is known to occur there (Ibid).

Pressured brine pockets associated with salt anticlines constitute a potential hazard to mining operations in a nuclear waste repository. Affected salt masses would be of doubtful value for waste storage. Domal and anticlinal structures in bedded salt should be suspect and probing techniques to search for brine pockets such as radar should be routinely used in their vicinity during repository development.

The presence of anticlinal structures may affect performance modeling in several ways:

- Models may have to be modified to describe flow through units of uneven thickness.
- Deviations in direction and possible increases in frequency will be noted in fractures in brittle beds in anticlinal structures. Changes in hydrologic and mechanical parameters are likely to be necessary.
- Additional failure scenarios such as effects of brine migration may need to be included in models.

With increasing deformation, salt masses will break through overlying strata in areas of structural weakness and salt diapirs or domes will form. Dome structures are particularly widespread in the Gulf Coast salt basin.

Despite much study and numerous hypotheses, the origin of salt diapirs or domes is not well understood. The prevailing view invokes flow and upward movement of plastically deformed salt in response to overburden pressure from the overlying sediments, and gravitational inequilibrium (Johnson and Gonzales, 1978). Presumed stages in the formation of Gulf Coast salt domes are shown in Figure 12.

Geotechnical considerations in the salt dome environment are beyond the scope of this report. However, the presence of salt domes, as with salt anticlines, is indicative of past unbalanced stress fields and

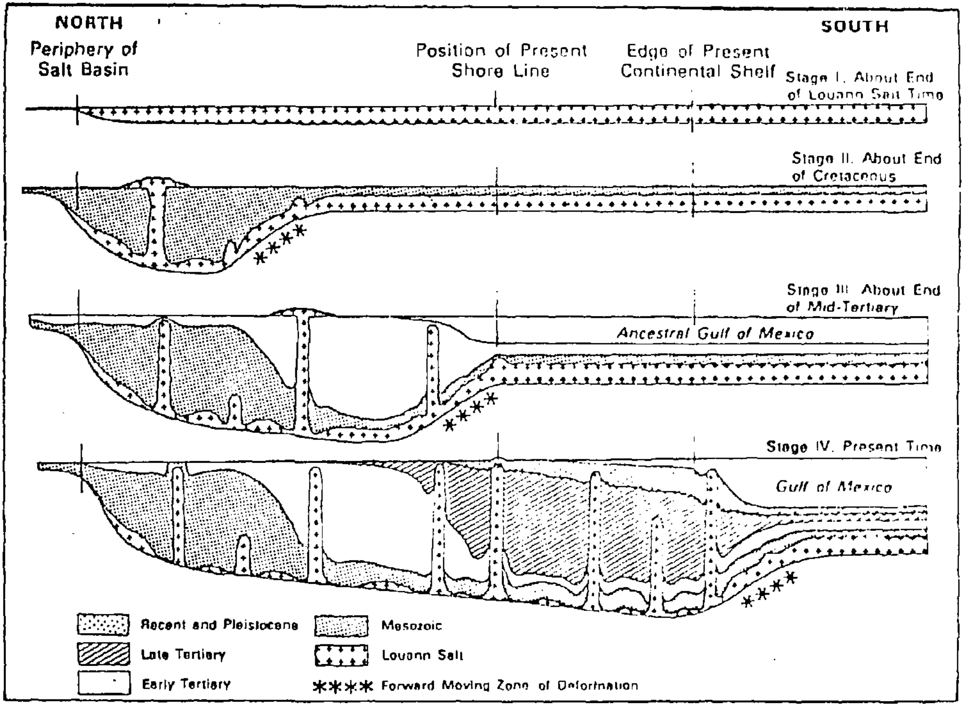


Figure 12 Stages in the formation of Gulf Coast salt domes.

tectonism. Therefore, detailed geotechnical investigations sufficient to establish the absence of present movements and the impossibility of thermally induced activation would be necessary before the long-term integrity of a nuclear waste disposal site in a basin containing salt domes could be assumed. Performance models constructed for basins or sites containing salt domes would have to be modified to include the perturbing effects of domal structures.

2.4 Discontinuities

Discontinuities include such features as random fractures, joints, bedding planes, shear and fault zones, and pore spaces. These features influence rock mass strength, anisotropy, and structural integrity. Open discontinuities provide conduits whereby water may enter or exit a repository. Occasional open water-bearing joints or fissures have been reported in bedded salt (Baar, 1977).

Joints and Fractures: Joint systems (sets of planar fractures induced in rocks by tensional or compressional forces) and random fractures may affect repository designs primarily in terms of rock support requirements and need for room stabilization, and secondarily, because of their potential to provide permeable pathways (GAI, 1979a). During performance modeling, joint sets could define finite element boundaries and introduce anisotropies into hydrologic flow models. The presence of subhorizontal, pervasive joints may necessitate roof support where spacings and stresses create a potential for roof falls. The existence of two or more joint sets may create blocks in the roof and cause potential stability problems that will affect the design. The need for roof support is likely to depend on local conditions within the repository and these may not be predictable prior to excavation (GAI, 1979a).

It is possible that a pervasive set of high-angle joints possibly created by doming or diapirism beneath the repository could be reopened by thermal stresses and provide nuclide escape paths (GAI, 1979a). The likelihood of such effects can be reduced by limiting the allowable thermal load.

Powers and others (1978) did not include a specific discussion of the jointing and fracturing within rocks at the southeastern New Mexico (WIPP) site. However, the importance of fractures in providing permeable pathways in certain aquifer units overlying the planned repository horizon was noted and old fractures filled with clay, anhydrite and polyhalite were noted during petrographic studies. No joints or fractures are described in the log of test hole ERDA-9 which was continuously cored through potential repository horizons and adjacent strata. It is not clear from the log whether no fracture zones were present or whether they were not recorded by the well site geologists.

Although the orientations and frequencies of fractures have been recorded during engineering studies of numerous dams, tunnels, and other major works, there has been little synthesis of these data, particularly with reference to water flow through fractures. The principal works are that of Snow (1965, 1968) who found that for a rock of given conductivity, the fracture porosity depends more on fracture spacing than on aperture widths and fracture orientations. Snow found that fracture porosity decreases approximately logarithmically with depth and that neither aperture width nor fracture spacing differs notably from one rock type to another, nor do the associated porosities and permeabilities.

Snow (1968) reported upper porosity limits of 0.05% near the ground surface and 0.005% at 122m. Snow obtained his data largely from studies of dam foundations and related features and therefore did not have a significant amount of data potentially applicable to repository depths.

Rasmussen (1963) has published some data for conductivity of fractured rocks in the United States. Values for rocks that may occur in proximity to repository horizons are given in Table 1.

It should be noted that as flow velocities increase, roughness of fractures will cause turbulence and non-uniform flow within fracture planes. Gale (1975) investigated the problem in the field and found that the "equivalent apertures" differed from measured fracture apertures by at least an order of magnitude, the true apertures being larger. Because roughness of fracture walls and non-uniform flow within fracture planes are very difficult to evaluate directly, the concept of equivalent apertures is very significant in current approaches to modeling.

The design and performance modeling process must consider joints and fractures and their characteristics in the following ways:

- Make allowances for the unpredictability of joint and fracture patterns at depth within the repository horizon. The degree to

TABLE 1: Conductivity of Fractured Rock in the United States ([illegible]).
(The data are taken from producing wells.)

Rock Type	Average Producing Thickness (m)	Apparent Conductivity, cm/s			No. of wells
		Minimum	Average	Maximum	
Arkoisic sandstone, siltstone and shale	93	4.7 × 10[illegible]	7.1 × 10[illegible]	[illegible]	[illegible]
Shale	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sandstone	41	3.3 × 10^-7	[illegible] × 10^-4	6.4 × 10[illegible]	[illegible]

which joints persist and are interconnected must also be estimated.

- Determine roof and side support requirements in accordance with expected joint fracture characteristics, including such matters as surface roughness and aperture widths.
- Locate and orient rooms to minimize joint related instability.
- Allow some flexibility in room locations and fracture sealing plans to permit isolation of joints that provide potential radionuclide escape pathways.

Bedding: Bedding thickness, attitude and the characteristics of contacts between beds will influence the location and geometrical layout of a repository. Effects of bedding thicknesses and attitudes have been previously discussed under Structural Complexity and Predictability. Contact nature can influence room stability in that sharp, weak and/or sheared bedding planes can provide low angle discontinuities along which roof slabbing and pillar failure may occur. Design and performance modeling considerations would be similar to those required because of the presence of low-angle joints.

Powers and others (1978) provided descriptions of the characteristics of beds within the Salado Formation (proposed host rock for repository horizons) at the southeastern New Mexico WIPP site. Their descriptions are as follows:

"Close examination of the Salado in drill cores and geophysical logs of boreholes in the Los Medanos area and vicinity reveals that rock sequences show a regular order of succession. A typical sequence, repeated many times between the base and top of the formation, involves a change from claystone upward through anhydrite or polyhalite and halite to clayey halite capped with claystone. In other sequences the change is from halite to clayey halite capped by claystone. Boundaries between individual members of a rock sequence are gradational, but those along the lower and upper sides of the individual sequences are corrosion surfaces that form sharp, clear-cut breaks in the evaporite section but, nevertheless, are laterally persistent and convergent northward. The rock sequences represent a fundamental sedimentation unit or evaporite cycle, and they are believed to record discrete periods of influx and subsequent precipitation of calcium sulfate and sodium chloride during evaporation of sea water or an initially dilute brine. The ubiquitous claystone is thought to be a residue concentrated during dissolution of clayey halite by inflowing sea water or dilute brine.

The Salado Formation is divided into three members, but more subtle divisions can be made, for the beds are very persistent. In fact, the persistence of individual beds is the prime basis for the system of numbering individual seams of anhydrite and polyhalite which was introduced by geologists of the United States Geological Survey (USGS), such as Jones (1960) and is widely used by mining companies in the Carlsbad potash field."

Powers and others (1978) did not provide specific information on bedding thicknesses. However, examination of the core log for test hole ERDA-9 indicates that where individual beds of common salt, potash salts or anhydrite could be identified, their thicknesses ranged from 0.1 foot to 17.1 feet. Most individual beds are less than 2 feet thick.

A rational lumping or property averaging process will be necessary before a near-field performance model can be created for a sedimentary sequence containing numerous thin beds. As noted previously, such a process must be an interdisciplinary effort including geologists as well as persons skilled in the construction and exercising of numerical models.

Faults: Faults are ruptures in the rock mass along which the opposite walls have moved relative to each other. Active faults have the potential to disrupt repository operations or compromise waste isolation; their effects are summarized in a following chapter on seismic hazards.

Inactive or extinct faults would constitute planes of weakness through a repository site. The juxtaposition of different rock types across a fault could lead to distortions of rock mechanical and/or thermal properties and create additional structural problems. Under certain conditions, stress changes caused by excavations can cause movement or dilation along old faults with adverse mechanical and hydrologic effects (GAI, 1979a).

Faults at the southeastern New Mexico (WIPP) site have been described in a preceeding section dealing with the structural complexity and predictability of salt deposits. Most of the faults described have been inferred from stratigraphic and geophysical data and the characteristics of individual fault zones are unknown. No fault known in the vicinity of the WIPP site displaces strata younger than early Permian age (about 250,000,000 years ago).

A fault can function as a groundwater conduit or barrier depending upon the characteristics of its fault gouge and degree of infilling. A breccia type of gouge is usually very permeable, while a cemented or clay rich gouge is often relatively impermeable (GAI, 1979a).

Although areas containing known faults are not likely to be considered as suitable nuclear waste repository sites, it is likely that some minor faults will be encountered during repository excavation. Since faults are potential nuclide escape paths, the repository layout will have to be modified 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 canister rooms to the fault (GAI, 1979a). The repository design must allow for rearrangement of corridors, rooms and pillar geometry to isolate faults within large pillars.

For performance modeling, the orientation (strike and dip), average thickness, and physical characteristics of faults must be known. The strike of a fault is particularly important during three-dimensional modeling. Major changes in fault thickness and characteristics along strike could also influence three-dimensional models. For hydrologic modeling, the most important factors would be determinations as to whether a fault zone acts as a groundwater barrier or permeable pathway and the establishment of an appropriate hydraulic conductivity. For thermal-mechanical modeling, factors bearing on the strength of the fault zone as well as its orientation with respect to repository workings would be necessary.

Pores and Brine Pockets: Katz and Coats (1968) report porosities of rock salt from 0.6 to 2.0 percent. These values are low when compared to most sedimentary rocks, and are in a range where variations in porosity are unlikely to have influence on the mechanical behavior of salt. However, large brine inclusions, up to 100,000 gallons, have been encountered in bedded salt deposits (GEI, 1977b) and the presence of such large inclusions could pose the risk of operational accidents and roof or wall instabilities, particularly since the brines in these inclusions are under high lithostatic pressures.

During early phases of WIPP characterization studies, a geopressured brine pocket was encountered by Test Hole ERDA-6 (Powers and others, 1978). The brine pocket was closely associated with a salt anticline and its presence caused a several mile relocation of the proposed WIPP site. The amount of brine discharge was not reported by Powers and others (1978).

Repository designs must provide for the rearrangement of workings to avoid areas of large brine inclusions. Probing techniques such as radar could be used during repository development to detect such features (ILCO, 1979). The effects of a large brine pocket on repository stability should be assessed during performance modeling.

Mining Induced Fractures: The excavation of any underground space produces a fracture zone around the excavated opening. Two important sources of these fractures may be identified: stress relief associated with stress field redistribution around the newly excavated opening, and damage to the rock caused by the excavation techniques used. The fracturing produced by these two mechanisms is influenced by pre-existing discontinuities such as have been previously listed. The fracture zone around underground openings is significant due to both the resulting zone of increased permeability and the corresponding ground stability implications.

Fractures caused by redistribution of the in situ stresses as the opening is excavated can occur regardless of the excavation techniques used. The formation of these fractures is chiefly a function of the size, shape, and orientation of the excavated opening, the stress field prior to excavation, and the physical properties of the medium being excavated. There is little quantitative information available with which to predict the extent of these fractures. Table 2 summarizes estimates of the preferred dimensions to which the fracture zone around an underground opening may extend (GAI, 1977). These dimensions, with corresponding estimated permeabilities and porosities, are based upon an elastic analysis in which the rock is assumed to fracture outward from the opening to a point where the calculated stress is about one third of the assumed rock strength.

TABLE 2

Fracture zones in salt repositories

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 4m radius shaft in shale, the width of the fracture zone is estimated at 1.1 (4 + 0.5) = 4.95 meters.

Fractures created as the rock is damaged by excavation techniques are associated with drill-and-blast methods. Little information is available that quantitatively compares the results of blasting and machine excavation methods on this matter. Blast-induced fracture formation is principally a function of the blast parameters such as amount and type of explosive, blasthole pattern and blast delays used, physical properties of the medium being excavated, and the presence and characteristics of pre-existing discontinuties. Certain research on the extent of fracturing caused by confined high explosive blasts has been summarized (Butkovich, 1976) and would indicate that the fracture zone thus produced would not extend significantly past that produced by stress redistribution. However, this estimate is somewhat conservative if applied to routine underground excavation blasting, as such shots are designed to create and provide a free face for the perimeter holes to blast to rather than having the perimeter holes be entirely confined.

For fractures produced both by stress relief and by excavation techniques, the degree of fracturing and the corresponding permeability are expected to decrease exponentially from the tunnel or shaft excavation surface. While all excavations are surrounded by a fracture zone resulting from one or both of these causes, a more intensely fractured zone may be assumed to form in shale than in salt (GAI, 1979b)

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 possibly accessway for groundwater to enter the repository or for wastes to migrate from it. Baar (1977) has documented several European experiences where progressive dissolution along fractures led to flooding and eventual loss of salt mine workings.

Therefore, 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:

- Selecting an excavation method to minimize fractures created by the techniques used.
- Selecting opening shapes and sizes to minimize fracturing caused by stress redistribution.
- Sealing all shafts and boreholes.
- Isolating boreholes within pillars.

Performance models should have the capability to test variations in such factors as room configurations and seal locations in providing structural stability and waste isolation. Models should also be able to assess the effects of placing engineered barriers such as tunnel plugs or sorptive backfills in the system.

2.5 Dissolution Structures: Because of the high solubility of salt deposits, dissolution may occur in a geologic time frame sufficient to compromise waste isolation. As noted previously, salt may dissolve so rapidly that repository operations could be disrupted and catastrophically flooded. Three dissolution modes may be recognized which may lead to structural compromise of a nuclear waste repository or of the rocks overlying a repository. These are:

- Breccia Pipe Formation
- Breccia Blanket Formation
- Dissolution Around Boreholes and Shafts

Breccia Pipe Formation

Water flowing through a ifers adjacent to salt formations is usually not saturated with salt (otechnical Engineers, Inc., 1977a). If this water comes in contact with s lt, dissolution will occur. If the contact is made at the base of the salt unit, the dissolution process will cause the development of cellular flow, and the resulting cavity will grow upward through the salt (GEI, 1977a).

Cellular flow may be envisioned as a process whereby density differences in the brine within the cavity result in the development of discrete, vertically oriented fluid cells. Within a given cell, denser, more saturated brines sink in certain portions of the cell, while less dense, less saturated brines move upward in other portions of the cell. This type of cavity development promotes formation of collapse chimneys or breccia pipes as a result of progressive loss of support for overlying beds. An idealized sequence for breccia pipe formation is shown in Figure 13.

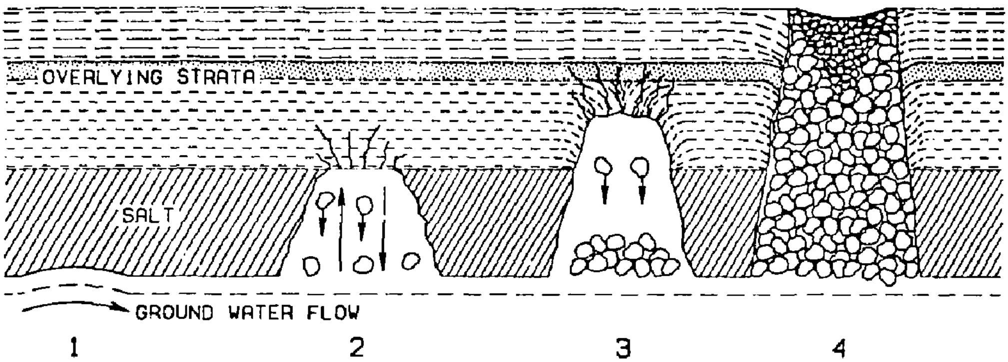


Figure 13: Progressive development of a breccia pipe (adapted from Geotechnical Engineers, Inc., 1977a).

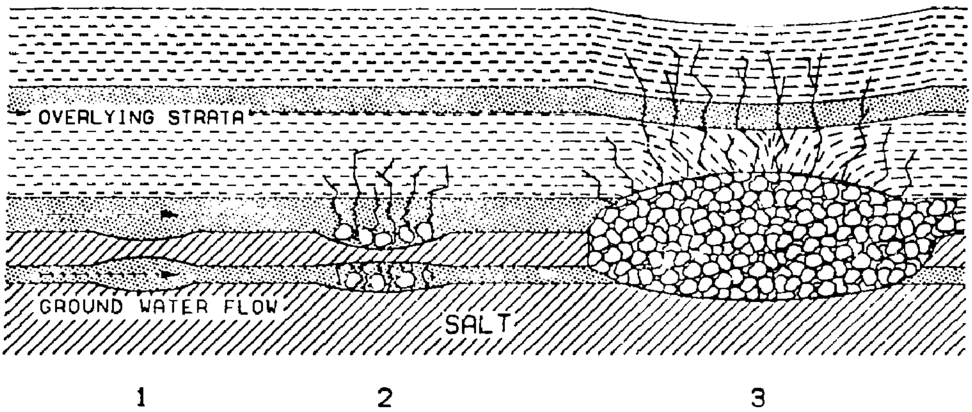
It should be noted that complete development of the breccia pipe (Stage 4 in Figure 13) is unnecessary before the pipe may result in structural compromise of a nuclear waste repository. As the pipe grows upward in Stage 2, weakening of the repository floor occurs, fractures form, and ultimately collapse occurs, creating a pathway to an underlying aquifer. Further growth would cause roof collapse (as in Stage 3) and create an interconnection with an overlying aquifer. The breccia pipe need not reach the ground surface to result in structural failure or hydrologic communication.

Breccia Blanket Formation

If groundwater flow occurs in an aquifer in contact with the top of a salt formation, dissolution will promote formation of very wide, shallow, flaring cavities (GEI, 1977a). This will occur because the groundwater will be denser, containing more dissolved salt at the base of the aquifer than higher in the section. Therefore, the ability of the groundwater to leach downward will be reduced, and dissolution will be concentrated on the top surface of the salt layer. The resulting shallow cavities will eventually coalesce and cause a loss of support for the overylying strata. These undermined strata can fracture and form rubble that will progressively fill the cavity until adequate support is restored. Surface subsidence over broad areas may result. Normal faults may develop near the margins of subsided areas in response to increased stresses imposed on the materials overlying the zone of breccia blanket formation. These stresses will be created by the loss of support resulting from salt dissolution. An idealized sequence for breccia blanket formation is illustrated in Figure 14.

Salt dissolution, essentially of the breccia blanket type, has affected the upper portion of the salt-bearing sequence at the southeastern New Mexico (WIPP) site (Powers and others, 1978).

The upper portion of the salt-bearing sequence, the Rustler Formation, outcrops about 5 miles west of the WIPP site along the eastern margin of a topographic depression known as Nash Draw. In outcrop, the Rustler Formation has been leached of its salt and consists of a jumbled mass of cavernous, brecciated gypsum with minor dolomite and a few seams



1. Initial groundwater flow in permeable unit within or at top of salt initiates dissolution.
2. Solution of overlying or underlying salt bed continued.
3. Overlying unit collapses.

Figure 14: Progressive development of a breccia blanket (adapted from Geotechnical Engineers, Inc., 1977a). (UCID 18119)

of virtually unconsolidated sands and clays. Because of the effects of leaching, alteration and collapse, it is impossible to piece together a meaningful stratigraphic section from a study of these outcrops (Powers and others, 1978).

Eastward from the outcrop area, as the Rustler Formation dips into the subsurface, all the gypsum in the formation gives way to anhydrite and minor polyhalite and the sands and clays grade into sandy and clayey rock salt. Simultaneously, with the eastward down-dip change in composition, the thickness of the Rustler Formation changes significantly. The thickness ranges between 280 and 300 feet near the Nash Draw outcrop, but increases eastward to about 490 feet about 20 miles southeast of the WIPP site and to about 385 feet about 10 miles to the northeast (Powers and others, 1978).

At the proposed WIPP site, ERDA-9 encountered 310 feet of Rustler Formation. The thickness of the formation as a whole would indicate that much of the halite originally present has been leached away, particularly from the upper part of the formation. The log of ERDA-9 shows that clayey halite was encountered in the Rustler below the Culebra dolomite member. This distinctive marker bed is located about 100 feet above the base of the formation (Powers and other, 1978).

The proposed upper storage zone at the WIPP site is separated from the leached portion of the Rustler Formation by approximately 1300 feet of undisturbed strata (Powers and others, 1978).

West of the WIPP site, beneath Nash Draw, the Salado Formation, which includes proposed repository horizons has been extensively leached. As little as 150-170 feet of insoluble residue remain from an originally 450-500 feet thick section of rock. The eastern edge of the dissolution front in the Salado Formation is about one mile west of the WIPP site (Powers and others, 1978).

Estimates prepared by Bachman and Johnson (1973) indicate that the rate of salt removal by dissolution may amount to as much as 0.5 foot per 1000 years. This rate suggests that roughly 1 million years would be required to reduce 450 to 500 feet of the Salado Formation to the existing insoluble debris.

No estimates appear to have been made as to the rate of eastward progression of the dissolution front in the Salado Formation. If the rate of 0.5 feet per 1000 years estimated by Bachman and Johnson (1973) applies to lateral as well as vertical dissolution, then over 10 million years would be required for the dissolution front to migrate one mile east to the WIPP site.

Dissolution Around Boreholes and Shafts

Abandoned or inadequately sealed boreholes and shafts that penetrate salt formations can provide pathways for dissolution as water migrates through the openings in response to pressure differences between aquifers. This process is the natural equivalent of solution mining, where water is forced down a hole into the salt stratum, dissolution occurs, and the resulting brine is then pumped to the surface for recovery of the resource. GEI (1977b) has reported that test holes are commonly enlarged to about three times the bit diameter where they penetrate salt strata and that similar or greater enlargements can reasonably be expected along old wells or boreholes drilled during past exploration for salt, natural gas, and oil. Older holes represent the greatest risk, because past record keeping was poor or nonexistent, and because sealing was either not attempted or was incomplete.

The risks associated with dissolution along old wells, boreholes or shaft, are of two kinds: (1) an encounter with such an old well or borehole during repository mining can result in a large inflow, or (2) continued dissolution along an inadequately sealed hole or shaft located near repository workings can eventually compromise repository integrity.

With respect to solution structures, the repository design should:

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

Performance models must consider of following aspects of dissolution.

- Leaching is a time dependent process. Models simulating effects of leaching such as dissolution around shafts and boreholes and the formation of breccia pipes or blankets must include rate functions and be able to incorporate differing conditions at different times.

- Leach rates will be sensitive to the salinity of aquifer fluids. As leaching proceeds upstream, groundwater becomes more salt saturated and has a reduced capability for additional leaching downstream.

- Thermal effects must be considered. Salt dissolution will be increased as groundwater is warmed and the warm water will be able to retain more salt in solution. Rock permeabilities will be increased. Conversely, as the thermally affected aquifers cool, salt may be precipitated thereby reducing aquifer permeability.

- As discussed previously, the formation of a breccia blanket will result in a loss of support in overlying beds. Increased fracturing and subsidence can be expected. An increase in permeability and decrease in rock mass strength are likely. For long-term analyses, the time dependent changes in permeability are more important. Operational models must consider potential hazards associated with leaching behind shaft or tunnel linings, at shaft hardware attachment points or the risk of repository flooding as a result of dissolution along fractures or an encounter with a highly permeable, leached zone during repository mining.

2.6 Other Features

Two other geologic features are infrequently observed in bedded salt deposits and may escape detection during site exploration. These are so-called "mud plugs" and igneous dikes (GAI, 1979a).

"Mud plugs" appear periodically throughout the potash sequences within the Delaware Basin evaporites. These features are irregularly-shaped vertical columns containing a high percentage of suspended salt crystals within a salty clay matrix. Their vertical dimensions are unknown; horizontal dimensions may range up to hundreds of meters (GAI, 1979a).

A system of mostly narrow, steeply dipping lamprophyre dikes cut the salt-bearing formations in the Delaware Basin (Jones and others, 1973; Powers and others, 1978). At its nearest approach, the dike system passes about 7 miles northwest of the WIPP site. Small 2 to 8 cm thick dikes have been observed in a salt mine in the Appalachian Basin in New York (GAI, 1979a). Bleaching and recrystallization of salt for a distance of 2 to 15 cm from dike boundaries is observed but no major structural effects are reported. Some dikes are brecciated in the salt but appear undeformed in overlying shale beds (GAI, 1979a). Powers and others (1978) report that some of the igneous features encountered in the Delaware Basin may be sills, that is nearly horizontal, sheetlike intrusive masses.

These minor geologic features are not expected to have significant impacts on nuclear waste repository sites. "Mud plugs" may be structurally weaker than more homogeneous salt, and therefore, should probably be left as part of an enlarged avoidance pillar. Since the properties of igneous dikes and sills differ considerably from those of salt, local instability problems may occur in a storage room intersected by a dike or sill. Also, fractured igneous rock could provide a hydrologic conduit. Therefore, the design process should include provisions for avoiding the presence of dikes or sills in or near storage areas (GAI, 1979a). Geophysical exploration techniques such as magnetometer and gravity surveys may be very beneficial in locating igneous dikes in salt basins. These methods would take advantage of the presence of iron-bearing minerals in most igneous rocks (especially basalts) and the higher density of most igneous rocks relative to the enclosing sedimentary strata.

The physical and chemical properties of mud plugs and igneous dikes should be incorporated in performance models if applicable. A steeply dipping dike could be modeled similarly to a steeply dipping fault zone in that it would represent a conduit or barrier depending upon site specific properties and be much more extensive in length than in width. The strike of the dike would be important in 3-dimensional modeling. A sill could be modeled in the same way as a sedimentary bed with appropriate mechanical, thermal and hydrologic properties assigned based on site-specific data.

3.0 SEISMIC HAZARDS

3.1 Introduction

Earthquake induced ground movements could conceivably damage equipment in a nuclear waste repository, injure personnel, hamper operations, damage underground openings, propagate flaws that could compromise the integrity of natural or engineered seals in the system, or create other pathways for waste migration. The subject of seismic hazards as they may affect nuclear waste repositories in general has been extensively summarized (Carpenter and Towse, 1979) and will not be further discussed here.

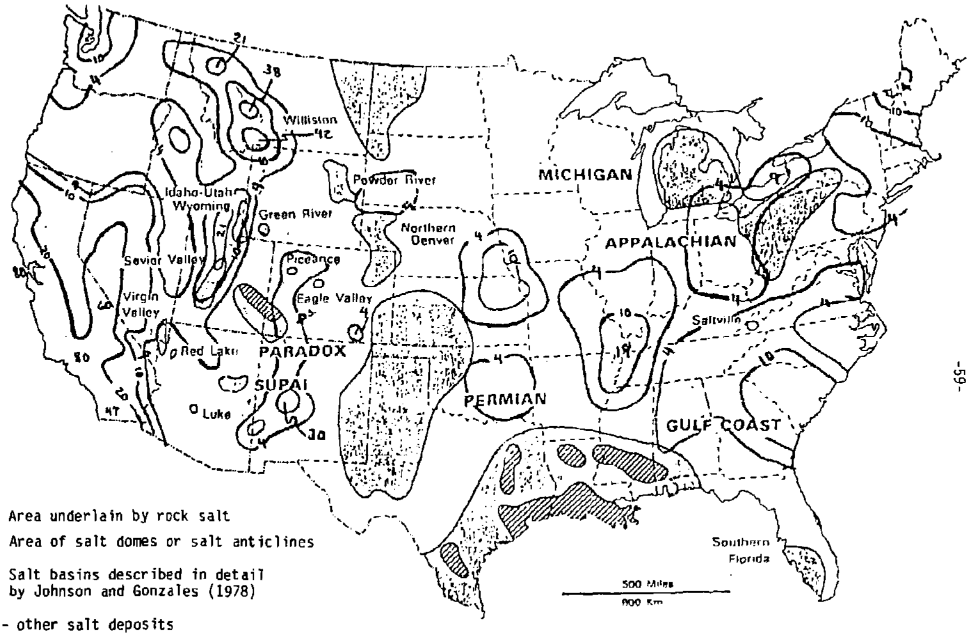
3.2 Seismicity of Bedded Salt Basins

Figure 15 provides an estimate of the relative risk of seismic activity on a nuclear waste repository in bedded salt. As can be seen in Figure 15, major salt deposits within the coterminous United States are almost entirely outside of seismically active areas. This situation reflects the geologic environment of salt deposition and subsequent tectonic history which has led to the preservation of salt deposits.

3.3 Effects of Earthquakes on Underground Structures

A survey of reports on earthquake damages to underground structures such as tunnels and mines leads to several conclusions:

- Damage underground is less severe than that on the surface, and motion and damage decrease with depth.
- Tunnels in epicentral regions when subjected to accelerations over 0.4g or velocities over 60 cm/s may suffer severe damage



Area underlain by rock salt

Area of salt domes or salt anticlines

Permian - Salt basins described in detail by Johnson and Gonzales (1978)

Piceance - other salt deposits

—10— Horizontal acceleration contours at 4, 10, 20%g (from Algermissen and Perkins, 1976)

Figure 15 Relative Seismicity Map, Coterminous United States

Contours shown have a 90% probability of not being exceeded in 50 years, but will be attained statistically in a period of about 475 years.

or collapse. Outside of those areas or with less motion, damage is seldom severe.

- Most major damage occurs where movement is along faults cutting the tunnel, or in unstable areas around surface openings.

Dowding and Rozen (1978) analyzed 71 water and transportation tunnels that were subjected to earthquakes. The tunnels studied were built between the late 1800's and the present, and represented a wide variety of construction methods and lining types. They found that tunnels subjected to accelerations up to 0.19g suffered no damage and that with accelerations of up to about 0.5g, minor damage such as lining cracks and local rock falls was experienced.

Reported damage was separated into three main groups: shaking, active faulting, and ground or portal damage. Fault displacement, where experienced, always resulted in significant damage. They noted that the hazard of active fault displacement could be largely eliminated from future tunnels by careful site studies.

Approximately 57% of the cases of significant damage to tunnels studied by Dowding and Rozen involved failures near portals or under shallow cover. Some of these tunnel failures also involved surface effects such as landslide damage at portals. Damage at depth consisted primarily of minor rockfalls and formation of new cracks. Their investigations yielded the following conclusions:

- Collapse of tunnels from shaking occurs only under extreme conditions. It was found that there was no damage in both lined and unlined tunnels at surface accelerations up to 0.19g. In addition, very few cases of minor damage due to shaking were observed at surface accelerations up to 0.25g. There were a few cases of minor damage, such as falling of loose stones, and cracking of brick or concrete linings for surface accelerations above 0.25g and below 0.4g. Most of the cases of similar damage appeared above 0.4g. Up to surface acceleration levels of 0.5g, no collapse (damage) was observed due to shaking alone.

- Tunnels are much safer than above-ground structures for a given intensity of shaking. While only minor damage to tunnels was observed in Modified Mercalli Scale[1] VIII to IX levels, the damage to above-ground structures at the same intensities is considerable. It should be noted that the effect of the damage is a function of the use of the tunnel relative to that of the building.

- More severe but localized damage may be expected when the tunnel is crossed by a fault that displaces during an earthquake. The degree of damage is dependent on the fault displacement and on the conditions of both the lining and the rock.

1. For a description of the Modified Mercalli (MM) scale of earthquake intensity, see Richter (1958).

- Tunnels in poor soil or rock, which suffer from stability problems during excavation, are more susceptible to damage during earthquakes, especially where wooden lagging is not grouted after construction of the final liner.

- Lined and fully grouted tunnels will only crack when subjected to peak ground motions that result in rock drops in unlined tunnels.

- Tunnels deep in rock are safer than shallow tunnels.

- Total collapse of a tunnel was found associated only with movement of an intersecting fault.

Stevens (1977) investigated effects of earthquakes on underground mines. His study included some instances of tunnel damage, which were also reported by Dowding and Rozen.

Stevens' investigation revealed a number of instances in which earthquakes that were strongly felt on the surface were little noticed by persons in caverns or mines. Available reports ranged from instances of earthquakes not being felt in mines, to reports of flooding - possibly indicating fault displacement - to collapses. Stevens did not report any accounts of damage in salt mines as a result of earthquakes. Stevens' findings may be summarized as follows:

- 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 on either side of the fault, destruction of timbering, collapse of roof and walls of workings, and flooding of the mine, all of which could have disasterous consequences.

- 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 enlargement and interconnection of joints or old fractures is possible.

- 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.

- Other factors being equal, it appears reasonable that the severity of damage due to shaking would probably be least when the mine is located in highly competent, unweathered rock. Somewhat greater damage would probably be expected in a mine in weathered or less competent rock; greatest damage would be expected in a mine located in loose, unconsolidated or incompetent rock. However, comparative data on this are inadequate.

- The intensity of shaking below ground is commonly less severe than on the surface due seemingly to rock properties. In general, the progression of rock properties upward from depth is from highly competent unweathered rock, through weathered rock, to loose unconsolidated rock near the ground surface.

Dowding and Rozen (1978) noted that certain site-specific studies point to deamplification of peak amplitude with depth, greater for soil and less for rock. Ground motion may be amplified upon intersection with a tunnel if wavelengths are the same as the tunnel's diameter or, at most, up to four times the diameter. They reported that measured peak accelerations are recorded at wavelengths much longer than normal tunnel diameters (their study involved tunnels 2 to 6m in diameter) and therefore, amplification was not judged to be an important factor in damage analysis.

Dowding and Rozen expressed the opinion that in future work, high-frequency motions (not normally measured by strong motion equipment) should receive more attention, as they may contribute to the possibility of relative displacement between blocks along planes of weakness. This high-frequency effect was judged to be a possible explanation of the local spalling of rock or concrete, which was reported in several cases after earthquakes. Higher-frequency waves attenuate more rapidly than lower-frequency waves, and therefore, destructive effects of such motions may be expected to extend outward only short distances from the source.

Duration of strong-motion shaking during an earthquake is of great importance since it may cause fatigue failure and lead to large deformations. This mode of failure is dependent on the total number of cycles induced by the ground shaking. Haimson and Kim (1972) found that long duration cyclic loading may cause fatigue failure in intact rock and Brown and Hudson (1974) proved it experimentally for jointed media.

The number of cycles required to cause fatigue failure is usually too large to be reached during a single earthquake. The cumulative cyclic effect, if any, has not been evaluated owing to a lack of available field data.

3.4 Potential Seismic Effects on a Nuclear Waste Repository in Bedded Salt

Data summarized in the preceeding paragraphs indicate that the overall degree of seismic risk to a nuclear waste repository in salt deposits is lower than may exist for other media. Bedded salt deposits are generally outside of seismically active regions where high levels ground shaking or fault movements may be experienced. However, Algermissen and Perkins (1976) have noted lower attenuation rates for seismic waves in the midcontinental and eastern areas where most major salt deposits are located relative to those seen in the tectonically active western United States. Therefore, a nuclear waste repository in bedded salt could be vulnerable to the effects of a distant earthquake if not constructed to seismic resistive standards. This would be especially true for surface facilities.

Surface facilities would be subjected to the same conditions as other structures on the surface for which there is a good background in engineering experience. Subsurface facilities would be similar to other underground workings. However, shafts and contained machinery would respond partly as surface and partly as underground facilities, and therefore, would require engineering that is a blend of the two. Shafts would be critical in maintaining access, communication and ventilation following a major earthquake and should therefore be considered as critical facilities that must be capable of continued operations following a major event.

An example of a seismic hazards evaluation of a prospective nuclear waste repository in bedded salt is provided by the study performed for the southeastern New Mexico (WIPP) site (Powers and others, 1978).

A detailed discussion of regional and local seismic activity is provided by Powers and others (1978) and interested readers are referred to their work. The following brief summary is provided to illustrate problems associated with a seismic hazards investigation and to review a preliminary, probabilistic surface ground motion assessment for a specific site.

Prior to 1960 no earthquake recording instruments existed in New Mexico or nearby areas. Two instruments were installed in 1960 and four additional units were installed in New Mexico and adjacent areas in 1962.

Prior to 1960 20 historic earthquakes had been experienced in the vicinity of the WIPP site. Five of these made up the strong (MM VIII, M = 6.4) Valentine, Texas earthquake of August 16, 1931 and associated aftershocks. The Valentine, Texas earthquake is the strongest earthquake recorded historically or instrumentally within 300 km of the WIPP site.

Since the installation of recording equipment, 38 earthquakes have been detected within 300 km of the WIPP site. The strongest of these (M = 4.6) occurred in northern Mexico on August 19, 1966. This event would have been felt by persons in an area extending at least 20-30 miles from the epicenter and would likely have had a maximum intensity of MM IV-V. It would therefore have been comparable with many of the lesser events in the preinstrumental historic record. Some other events in the instrumental record ($M \geq 2.5$) might have been felt by persons favorably located but many could have escaped human detection especially in view of the generally sparse population in southeastern New Mexico and western Texas.[1] However, more than one-third of the instrumentally recorded earthquakes detected within 300 Km of the WIPP site since the installation of seismographs in the area would probably have escaped detection if instruments had not been present.

A further increase in sensitivity to seismicity in the vicinity of the WIPP site was provided in April 1974 when a high-gain seismograpgh was installed at the WIPP site itself. Details concerning this station are given in Powers and others (1978).

During the period April 1974 to October 1977, 291 events identifiable as local and regional earthquakes were recorded at the WIPP site

1. There is one earthquake recorded in the Central Basin Platform area southeast of the WIPP site for which a local intensity of MM VI is reported. However, the local magnitude for this event on August 14, 1966 was given in Powers and others (1978) as $M_L = 2.8$. Since earthquakes below M = 3 are near the limit of human detection and well below normal damage threshholds, a reported intensity MM = VI, characterized by incidents of damage to well-built structures, is unusually high and difficult to accept.

station. Many of these can be correlated with seismicity [illegible] [illegible]ated southwest and west of the WIPP site but a number of low magnitude earthquakes were detected in an area southeast of what is known as the Central Basin Platform (Powers and others, 1978). A regional "background" seismicity was also recognized; this included one event of M [illegible] 3.6 located about 40 km northwest of the WIPP site.

The discovery of seismicity in the Central Basin Platform area led to installation of an instrument array in the area during [illegible]. Unfavorable surface geology and locally high "noise" levels resulting from oil field activity have reduced the effectiveness of the array. However, during the period November 1975 through July 1977, 407 events were detected of which 135 were well enough recorded to be located although only 20 of the events were detected by enough stations to permit an estimate of both depth and hypocentral uncertainty. Nineteen of the events detected by the Central Basin Platform array were also detected by other regional stations; most of these events were peripheral to the Central Basin Platform array resulting in some uncertanty in location. The seismic activity in the Central Basin Platform area may be related to secondary oil recovery projects in the area; all events were of low magnitude (Powers and others, 1978).

The above discussion reflects a fundamental problem in seismic hazards studies. As the ability to detect earthquakes increases, the number of earthquakes detected also increases and leads to an altered perception of earthquake activity in a given region. This problem has been noted elsewhere (see Cramer and others, 1978).

A seismic risk assessment for design of surface facilities has been prepared for the WIPP site (see Powers and others, 1978). The assessment is based on geologic and tectonic data as well as historic seismicity and is regarded as primarily valid for relatively short-term, operational phase considerations.

The risk analysis presented by Powers and others (1978) is based on risk methodology developed by Cornell (1968) and concepts of source areas developed by Algermissen and Perkins (19). Assumptions necessary for the risk analysis and for risk analyses in general included:

- The level of seismic activity in the future will be similar to that historically experienced. The applicability of this assumption to long-term considerations is uncertain.

- Adequate data exists to determine acceleration attenuation as a function of earthquake magnitude, epicentral distance and regional geologic characteristics.

- The empirical relationship between earthquake intensity and magnitude developed by Gutenberg and Richter (1942) is reasonably approximated. This judgement is necessary so that preinstrumental data may be included in the analysis.

- Geologic studies are sufficient to identify all potential source zones.

- Earthquakes with epicenters which fall significantly outside of seismic source areas defined for a particular risk analysis may be regarded as regional background. The possibility that the maximum earthquake expectable based upon assessment of these random regional events may occur at the proposed site must be included in the risk analysis.

- A credible maximum magnitude earthquake can be specified for each source zone.

- Reasonable focal depths can be established. This is particularly important for near site events.

For a detailed discussion of the ways in which these assumptions influenced the specific risk assessment, interested readers are referred to Powers and others (1978).

Validation of any performance model of seismic response for a nuclear waste repository in bedded salt or any other medium will require careful inquiry into the validity of each assumption made during the risk analysis. This historic seismic record for the United States is relatively short and relationships which link such factors as intensity with magnitude, rupture length or displacement with magnitude and acceleration (peak or sustained) with attenuation or structural response are all empirical. These relationships have been mostly developed based on data for the western United States and the extent to which they can be applied in other areas is very uncertain.

With respect to potential seismic hazards, the design and performance modeling processes should:

- Include detailed geologic studies sufficient to assure facility siting remote from an active fault and to assess the regional level of seismic activity.

- Demonstrate that the integrity of surface structures, shafts, hydrologic seals and canister storage wells would not be threatened by violent ground shaking or ground failure caused by a major earthquake. Detailed structural analyses of HLW and man shafts will incorporate elements of response spectra developed for surface facilities and underground facilities. These analyses will constitute challenging structural engineering problems.

- Evaluate potential vertical and horizontal ground accelerations and event duration for both surface and underground repository facilities. Probabilistic methods appear most applicable for sites in regions where seismic sources cannot be readily constrained to a particular fault or group of faults.

- Provide dynamic response analysis and appropriate design safeguards to reduce the risk of structural failure in canister handling, transport, and storage areas.

- Testing and performance modeling of shaft seals and other engineered barriers should include simulated effects of shaking and evalution of potentials for failure along seal-rock interfaces as a result of differential response to earthquake shaking. The value of multi-component seals should be investigated as a potential method of mitigating this problem.

4.[illegible] [illegible]

4.[illegible] [illegible]

[illegible] [illegible] CH_4 under pressure have been encountered [illegible] appears to form as a result of alteration of [illegible] potash salts by brines which migrate through the [illegible] slight tectonic activity. Gases have not been [illegible] in potash-free salt deposits in the U.S. Gulf Coast.

Baar (1977) reported one incident where an explosive release of CO_2 displaced air in a mine shaft, reached the surface and then flowed down-slope as a density cloud into a nearby village causing loss of life by suffocation.

GAI (1979a) stated that gas pockets in potash deposits in the Delaware Basin are believed to contain N_2 gas ("dead air") and that gas has been encountered under sufficient pressure to cause blowouts while drilling (Jones and others, 1973). Gases evolved by heating specimens of WIPP materials included N_2, H_2O, HF, O_2, HCL, CO_2 and materials derived by decomposition of sulfates (Powers and others, 1978). Many of these materials were evolved at temperatures high enough to rupture fluid inclusions in evaporite minerals.

Hydrocarbon gases - chiefly methane - commonly occur in shale and may be found in other sedimentary rock types associated with bedded salt. The potential exists for damaging and fatal explosions if methane-bearing

[illegible]

4. [illegible]

[illegible] may exist during the [illegible] threat to structural stability and worker safety [illegible] the repository during the [illegible] develop in shaft and tunnel linings. [illegible] repository [illegible] should be treated as [illegible] sufficient experience is gained to support a definite classification.

The repository design should eliminate the possibility of explosion, shock waves, or fire reaching the active storage sections of the repository. GAI (1979a) suggested that the most effective method of accomplishing this would be to isolate excavation areas from waste storage areas and to connect newly excavated storage areas to older areas only as a last phase in block development. Development of the repository in blocks or modules would provide an increased measure of safety against widespread effects of explosions.

5.0 [illegible] CONSIDERATIONS

5.1 [illegible]

[illegible] generally [illegible] recognized that the greatest [illegible] nuclear waste repository [illegible] system. [illegible] recognition has been the driving [illegible] and archetypal [illegible] to determine potential waste migration [illegible] features of importance to repository siting.

[illegible] environment can also have significant effects on repository operations and safety as well as upon long-term waste migration. [illegible] groundwater inflows have often constituted major hazards during mining and tunnel driving and have caused losses of life, headings and even entire facilities including some workings in bedded salt (for examples, see Baar, 1977). Smaller inflows represent nuisances and adversely affect costs and efficiencies of operations.

Twelve scenarios have been described whereby groundwater may enter and/or exit a nuclear waste repository in bedded salt (Carpenter, Steinborn and Thorson, 1979). These scenarios will be discussed in a following section.

5.2 Regional Setting

Summaries of the geohydrologic characteristics of several bedded salt basins have recently been provided. These include general descriptions of the Michigan, Appalachian, Gulf Coast, Paradox and Supai Basins

(Johnson and Gonzales, 1978) and the Williston Basin (GAI, 1979c). Geohydrologic characteristics are basin specific and few generalizations are evident.

GAI (1979c) demonstrated that in order to minimize the risk of nuclear waste entering the biosphere as a result of groundwater flow, a nuclear waste repository should be located in an area where hydraulic gradients are downward; that is, beneath recharge areas.

The summaries by Johnson and Gonzales (1978) and GAI (1979c) indicate that fresh water supplies suitable for domestic or agricultural uses are generally limited to shallow aquifers in sedimentary basins containing bedded salt deposits. In semiarid regions such as the Permian basin or southwestern Gulf Coast basin, potable water supplies may be very limited because of salt contamination. Deeper aquifers are progressively more saline although salt-saturated brines are generally not present (Johnson and Gonzales, 1978).

These regional geohydrologic characteristics would influence a nuclear waste repository in bedded salt in the following ways:

- Hydraulic gradients will be largely downward directed, that is, most water will enter the repository from overlying strata under gravitational forces. Shaft linings and borehole seals should be designed mainly to seal off flows from above.

- Water migrating toward the repository will not be salt saturated and therefore the potential will exist for progressive dissolution along fractures and behind shaft linings.

- [illegible]

[illegible] Repository [illegible] hydrologic [illegible]

Twelve potential scenarios have been [illegible] whereby [illegible] may enter or exit a nuclear waste repository [illegible]. These scenarios may be grouped into 4 failure modes. These are: dissolution, fracturing, voids, and penetration. Dissolution modes include breccia pipe and breccia blanket formation and dissolution around boreholes. Fracture modes include flow through pre-existing or new fractures. The effects of facies changes are also included in this category. Voids include pores and fluid inclusions; penetration modes include shaft and borehole sealing failures, undetected boreholes and mines or wells constructed after repository decommissioning (Carpenter, Steinborn and Thorson, 1979).

Brief descriptions of these failure scenarios are provided in the following paragraphs. Several of the failure scenarios also have structural or stratigraphic significance and have therefore been described previously. However, for the sake of completeness, these scenarios will also be briefly discussed below with emphasis on their hydrologic significance.

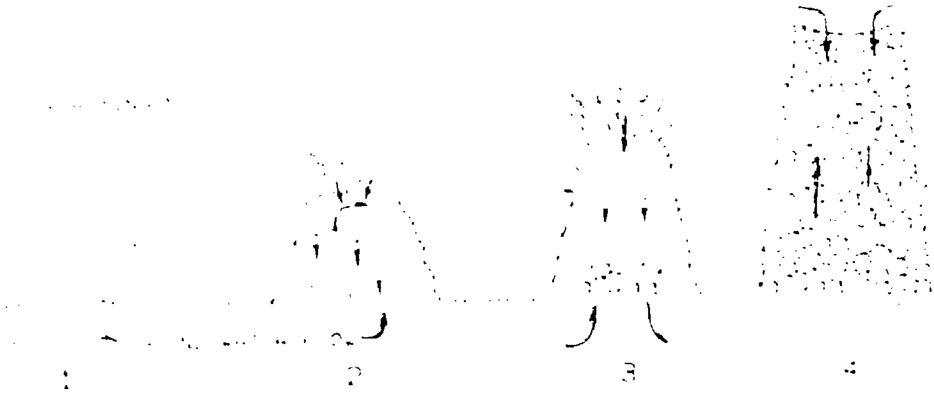
[illegible]

Breccia Pipe Formation [illegible] The schematic formation of a breccia pipe is shown in Figure [illegible]. Fractures resulting from upward growth of the pipe can provide permeable pathways [illegible] the repository from overlying aquifers and unless thoroughly healed with salt, the pipe breccia should provide a permeable pathway from an underlying pressure aquifer to the repository.

These potential pathways are shown in Figure [illegible] which is a repeat of Figure 13 with pathway arrows added. Note that potential flow paths change as the breccia pipe grows with time. For long-term performance modeling, this situation creates a time-dependent variable.

GEI (197[illegible]a) obtained their data concerning breccia pipes from descriptions of these features as they exist in the Permian Basin which includes the WIPP site. However, Powers and others (1978) state that no breccia pipe dissolution features have been detected in the vicinity of the WIPP site.

<u>Breccia Blanket Formation</u> The schematic formation of a breccia blanket is shown in Figure 14. The blanket deposit itself is a potentially highly permeable pathway located in close proximity to the salt layer and is evidence of either active dissolution or past dissolution that could be reactivated during the life of the repository. Rocks overlying the breccia blanket have been undermined during blanket formation and may be expected to be more fractured and potentially permeable than those in unaffected areas. Therefore, there is a greater potential for hydrologic communication and increased flow in rocks underlain by breccia blankets than in equivalent unaffected strata.



1. Initial cavity develops when salt is dissolved by moving groundwater in an underlying permeable unit. Flow upward from underlying pressure aquifer.

2. With continued solution, caving begins. Flow still upward although seepage through fractures in roof may result in minor downward flow.

3. Caving front migrates upward through overlying formations. Groundwater movement may be upward or downward depending upon pressure distributions in aquifers.

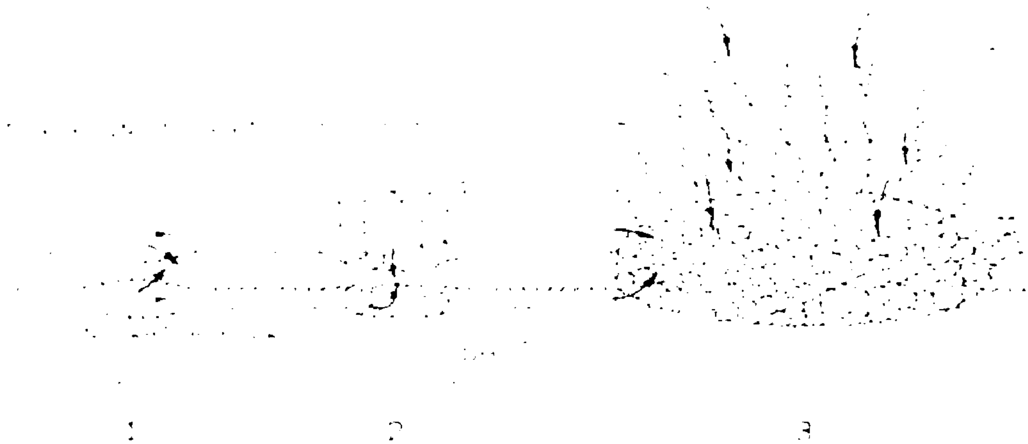
4. Breccia pipe may reach ground surface. Groundwater flow controlled by pressure distribution in aquifers and permeability of pipe; added potential for surface water infiltration through pipe.

Figure 16 Progressive development of a breccia pipe (adapted from Geotechnical Engineer Inc., 1977a).

[illegible]

[illegible] of WIPP in the Salado Formation, the potential [illegible] (Powers and others, 1978), dissolution has doubtless affected Salado salt beds in areas west of the WIPP site where the formation approaches the ground surface. Powers and others (1978) indicate that studies are under way to define the extent of affected areas.

Dissolution Around Boreholes and Shafts. As previously noted, dissolution of salt around abandoned or inadequately sealed boreholes or shafts can provide permeable pathways in which water can readily migrate in response to pressure differences between aquifers. Also, as noted previously, such dissolution could result in a large and continuing inflow if the borehole or shaft were encountered during repository mining. Future dissolution along an inadequately sealed hole or shaft located near repository workings could eventually compromise repository integrity. Figure 18 is a schematic showing dissolution along a failed well or borehole which intersects salt. As shown by the arrows, various pathways are possible and may change with time as the solution cavity along the well or borehole enlarges. The process is time dependent and may be exponential since the cavity can enlarge at an increasing rate as dissolution creates ever larger and more efficient pathways.



1. Initial groundwater flow in permeable unit within or at top of salt initiates dissolution. Flow downward into assumed repository horizon; possibly upward if dissolution is associated with underlying pressure aquifer.

2. Solution of overlying or underlying salt bed continues. Flow paths as above.

3. Overlying unit collapses, inducing fracturing and subsidence of overlying strata. Various flow paths possible depending on pressure distributions. Possible surface infiltration because of increased fracturing in subsided area.

FIGURE 17 Progressive development of a breccia blanket (adapted from Geotechnical Engineers, Inc., 1977a).

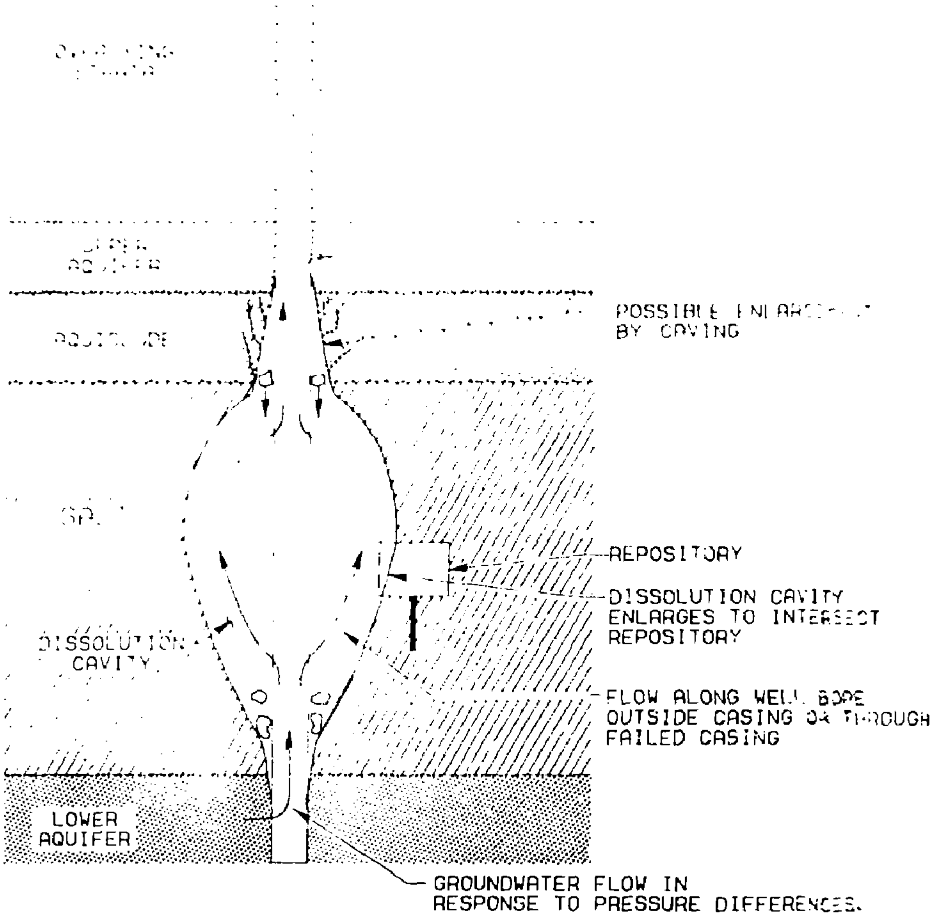


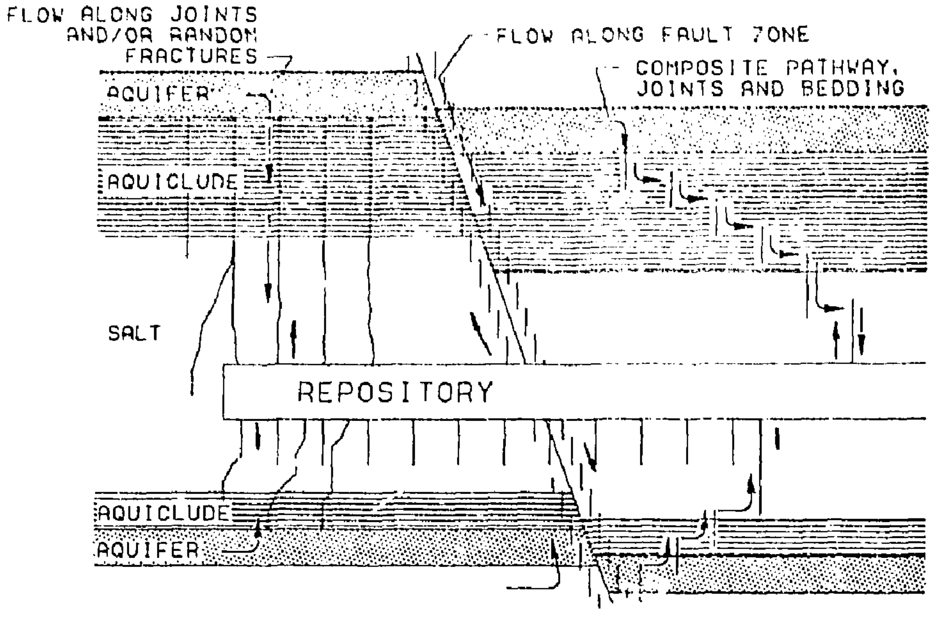
Figure 18 Dissolution along a well or borehole penetrating salt.

5.3.2 Fracture Modes

Flow Through Existing Fractures At contemplated repository depths, salt is expected to deform plastically, and therefore, should not sustain fractures (GEI, 1977a). However, Baar (1977) has reported the presence of fractures in salt that have permitted groundwater flows into some European mines.

Fracture networks such as bedding planes, joint systems and old faults are common in shale beds within and enclosing salt deposits. These fractures may significantly reduce the effectiveness of the shale beds as groundwater barrier layers. Similar fracture networks may persist in other brittle beds within the salt sequence such as anhydrite layers and contribute to rock mass permeability. Flows through fracture networks are shown schematically in Figure 19. While flow directions through existing fracture systems are not likely to change materially with time, repository excavations could permit interconnection of previously isolated fracture systems and thereby affect flow. As an example, an underlying pressure aquifer could recharge a repository through fractures intercepted by the repository floor. If artesian pressures in the underlying aquifer were high enough, the upward directed flow would enter fractures in the roof through which water had been previously seeping downward into the repository by gravity. In this way, a flow reversal could be accomplished.

As noted previously, no information is known to have been published regarding fracture systems at the southeastern New Mexico (WIPP) site.



Flow paths may be either downward in response to gravity or upward in response to artesian pressure within a confined aquifer.

Figure 19 Groundwater inflow through new or existing fractures.

Flow Through New Fractures Mining of a repository will change the stress field in the enclosing rock mass, and the resulting strains could induce development of new fractures. In extreme cases, large-scale failures such as a roof collapse may occur and cause repository flooding. The formation of such fractures by mining activities or stress relief has been discussed in Chapter 2.

New fractures may develop in rocks overlying repository workings in response to a loss of support caused by salt creep into repository openings. GEI (1977) reports increased salinity in aquifers over potash mines as evidence for this process. A measured surface subsidence of 3 ft., caused by high extraction potash mining at a depth of 1600 ft., is cited as evidence for propagation of stresses throughout the entire overlying section (GEI, 1978). At the much lower extraction ratios contemplated for a nuclear waste repository in bedded salt, the potential propagation is considerably less.

Natural processes may also create new fractures. Haimson and Kim (1972) found that long-term cyclic loading (as by repeated earthquakes) may cause fatigue failure in intact rock. The development of a new fault through a repository as a result of future tectonic activity is a geologic event that must be considered, although it is of extremely low probability (Carpenter and Towse, 1979).

Flow paths through new fractures are the same as those for existing fracture systems and are shown in Figure 19 above.

As previously noted, thermal stresses may play an important role in the development of new fractures in rocks surrounding a nuclear waste repository and migration of hot water or steam may also lead to rock fracturing. Ways whereby thermal stresses may lead to increased fracturing were listed by Carpenter, Steinborn, and Thorson, (1979) as follows:

Rock Weakening and Failure:

- Heat lowers salt and rock strength, leading to caving, floor cracking, and/or subsidence.
- Heat induces melting of salt.
- Heat-induced chemical alterations lead to reduced strength in salt.
- Greater expansion of some beds causes tensile fracturing in other beds with less expansion.
- Differential heating across faults causes differential movement between the two sides, opening flow paths.
- Differential expansion between beds creates permeable cracks along bedding surfaces.
- Differential expansion between rock, salt, seal, and plug materials creates fractures in seals and plugs.
- Steam causes hydrofracturing of rock (unlikely at depth).

Creep:

Heat induces high creep rates, leading to distortion of salt beds.

- Distortion exposes canisters to aquifers.
- Distortion induces fracturing in salt and other rocks.

Paths Formed by Differential-Temperature Water Processes After Emplacement:

- Cold water enters hot, dry repository.
  (1) Sudden cooling of rock promotes shrinkage accompanied by fracturing, caving, and/or subsidence.
  (2) Steam forms and builds up pressure, forcing contaminated water from repository.
  (3) Cold water contacts hot shaft and borehole seals and fractures them.

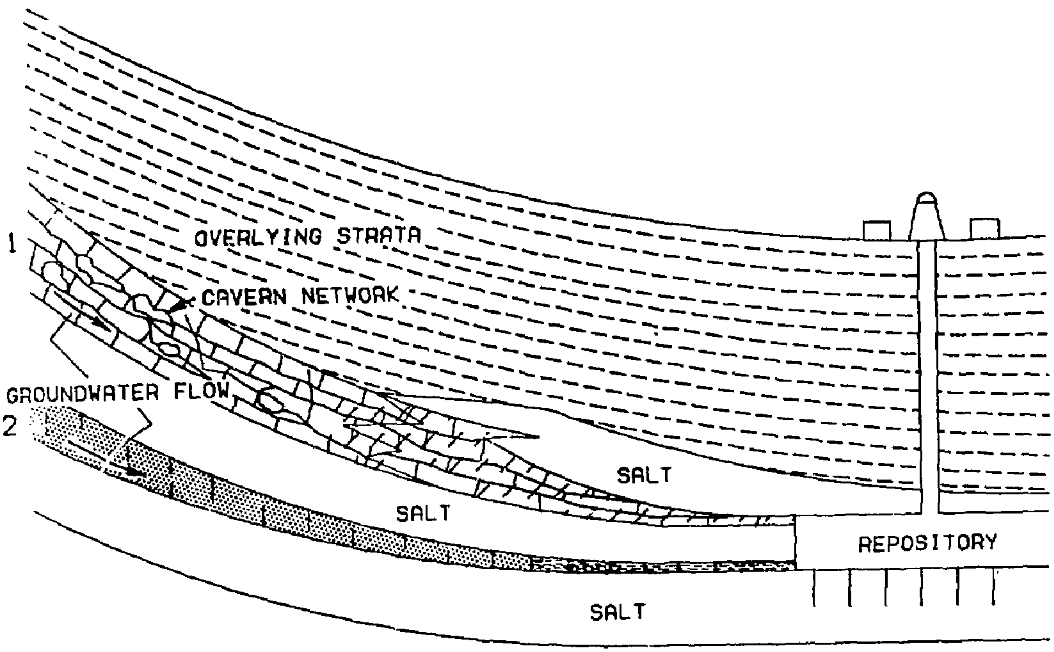
- Hot water from repository contacts cool rock.
  (1) Hot water contacts cool rock and causes expansion. Effects are unknown.
  (2) Hot water contacts cold shaft and borehole seals. Effects are unknown.
  (3) Hot water leaks from repository and flashes to steam, increasing permeability.

Facies Changes The effects of facies variations have been described in the section of this report concerning geology of the repository horizon. These interbeds and lateral variations in sedimentary facies provide potential pathways for water seepage into repository workings. Wet clay and shale beds have been noted in salt and potash mines, although the quantities of water discharged are generally very slight (GAI, 1979a). Groundwater flow pathways through interbeds and facies variations are shown schematically in Figure 20. In general, such pathways will be lateral and will be controlled by regional hydraulic gradients.

Powers and others (1978) indicate considerable continuity in major and many minor stratigraphic units at the WIPP site. Therefore, facies variations may not be significant to performance modeling and analysis of WIPP. However, continuity of strata nd facies relationships may be important coniderations at other proposed bedded salt sites.

Voids Voids are open spaces between or within grains or crystals. Voids that have developed as a result of dissolution have been previously discussed.

Interstitial Voids Voids or pores occur to some extent in all sedimentary rocks. However, before flow can occur, interconnections must exist between voids, and the voids must be of sufficient size to allow water molecules to migrate without being absorbed by charged clay mineral surfaces present on the walls of the voids. Effective porosity is, therefore, that fraction of the total void space that permits flow through the rock mass. GEI (1979b) has estimated average values of 0.01% and 0.07% for salt and included, or adjacent shale beds, respectively. Potential inflows to a repository based on an assumed hydraulic gradient of 0.005 were calculated to range from 6.9×10^{-6} to 8.2×10^{-6} cm^3/s for



1. Carbonate facies grading laterally to gypsum-anhydrite sequence.
2. Clastic facies: sandstone grading to fractured shale.

Figure 20 Groundwater inflow through interbeds and facies variations.

salt and from 7.7 x 10^{-5} to 2.8 x 10^{-6} cm^3/s for shale. These are very small quantities and would, by themselves, contribute negligible amounts of recharge to a nuclear waste repository. The porosity ranges for WIPP site rocks given in Table 6 (Powers and otners, 1978) are an order of magnitude higher. An interstitial flow path is shown schematically in Figure 21a.

Inclusions Brine-filled inclusions are common in salt deposits and range from a few microns in size to pockets containing as much as 100,000 gallons (GEI, 1977). Studies of fluid inclusions in single salt crystals show that those with less than 10% vapor will migrate toward a heat source (Holdoway, 1973). Migration is accomplished by preferential dissolution on the warmer side and deposition on the cooler side as shown schematically in Figure 21b.

Biphase droplets (> 10% vapor) migrate away from a heat source; therefore, it is possible for a transport mechanism to develop as a result of the movement of fluid inclusions in salt. GEI (1977) suggested that such a transport mechanism would be an inconsequential pathway for radionuclide escape, because high canister temperatures are expected to persist for relatively short periods and because the canister heat affects only a limited area. Migration over long distances, out of the salt unit, was considered improbable. Fluid inclusions are common in WIPP salt and have been the subject of considerable study.

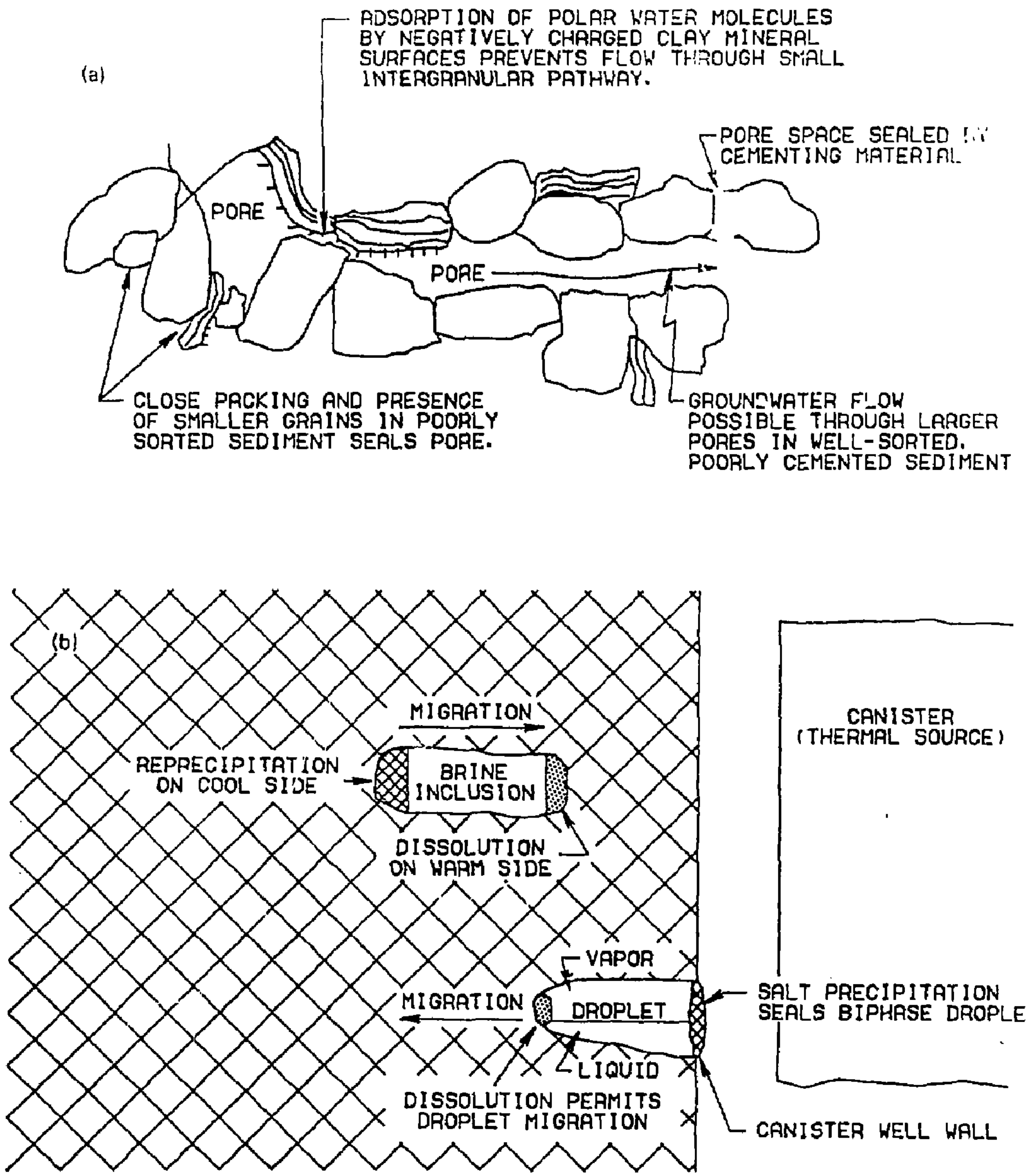


Figure 21 (a) Porosity and effective porosity in a sedimentary rock;
(b) Migration of brine inclusions in salt.

5.3.3 Penetration Modes

Borehole Sealing Failures GEI (1978) has determined that all of the coterminous United States in which oil and gas are produced enforce regulations that require the sealing of wells and boreholes prior to abandonment. However, the long-term effectiveness of any well sealing and plugging system has not been demonstrated, and a study by Herndon and Smith (1976) indicated that existing well plugs and seals must be suspect. Furthermore, well enlargement and a zone of increased fracturing may develop about a well or borehole, either as a result of drill action or in response to changes in the local stress field caused by the presence of the hole. The fractures and enlarged zones around a hole would provide pathways for fluids to bypass seals. Such fracture zones may also result from reservoir stimulation efforts, such as hydrofracturing.

Repository thermal effects may contribute to borehole sealing failures in several ways. Leaching or chemical alteration of sealing materials can lead to loss of strength and subsequent failure. Fracturing of seals as result of steam pressure, and bypassing of seals as a result of dissolution of evaporites by hot water or differential expansion of borehole walls relative to seals can also cause failure.

Potential well or borehole sealing failures are shown schematically in Figure 22. Flow paths may be upward or downward depending upon pressure distributions in aquifer systems penetrated by the well or borehole.

A site selection criterion for the WIPP site was the absence of known exploratory holes or wells near the site. However, the site

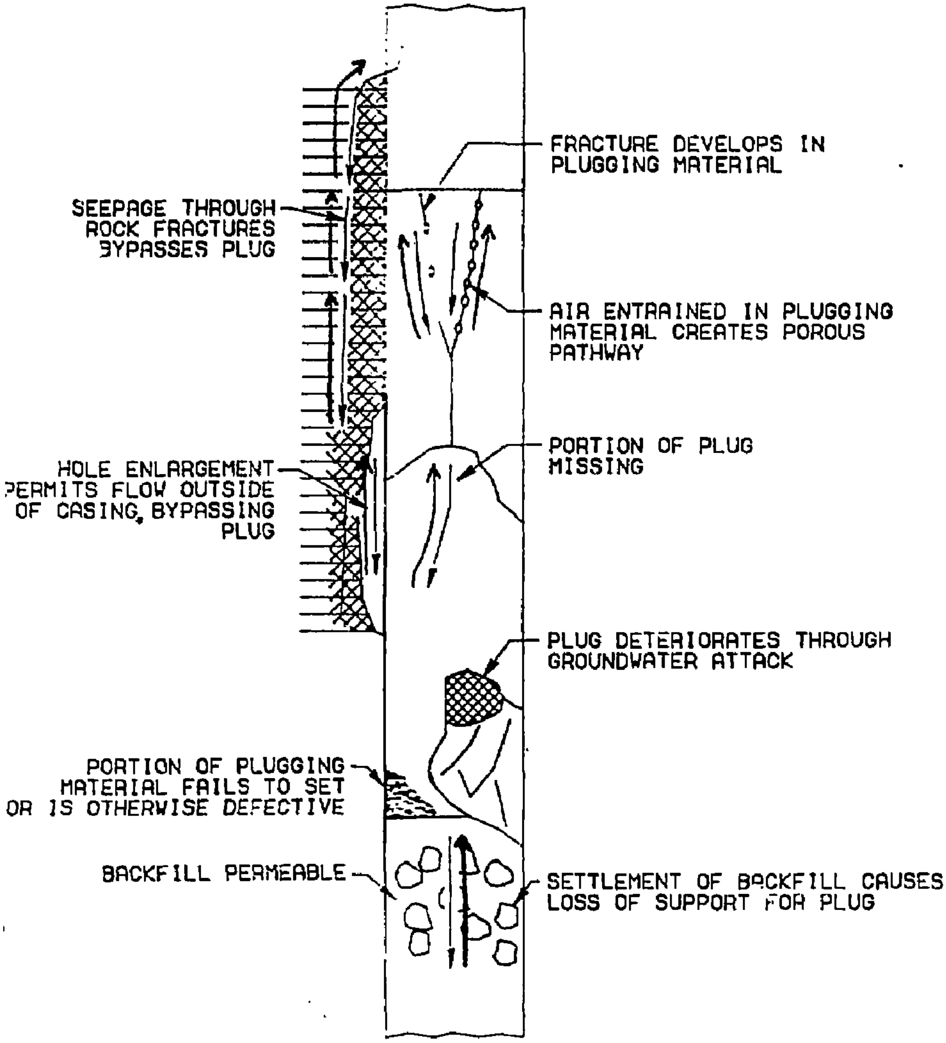


Figure 22 Well, borehole, or shaft sealing failures.

characterization process required the drilling of a deep exploratory hole, ERDA-9, at the center of the WIPP site and shallower holes have been drilled near the site for potash reserve estimates. Therefore, several partial or complete aquifer penetrations have been made at WIPP. There is no discussion of well sealing techniques in the site characterization report (Powers and others, 1978).

Shaft Sealing Failures Potential shaft seal failures are of the same type as those for wells and boreholes and are shown schematically in Figure 22. The problem is complicated by the large size of the shaft relative to a well or borehole. The failure can thus develop in a much larger volume of material.

Excavation of a large-diameter shaft can currently be accomplished only by conventional mining methods (for example, by using explosives in rock), but the size of shafts that can be mined by boring methods is steadily increasing. As a result of blasting and stress relief, a zone of increased fracturing develops around a shaft. Dimensions have been suggested by GAI (1977).

This problem could be mitigated in part by grouting fractures in aquifer zones and/or by lining the shaft to safeguard subsequent excavations and operations against hazardous water inflows and rock falls. However, complete sealing may not be achieved, and grouts and shaft linings may deteriorate with time. Thermal effects could contribute significantly to shaft sealing failures; potential modes are the same as for borehole seal failures. Therefore, leakage through shafts must be considered an important pathway whereby water may enter a nuclear waste repository.

Undetected Boreholes Salt dissolution caused by an undetected borehole has been previously discussed. Undetected boreholes and wells can also provide pathways for groundwater movement into a nuclear waste repository independent of dissolution. Such pathways would also be as shown in Figure 22. Since most unknown wells or boreholes are old and were drilled either before state permit procedures existed or without coming to the attention of permit authorities, such wells are likely to be inadequately sealed or not sealed at all.

Unrecognized wells and boreholes will probably exist near nuclear waste repositories, but techniques have been developed to facilitate the search for them. Development of these techniques has received impetus from the need to seal old wells to permit effective pressurization of underground gas storage facilities. Herndon and Smith (1976) have reported efforts that have led to the successful location of old wells under buildings and as much as 3m of earth.

New Wells or Mines Bedded salt and associated evaporites represent mineral resources that may be exploited in the future. The radioactive elements in a waste repository may also represent an attractive future resource, especially as man depletes his supply of fossil and nuclear fuels. If a repository is penetrated by future man with full knowledge of its existence, the act becomes one of judgment based upon an assessment of risk. If knowledge of the repository is lost, however, inadvertent intrusion is possible, and the probability of such an event is a matter to be assessed by social scientists taking into account the persistence of records and the stability of societies.

The risk of intrusion as a result of water-well drilling is low because the presence of highly saline groundwaters overlying bedded salt deposits will discourage further drilling. The drilling of solution wells to exploit the salt resource or to search for hydrocarbons in strata below the salt deposits are more likely to lead to inadvertent intrusions which could in turn compromise repository integrity.

5.3.4 Recharge and Discharge Mechanisms

During repository operations and at the time of closure, a nuclear waste epository will be at atmospheric pressure and the local hydraulic gradients created by dewatering or evaporation will be toward the repository. As nuclear wastes are emplaced, the temperature within the repository volume will rise. The temperature rise will be a function of ventilation and backfilling and may exceed the boiling point of water at 1 atm (Altenbach, 1979).

If open pathways exist, water will migrate toward the repository from an overlying aquifer by gravity and will enter the repository from an underlying aquifer if the pressure in the underlying aquifer exceeds one atmosphere. The rates at which water would enter the repository would depend upon the extent and efficiency of the various pathways. Thus, a large fracture could suddenly admit a large quantity of water while very slow seepages could be experienced from fractured shale interbeds or porous, impure salt.

Any water movement within the repository during the operational phase would most likely be by gravity flow and would require control by sumps and/or pumping. Water discharge from the repository during the operational phase would be through the ventilation system by evaporation or by pumping if inflows became significant. In the latter case, surface storage and evaporation facilities would be necessary.

Following decommissioning, as water flows into the repository, the head within the repository will increase producing a decrease in the hydraulic gradient and thereby reducing the inflow. Eventually, the head within the repository will increase to equal the head of either the overlying or the underlying aquifer, whichever is lower. Thereafter, water will flow through the repository toward the aquifer with the lower head.

As groundwater approaches the repository, it will be heated by the repository's thermal field. Calculations by Altenbach (1979) indicate a high probability of steam formation, for emplaced high-level waste, at least during the early period following repository closure. The thermal field for spent fuel, however does not indicate that steam formation will occur (Cheung and Otsuki 1980). As viscosity decreases, flow velocities will increase as the water is heated and is eventually converted to steam. Also the potential for dissolution and enlargement of fractures and voids (either pores or around boreholes and shafts) will increase because of the higher solubility of evaporites in hot water. However, if the water flashes to steam, dissolved materials will remain in the brine, because the ability of steam to transport non-gaseous ionic species is very low. This could create a complex pattern of dissolution and possible reprecipitation as groundwater moves into the zone heated by the repository.

Within the repository, steam formation will provide a means for conveying water from areas of high heat energy (for example, canister rooms) to cooler areas, such as former workshops and shaft locations. These movements may not follow ordinary hydraulic gradients and could have unanticipated effects. Moisture and gaseous radionuclides could concentrate at potential weak points, such as shafts and areas where less attention may have been paid to rock integrity because of an absence of waste. As water pressures in the repository increase and as the thermal load falls, steam formation will be retarded. If leaks occur, the hot water or steam will flow along the escape path, and the total head will decrease. This will tend to prolong the period during which steam will be present.

In the region around the repository, a complex convection pattern will develop as a result of the thermal cell created by the repository (Dames and Moore, Inc., 1978b). Qualitatively, cooler water approaching the repository along the regional hydraulic gradient will be warmed and will rise through and over the repository. As cooling occurs, the water will sink in the aquifer, completing the convection cell. The rising water will be deflected downstream by flow in the overlying aquifer so that a distorted convection cell will form. A sketch of the convection cell based on prel' nary thermal analyses by Dames and Moore, Inc. (1978b), is shown in Figure 23.

As during the recharge process, a complex pattern of dissolution and reprecipitation may be expected. Dissolution will enlarge pathways and increase flow, while precipitation of materials from cooling groundwater will tend to plug voids and fractures, thereby further perturbing flow patterns.

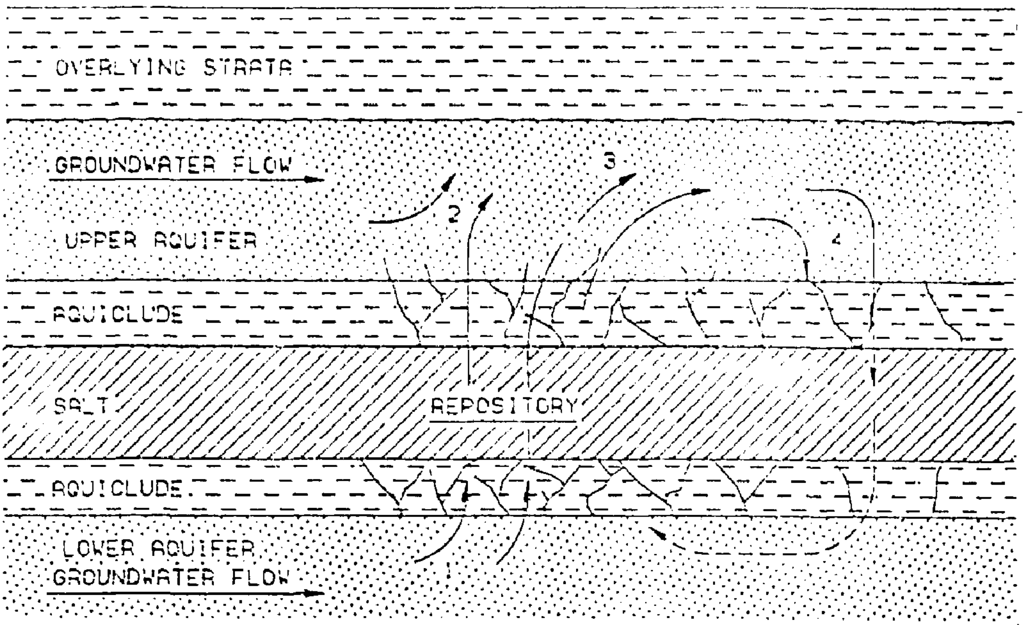
5.4 Repository Design Considerations

The design and performance modeling process for a nuclear waste repository in bedded salt must consider hydrologic effec in the following ways:

- Probable groundwater seepage into the repository must be accurately assessed and facilities to handle, store, and dispose of anticipated water inflows included in the design.

- During repository excavation, standby equipment must be present sufficient to handle large water inflows from brine pockets and fractures. Adequate water storage and disposal facilities must be included in the repository design. A system to isolate water encountered in excavation areas from areas in which emplacement is in progress must be included in the project design.

- Shaft linings must be able to withstand aquifer pressures determined during site characterization studies. The design



1. Groundwater flow in lower aquifer is deflected upward in response to pressure-density differences.
2. Water heated by repository rises into upper aquifer as thermal plume.
3. Plume is sheared by groundwater flow in upper aquifer; warmer water is deflected downstream.
4. Water cools and sinks in upper aquifer, completing convection cell.

Figure 23. Idealized thermal convection pattern (adapted from Dames and Moore, Inc., 1978b).

process must specify materials that will not deteriorate in the anticipated hydrologic environment.

- Repository equipment must be specified to be constructed of corrosion resistant materials.

- The repository layout and excavation and emplacement cycles must be designed and executed to permit worker evacuation in the event of flooding and to minimize the risk that any canisters being handled at the time of the flood can be the source of a nuclide escape to the biosphere.

- An extensive effort to locate and seal all exploratory boreholes and old wells within the area underlain by the repository is necessary. To provide redundancy, the repository design should also isolate such holes in pillars.

- An accurate assessment of thermal buildup within the repository must be provided and a clear demonstration made that thermally induced fracturing and seal failures will not lead to unacceptable groundwater intrusion.

- The repository design process must result in a facility that can be backfilled and decommissioned so as to assure that subsequent resaturation and repressurization does not lead to unacceptable nuclide escape to the biosphere.

6 0 GEOTECHNICAL CONSIDERATIONS

6.1 Introduction

The geotechnical considerations summarized in this report are those that refer to the physical properties of rocks and rock masses which will control their response to repository excavation, thermal loading and general stability during the operating life of the facility. Long-term considerations will be briefly discussed to the extent that these influence repository design and performance modeling.

Geotechnical items included in this chapter are a consideration of rock stress state in the bedded salt environment and assessment of the rock mechanical, radiolitic, and thermal properties of bedded salt and associated strata.

6.2 State of Stress

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 in situ principal stresses, the shape of the opening, the presence of discontinuities 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.

Regional stress is the in situ stress state of a rock mass prior to any excavation. It is a function of the overburden weight and any tectonically induced stresses. It can include residual stresses remaining from past tectonic activity or previous overburden recently removed;

for example, the St. Lawrence Valley in eastern Canada is still adjusting to the melting of several kilometers of glacial ice, an event that was largely complete 10,000 years ago.

The existing state of ground stress must be determined before the stress distribution around any man-made excavation can be calculated. A number of instrumental methods have been developed to make this determination (IECO, 1979).

In bedded salt, the measured vertical stresses are generally in fair agreement with a simple prediction which equates vertical stress to the weight of overburden. This is a function of the plasticity of salt deposits under high confining pressure that results in an essentially hydrostatic environment. It should be noted, however, that stresses in unusual geological environments may exhibit significant variations and anisotropy due to tectonically induced regional stresses is possible (GAI, 1979a). There is also the possibility that associated brittle strata such as dolomite or anhydrite may retain stresses imposed by past overburden loads or tectonism.

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. However, 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.

Avoiding areas with regional, tectonically-induced stress states, for instance tectonically active areas, 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.

A problem related to regional stress state is long-term crustal movement in response to tectonic activity or isostatic readjustment. In tectonically active areas, such movements may occur at rates of centimeters per year, whereas they may be imperceptible in large stable basins. As previously noted, a nuclear waste repository in bedded salt could readily be located outside of tectonically active areas, and therefore, any crustal movements at the repository site would not be at a rate sufficient to impact the operational life of the facility. Studies prior to licensing should be expected to provide information on the long-term effects of crustal movements in order to determine if they could lead to exhumation of the waste or otherwise create nuclide escape paths. Changes in groundwater chemistry have been noted in rocks overlying potash workings and have been related to fractures caused by subsidence (GEI, 1977b). Long-term changes in groundwater chemistry could provide early warnings of loss of waste isolation resulting from increased rock fracturing.

The design and performance modeling processes should account for the regional stress state and potential for crustal movements by:

- Pre-excavation measurement of the in situ stress state of the repository horizon and surrounding strata.
- Adjusting room shape and layout to take into account the in situ stress distribution.
- Design structural supports and shaft linings to accommodate any additional loads due to regional stress or excess, near surface, horizontal stresses.
- Include an assessment of crustal movement potential in performance models and provide for long-term monitoring of crustal movements and groundwater chemistry.

6.3 Rock Mechanical Properties

The adequate performance evaluation of an engineered structure in rock requires a basic knowledge of the geomechanical properties of the material in which excavations are to be made, and the laws governing the material's behavior. The material surrounding an excavation in rock includes not only the intact rock material (that is, the assemblage of minerals or grains) but also its structural discontinuities such as bedding planes, joints, etc. This general medium is referred to as the rock mass. Depending upon the scale of the workings and the geological history of the site, the rock mass can be very variable although the persistence of significant discontinuities at depth in bedded salt is unlikely (GAI, 1979a).

Most rocks respond initially to the application of stress (force) by elastic deformation in obedience to Hooke's Law. That is, the applied stress results in some proportional strain (deformation) in the rock and the application of increasing stress results in a linear pattern of increasing strain. If the stress is removed, the specimen relaxes and returns (ideally) to its original condition. This situation is shown schematically in Figure 24.

With continued stress application, the elastic limit of the rock is reached (point A in Figure 24) and the material begins to deform plastically. Stress and strain are no longer directly proportional and permanent deformation appears; that is, if the stress is relieved the specimen no longer returns to its original form.

Deformation continues until the rock can no longer sustain the applied force. Once this peak strength is exceeded, the rock collapses catastrophically or flows ductily.

Salt, however, deforms differently than most other rock materials. The elastic range of rock salt is limited (Mraz, 1979; Serata and Milnor, 1979) or may not exist at all as a practical matter (Baar, 1977; Powers and others, 1978). Rather, salt is believed to deform plastically, but the

a) HOOKE'S LAW:

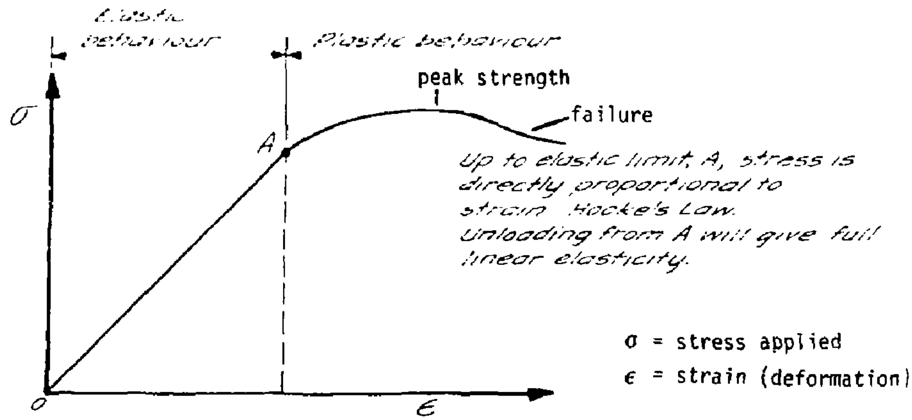


Figure 24 Example of normal rock response to application of stress (adapted from GAI, 1979b).

nature of the plastic deformation is uncertain and controversial. Specialists advocate various performance models (see for example, Baar, 1977, and Serata and Milnor, 1979) while potential users of these models express concern over their applicability (Powers and others, 1978; Dawson, 1979).

Problems are also noted in relating laboratory data to field experience (Baar, 1977; Powers and others, 1978). It appears that the geologic history of a salt deposit, effects induced in samples during drilling, shipping, and sample preparation, and methods of testing, all play a role in the data obtained (Baar, 1977; Powers and others, 1978).

Numerous investigators have performed laboratory experiments to assess the quasi-static and creep behavior of single crystal and polycrystalline salt (halite). Among these are Carter and Heard (1970), Hansen and Mellegard (1977), Heard (1972), Le Comte (1965), Lomenick (1971), Nair and Singh (1973), Poirier (1973), Thompson and Ripperger (1964), and Wawersik (1978). The results of in situ tests have been reported in Bradshaw and McClain (1971).

Dawson (1979) has provided a recent review of proposed constitutive models for the behavior of salt and has described uncertainties arising from their use. The following discussion is largely summarized from his work.

Creep can be defined in terms of the time dependent deformation of a material subjected to a constant stress state. Laboratory experiments are typically idealized into three stages of creep deformation for a specimen subjected to constant stress for long periods of time. These are described as (1) primary creep, demonstrating decreasing deformation rates, (2) secondary creep, demonstrating constant deformation rates, and (3) tertiary creep, exhibiting increasing deformation rates and normally terminating with fracture or instability. These three types of creep are shown schematically in Figure 25.

Experiments on rock salt have produced data that substantiate that all three creep regimes can be obtained depending on the stress state and temperature. The relative importance of each regime is controlled by the deformation mechanisms that are active under the imposed conditions of stress and temperature. Further, the rate of creep occurring as a result of a particular mechanism is a function of the imposed environmental conditions. Creep rates are increased by elevated temperatures and increased confining pressures (Dawson, 1979; Powers and others, 1978).

Constitutive equations for materials undergoing creep deformations (frequently called creep "laws") have been developed from available experimental data usually by empirically fitting an arbitrarily chosen equation containing the necessary independent variables to the data. In other instances, the form of the constitutive equation has been motivated from a model for the physical mechanisms dominating secondary creep. The

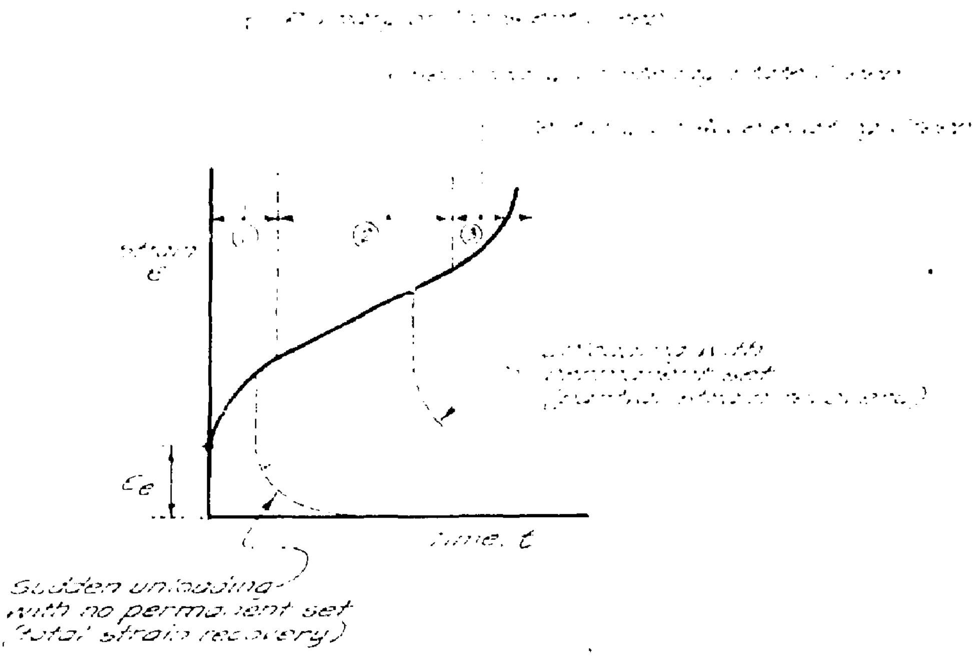


Figure 25 Idealized creep curve and strain recovery for a rock material *GAI, 1979b).

parameters appearing in the equations are determined such that the equations approximate the data. Equations associated with deformation mechanisms have also been applied to primary creep without thorough physical justification (Dawson, 1979). Dawson has discussed the physics and mathematical developments of creep "laws" in some detail. Interested readers are referred to his paper.

The distinction between strain-hardening and time-hardening is important in applications that have changing stress and temperature fields. Strain-hardening laws normally require that as the stress state changes, and thus moves from one constant stress and temperature creep curve to another curve, the shift occurs between points of equal total strain on the two constant stress curves. Time-hardening laws require that the change from one constant stress curve to another occurs between equal times on the two constant stress curves. These two interpretations can give very different results. Life fraction rules represent a means of compromising between time-hardening and strain-hardening by moving from one constant stress curve to another according to equal percentages of the total deformation that can be tolerated by the material. Time-hardening laws are the simplest to implement in a solution algorithm and are probably the most commonly used. They are most successfully applied when the problem involves a stress state that is constant in time, but can produce very poor results if this is not the case. Although time is not an intrinsic material property, it is critical for dimensional purposes, and therefore, is essential in any inelastic constitutive model (Nickell, 1980).

Secondary creep (also called steady-state creep) is characterized by constant deformation rates under conditions of constant stress and temperature. Dawson (1979) has discussed the development of constitutive equations which describe this process.

Tertiary creep exhibits increasing deformation rates that lead to failure. Some work has been done in developing constitutive models in terms of creep rupture theory that are appropriate for the tertiary creep regime. The onset of instability characterized by tertiary creep has been observed to be related to the total strain. However, little has been done to express either the transition from secondary to tertiary creep or creep rates in the tertiary creep range using constitutive equations for rock salt (Wawersik and Hannum, 1979).

It should be noted that while creep may be a time dependent process (rates change with time) or a time independent process (constant rate), total deformation as a result of creep is always time dependent. This is because it is the sum of all the deformations experienced during preceeding time steps and additional increments of deformation are continually being added as time progresses.

Primary and secondary creep models are separable in their form. This implies, for instance, that if two creep tests are performed at temperatures θ_1 and θ_2, with the stress state the same in each test, the ratio of strain rates between these tests must equal the ratio of strain rates of a second set of two creep tests performed at θ_1 and θ_2 but at a different stress state (Dawson, 1979).

Currently, several efforts to develop constitutive models for the creep deformation of salt are being conducted. Some of the efforts have been motivated by the assumption that more than one mechanism is active for a particular combination of independent variables. This assumption has led to constitutive models having additive primary or secondary creep functions and provides a means of having multiple activation energies and stress nonlinearities. A second effort currently being developed involves constructing a detailed deformation mechanism map that defines the transition zones between dominant creep mechanisms. This effort provides a means of quantifying where a given mechanism dominates over other mechanisms, but alone does not fully account for more than one mechanism being active at a particular stress and temperature state (Dawson, 1979).

In recent years, creep deformations of salt have been analyzed by numerical methods using finite element or finite difference methods in the space domain and various numerical techniques in the time domain. Some of the analyses use elastoplastic models to predict the stress state due to the applied loads.

Some investigators have included an elastic component in their analyses (see for example Serata and Milnor, 1979). These elastoplastic formulations normally assume linear elastic behavior for stress states lying below the elastic surface (typically a Mohr-Coulomb failure criterion is used). As stresses increase, the material enters a transition region in which both elastic and plastic behavior are experienced. Once the stress reaches the yield strength, the material deforms inelastically and independently of time. The stress state resulting from the elastoplastic analysis is introduced into the creep law to predict the creep strain increment for a specified time increment. Some analyses have applied the yield surface concept to the creep law in such a way that no creep deformations occur below a certain limiting stress (Serata and Milnor, 1979). The concepts of elastic, transition and yield surfaces are shown in Figure 26, taken from Serata and Milnor (1979).

Creeping viscous flow formulations have also been applied to the analysis of creep deformations. These formulations relate the applied stress field to the deformation rates of the material using the creep law as the constitutive model for a non-Newtonian fluid. Normally such formulations neglect the elastic portion of the deformation and, thus, apply to problems in which creep strain increments dominate over elastic strain increments for a given time increment.

Nickell (1980) expressed a preference for a model containing an elastic term. He stated that a model proposed by Serata (1978) is the best operational model currently available because it incorporates:

- A yield function to demarcate between viscoelastic and visco-plastic behavior of rock salt.
- A pressure and temperature dependence for yield stresses.
- A standard linear solid which can be readily extended into the non-linear regime to represent creep behavior.

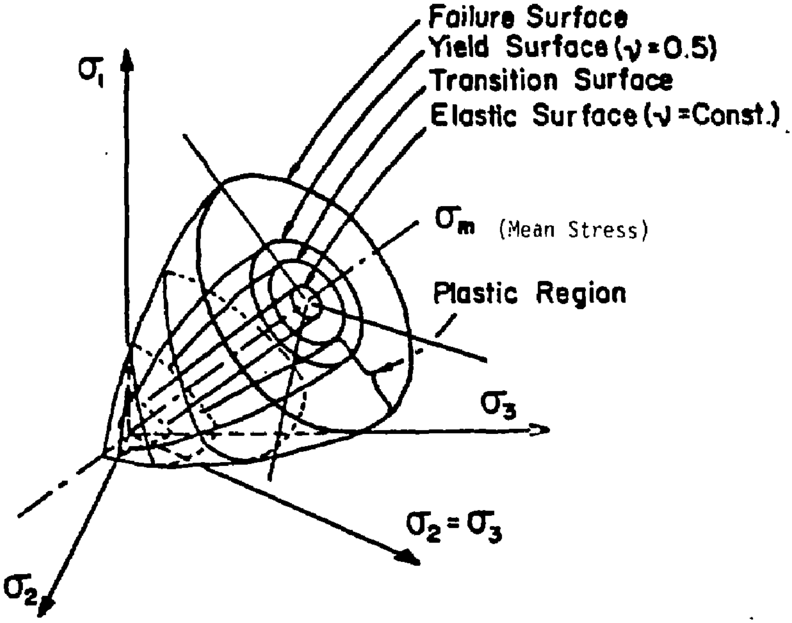


Figure 26 Elastic, yielding, and failure characteristics of rocks in stress space. Source: Serata and Milnor (1979).

Deficiencies noted in the Serata model by Nickell were the lack of a secondary creep term and arbitrariness about the Poisson's ratio (ν-0.5) argument for viscoplasticity.

It should be noted that for materials or environmental conditions in which elastic behavior is very slight or cannot be detected, constitutive equations which do not contain an elastic term would be sufficient.

Dawson (1979) noted that the bulk of the work performed to date has been within the context of primary creep. He stated that primary creep laws are necessary to describe the short term creep response of salt and are effective in providing constitutive equations for computational methods that are applied to analyze relatively short term phenomena. However, salt is known to deform in the secondary creep regime for a large portion of its total deformation under a wide range of stress and temperature conditions. Primary creep laws exhibiting monotonically decreasing strain rates as either a function of time or strain become non-conservative (in terms of mine closure) as secondary creep becomes dominant. For time periods extending well beyond the time span of measured data used to formulate the law, little confidence can be placed in computations based solely on primary creep laws. This is emphasized by Baar (1977), who cites several examples of constant convergence rates observed in mines. The convergence measurements represent an integrated effect over the pillar height (and include motion in the floor and ceiling) and, therefore, do not provide conclusive evidence that all of the material is deforming in a secondary creep mode. However, the measurements do strongly suggest that primary creep models are inadequate (Dawson, 1979).

Dawson notes that secondary creep laws with parameters determined using the deformation rates evaluated at the end of creep tests tend to be conservative over long time periods since the experimentally observed creep rates are usually still decreasing at the end of the creep test.

Dawson also noted that the use of some elastoviscoplastic models causes difficulty in properly accounting for the zero (or nearly zero) yield limit and the inseparable time-dependent and time-independent plasticity exhibited by salt during the initial loading phases. Further, the definition of a unique yield surface is questionable in light of the time-dependent behavior of salt.

Dawson concluded that all aspects of the creep response of rock salt have not been represented by a single comprehensive constitutive model. Additional data are needed to quantify fully the observed behavior. Among the areas requiring research emphasis are (1) criteria that define the transition from primary to secondary creep or from secondary to tertiary creep, and (2) formulations that account for possible history effects on secondary creep rates.

Uncertainties regarding mechanisms and time dependent behavior during salt deformation pose major problems during the assessment of the technical feasibility of salt deposits as a medium for nuclear waste disposal. Given present uncertainties, repository stability analyses would be vulnerable to the challenge that they are based on inappropriate data.

Dawson, (1979) has noted that existing primary creep laws predict differing strains of as much as three orders of magnitude for the same inputs of temperature and stress difference. He has also calculated that similar variations may be obtained with existing secondary creep laws.

In view of the prevailing situation, it appears that generic assessments based on existing analyses can at best bound the stability problem. However, such bounds can be very useful in quantifying aspects of the problem such as, given a set of physically reasonable assumptions, what is the likelihood that unacceptable tensions in overlying strata and/or closure rates would be experienced during time frames of interest.

In the near term, further research into the physics of salt deformation may permit better judgments as to the constitutive laws to be applied. The microfracture propagation studies summarized in Powers and others (1978) is an example of one such recent research effort.

An example of recent testing and analysis of rock salt is provided by the work underway at the southeastern New Mexico (WIPP) site. This work has been reported by Powers and others (1978) and Wawersik and Hannum (1979) who presented results and discussion of both short-term (quasi-static tests) and longer term creep tests.

Regarding the quasi-static testing, Wawersik and Hannum regarded the following results as particularly pertinent:

(1) New Mexico rock salt in the laboratory is very non-linear under all loading conditions with an initial elastic limit

$(\sigma_1 - \sigma_3) \approx 0$. This behavior appeared to be unaffected by differences in hydrostatic pressure history to 5000 psi (34.5 MPa) prior to deviatoric loading. It is conceivable that the low initial elastic limit is influenced by damage during coring in situ and subsequent core handling. However, it is impossible at present to separate out this effect because the exact stress history of the material before laboratory testing remains unknown.

(2) The elastic properties of New Mexico rock salt can be evaluated accurately only in load/unload/reload cycles provided the imposed loading rate is sufficiently high or the range of stresses, either hydrostatic pressure p or $(\sigma_1 - \sigma_3)$, is well below the previously attained peak stress. If the elastic constants are evaluated in this manner, then Young's modulus, E, and Poisson's ratio, ν, fall into the ranges $4.3 \times 10^6 \leq E \leq 5.3 \times 10^6$ psi ($29.6 \leq E \leq 36.5$ GPa) and $0.17 \leq \nu \leq 0.26$. These data compare very favorably with in situ measurements based on records of p- and s-wave velocities and rock densities.

(3) Quasi-static and recovery measurements indicate that practically all nonelastic rock salt deformation is permanent. Additionally, the elastic deformation of New Mexico rock salt subject to deviatoric loading constitutes a very small fraction of the total deformation.

(4) So far, it has been impossible to separate the permanent deformation of rock salt into time-independent and time-dependent components even at the relatively high loading rate, $d(\sigma_1 - \sigma_3)/dt \approx 20{,}000$ psi/min (0.14 GPa/min).

(5) At low confining pressures $\sigma_2 = \sigma_3 \leq 3000$ psi (20.7 MPa) New Mexico rock salt exhibits regimes in which deformation approaches isovolumetric conditions and in which deformation is associated with large dilatancy due to local fracturing. It appears that the near isovolumetric, ductile behavior predominates at low deviator stress, $(\sigma_1 - \sigma_3) \leq 1100$ psi (7.5 MPa) approximately, at elevated confining pressure, $\sigma_2 = \sigma_3 \approx 3000$ psi (20.7 MPa) and/or at high temperature $T \approx 200°C$.

(6) Strength and/or ductility of New Mexico rock salt depend both on temperature and pressure. At ambient temperature the ultimate (true) stresses and the corresponding greatest compressive strains, ϵ_1, vary from approximately 3000 psi (20.7 MPa) and 2% in uniaxial compression to 6500 psi (44.8 MPa) and $12.5 \leq \epsilon_1 \leq 14\%$ at 500 psi (3.5 MPa) confining pressure. At 3000 psi (20.7 MPa) confining pressure no signs of macroscopic failure were observed below 8000 psi (70.7 MPa) and $\epsilon_1 = 20\%$. Macroscopic failure was associated with large principal strain ratios ϵ_3/ϵ_1. For example, when the ultimate stress was reached the ratio ϵ_3/ϵ_1 amounted to -1.2, and -0.83 at zero and 500 psi (3.5 MPa) confining pressure, respectively. By comparison at 3000 psi (20.7 MPa) confining pressure, the greatest observed principal strain ratio was $\epsilon_3/\epsilon_1 = -0.69$. Temperature produced a pronounced decrease in ultimate stress and extended the rock salt ductility, i.e. the amount of rock salt deformation prior to a loss in load bearing ability (Table 3).

(7) Fracture at ambient temperature appears brittle and is followed by a near vertical post-failure curve up to approximately 250 psi (1.7 MPa) confining pressure. The slope of the post-failure curve in stress-strain space increases, i.e. becomes less negative, around and above 500 psi (3.5 MPa) confining pressure. At 200°C unconfined "failure" developed at $(\sigma_1 - \sigma_3)$ = 2100 psi (14.5 MPa) and $\epsilon_1 \approx 12\%$.

Wawersik and Hannum (1979) also presented the results of long-term creep testing at the WIPP site. Summary data are reproduced in Table 3; primary creep data are reproduced in Table 4 and secondary creep data obtained by them are shown in Table 5.

According to Wawersik and Hannum, available results demonstrate that New Mexico rock salt undergoes all stages of creep from primary creep through creep fracture. More important, all of these stages were observed at levels of stress and temperature which are of interest to the WIPP. This means that past modeling efforts which have concentrated on the prediction of primary creep must be extended.

Primary and secondary creep are recognized readily in a qualitative sense. However, the combined data obtained by Sandia Laboratories and RE/SPEC Inc., indicate independently that unambiguous descriptions of these phenomena are difficult. Particular difficulties arise because primary and secondary creep appear to be overlapping, because primary creep at small time steps probably depends upon the initial loading rate and

TABLE 3

Summary Statistic of Creep Tests

Stress and strain represent true stress and engineering strain(1), respectively

ε_1: axial strain; ε_3: radial strain; ε: volumetric strain. Parentheses denote uncertainties.

Question marks indicate that data are missing or not yet available.

Key - DD: large dilatancy (> 4%); DD: considerable dilatancy (> 1%); D: some dilatancy (< 1%); C: some compaction (C)

Sample (Hole# - Depth (ft))	$\sigma_1 - \sigma_3$ (psi)	$\sigma_1 - \sigma_3$ (MPa)	σ_3 (psi)	σ_3 (MPa)	Temper. (°C)	Test Duration (Hrs)	(ε_1) max (%)	$(-\varepsilon_3)$ max (%)	Direction of ε
				Upper Level Salt					
9-2078	2000	13.8	500	3.5	22	310	.273	.169	0
9-2078	4500	31.0	500	3.5	22	166	7.18	4.57	DD
9-2083	2950	20.3	500	3.5	22	1238	2.22	1.68	DD
9-2083	4500	31.0	500	3.5	22	360	13.80	>9.58	DDD
9-2078.5	1700	11.7	3000	20.7	22	311	.125	(0.02)	?
9-2078.5	4100	28.3	3000	20.7	22	166	3.62	2.78	D
9-2083.	2900	20.0	3000	20.7	22	1088	[illegible].02	?	(C)
9-2083.5	4400	30.3	3000	20.7	22	1256	[illegible].40	(>6.4)	(D)
9-2083.5	3000	20.7	3000	20.7	22	675	0.04	?	?
				Lower Level Salt					
9-2625	1200	8.3	500	3.5	22	1842	.22	.08	D
9-2625	2200	15.2	500	3.5	22	1481	2.27	(1.30)	D
9-2625	3300	22.8	500	3.5	22	356	5.31	(2.28)	?
9-2625	2300	15.9	500	3.5	22	595	0.13	(0.07)	?
9-2677	1150	7.9	3000	20.7	22	671	0.15	(0.06)	(D)
9-2672.5	1000	6.9	30	0.2	100	612	2.99	?	?
9-2624	1050	7.2	500	3.5	100	652	2.79	1.50	?
9-2686	1000	6.9	500	3.5	100	747	0.83	0.47	(C)
9-2686	2350	16.2	500	3.5	100	490	17.6	11.40	DD
9-2671	930	6.4	3030	20.9	100	1174	0.98	(0.48)	D
9-2671	2250	15.9	3000	20.7	100	868	29.3	(>19.6)	D
9-2688	1000	6.9	530	3.7	200	80	6.48	3.78	D
9-2668	1000	6.9	3020	20.8	200	165	15.18	9.8	DD
9-2777	4800	33.1	500	3.5	22	100	17.7	14.5	DDD

(1) Engineering strain is defined as $\Delta L/_L$ where L = sample length.

TABLE 4

Summary of Secondary Creep Estimates

(Parentheses denote upper bound values)

Stress and strain represent true stress and engineering strain(1), respectively.

Sample (Hole# - Depth (ft))	$\sigma_1 - \sigma_3$ (psi)	$\sigma_1 - \sigma_3$ (MPa)	σ_3 (psi)	σ_3 (MPa)	Temper. (°C)	Estimated Secondary Creep Rate $\dot{\varepsilon}_1$ (10^{-8}/s)
Upper Level Salt						
9-2078	2000	13.8	500	3.5	22	(0.0 2)
9-2878	4500	31.0	500	3.5	22	(5.02
9-2083	2950	20.3	500	3.5	22	(0.16
9-2083	4500	31.0	500	3.5	22	(5.8)
9-2078.5	1700	11.7	3000	20.7	22	(0.012)
9-2078.5	4100	28.3	3000	20.7	22	(2.25)
9-2083.5	2900	20.0	3000	20.7	22	(0.23)
9-2083.5	4400	30.3	3000	20.7	22	(1.10)
9-2083.5	3000	20.7	3000	20.7	22	0.018
Lower Level Salt						
9-2625	1200	8.3	500	3.5	22	(0.014)
9-2625	2200	15.2	500	3.5	22	(0.20)
9-2625	3300	22.8	500	3.5	22	(1.93)
9-2625	2300	15.9	500	3.5	22	(0.033)
9-2677	1150	7.9	3000	20.7	22	(0.008)
9-2672.5	1000	6.9	30	0.2	100	1.00
9-2624	1050	7.2	500	3.5	100	0.81
9-2686	1000	6.9	500	3.5	100	0.25
9-2686	2350	16.2	500	3.5	100	8.98
9-2671	930	6.4	3030	20.9	100	0.18
9-2671	2250	15.9	3000	20.7	100	3.61
9-2688	1000	6.9	530	3.7	200	14.6
9-2668	1000	6.9	3000	20.7	200	(19.7)
9-2777	4800	33.1	500	3.5	22	31.20

(1) Engineering strain is defined as $\Delta L/L$ where L = sample length.

TABLE 5

Summary of Primary (transient) Creep Data According to Data Fit of Type $\varepsilon_1 = Ct^n$(in/in); t: time (s); i = a,b

Stress and strain represent true stress and engineering strain(1), respectively.

Sample (Hole# - Depth)	$\sigma_1 - \sigma_3$ (psi)	$\sigma_1 - \sigma_3$ (MPa)	σ_3 (psi)	σ_3 (MPa)	T (°C)	C	n	Strain Measures at 100 hrs: ε_1 (%)	Strain Measures at 100 hrs: $\varepsilon_1/\varepsilon_i$
Upper Level Salt									
9-2078	2000	13.8	500	3.5	22	4.16E-4	0.133	0.23	2.2
9-2078	4500	31.0	500	3.5	22	2.53E-4	0.416	5.17	49.7
9-2083	2950	20.3	500	3.5	22	7.976E-4	0.185	0.85	8.2
9-2083	4500	31.0	500	3.5	22	6.60E-5	0.519	5.05	48.6
9-2078.5	1700	11.7	3000	20.7	22	1.597E-4	0.146	0.104 = ε_a	1.0
9-2078.5	4100	28.3	3000	20.7	22	3.33E-4	0.343	2.68	25.8
9-2083.5	2900	20.0	3000	20.7	22	1.49E-3	0.138	0.87	8.4
9-2083.5	4400	30.3	3000	20.7	22	4.62E-4	0.345	8.82	36.7
9-2083.5	3000	20.7	3000	20.7	22	-	-	-	-
Lower Level Salt									
9-2625	1200	8.3	500	3.5	22	1.06E-4	0.122	0.125 = ε_b	1.0
9-2625	2200	15.2	500	3.5	22	1.497E-4	0.307	0.76	6.2
9-2625	3300	22.8	500	3.5	22	1.41E-4	0.409	2.64	21.5
9-2625	2300	15.9	500	3.5	22	-	-	-	-
9-2677	1150	7.9	3000	20.7	22	8.75E-5	0.203	0.12	0.98
9-2672.5	1000	6.9	30	0.2	100	1.38E-5	0.454	0.46	3.7
9-2624	1050	7.2	500	3.5	100	5.26E-5	0.376	0.64	5.2
9-2686	1000	6.9	500	3.5	100	1.97E-5	0.330	0.13	1.1
9-2686	2350	16.2	500	3.5	100	5.97E-6	0.726	6.46	52.5
9-2671	930	6.4	3030	20.9	100	2.84E-6	0.477	0.13	1.1
9-2671	2250	15.9	3000	20.7	100	9.1E-5	0.485	4.51	36.7
9-2688	1000	6.9	500	3.5	200	1.56E-5	0.665	7.72	62.8
9-2668	1000	6.9	3000	20.7	200	1.59E-5	0.689	10.72	87.2
9-2777	4800	33.1	500	3.5	22	4.39E-3	0.255	11.46	93.2

(1) Engineering strain is defined as $\Delta L/L$ where L = sample length.

because most secondary creep rates are only upper bounds. As a result, the description of primary creep in terms of an exponential law creep, for example (Table 4), is sensitive to the time interval which is chosen to fit the experimental data in the space log (ε_1), log(t). Furthermore, the exponential creep relation which was used renders poor fits to experimental measurements at times less than approximately one hour. At elevated temperature, primary creep interpretations are distorted by fast secondary creep which is going on simultaneously. Whatever the reason, ambiguities in the interpretation of creep data probably produced errors in description and predictions. For example, based on Tables 4 and 5, the predicted total axial creep strain for sample 9-2671, $(\sigma_1 - \sigma_3)$ = 2250 psi (15.5 MPa) is 16.3% after 500 hours if $\varepsilon_{total} = \varepsilon_p + \varepsilon_{ss}$ as suggested by the nature of double logarithmic plots. This value overpredicts the actual strain accumulation (ε_1 = 12.5%) after that time by approximately 30%.

Some qualitative disagreement between various sets of results arises concerning the influence of pressure. According to Wawersik and Hannum (1979) available data led to the common conclusion that pressure enters as a first order effect into the prediction of tertiary creep and creep fracture. However, preliminary analyses of the present results suggested that the influence of pressure on transient and steady state creep was negligible. Wawersik and Hannam also noted this observation was contrary to earlier RE/SPEC data and to the results of short-term (quasi-static) experiments. To clarify this point, the recommended that more detailed examinations should be made of existing radial strain data. Also, further tests should be conducted, particularly below 500 psi (3.5 MPa) confining pressure.

Wawersik and Hannam (1979) stated that preliminary quantitative comparisons of Sandia Laboratories and RE/SPEC data are not totally satisfactory. They further stated that one power creep description of RE/SPEC Inc. appears to predict considerably larger creep strains than those which are indicated by the results of Tables 4 and 5. For example, for primary creep periods of 100 hours, several predictions at common stresses and temperatures differ by factors of approximately ten. They stated that the RE/SPEC results also suggest higher secondary creep rates. However, they emphasized that most of these comparisons have been carried out quickly and require checks and confirmation and that some of the observed differences might be due to specimen size. Values of average activation energies are relatively consistent and fall into the range $7.3 \leq Q \leq 13.8$ kcal/mole. The majority of data fit $Q \approx 13.3$ kcal/mole.

It is not clear at this point how serious the observations of history effects might be if they are proven typical under decreasing principal stress difference. However, history effects might influence stress calculations and therefore affect the prediction of creep fracture predictions.

Wawersik and Hannam reported that tertiary creep and triaxial creep fracture developed at 100°C and surprisingly low values of principal stress difference $(\sigma_1 - \sigma_3)$ 2300 psi (15.9 MPa) even at $\sigma_3 \geq 500$ psi (3.5 MPa) confining pressure. Although these stresses and temperatures are likely to develop only very locally, the phenomena are significant enough to require additional study. For lack of established theories, it will be necessary in part to conduct very long experiments. However, creep fracture predictions may also be aided by empirical correlations between creep fracture strains and quasi-static complete stress-strain characteristics. Triaxial tests on granite, sandstone and marble suggested that complete quasi-static stress-strain records can be used to establish loci of limiting stable creep strains. Specifically, it appears that the total nonelastic (time-dependent) strain at any stress will not exceed the nonelastic strain to fracture at the same confining pressure and principal stress difference in quasi-static tests. Although this procedure is strictly empirical, it appeals to the notion that nonelastic strains are a measure of damage and that the limiting strain establishes a maximum amount of damage as a function of stress state before an instability occurs with associated loss in load bearing ability. The foregoing empirical predictive scheme for creep fracture is invoked here because it correlates remarkably well with the available creep fracture observations (Wawersik and Hannum, 1979).

Additional physical properties test data for the WIPP site have been provided by Powers and others (1978). These are provided in Table 6.

Any analysis of the technical feasibility of bedded salt as a repository medium must be based on a thorough geomechanical analysis of the proposed site. The analysis must include both in situ and laboratory tests that take into account the physics of the system including perturbing effects associated with obtaining and preparing samples for testing and making excavations for in situ tests. Tests must be of sufficient length to clearly establish the operative creep modes. The investigation must demonstrate that the data obtained is applicable to the entire repository; this may necessitate in situ tests at several locations within the repository site.

TABLE 6

Physical Properties of Rock from WIPP Study Area (Powers and others, 1978)

Material	Depth (ft)	Density (gm/cc)	Avg. Porosity (Range) (%)	Mass (Moisture) Loss (% to ≤ 300°C)[1]	Resistivity in Ohm Meters	Avg. Air Permeability (Range in (md))[3]	(P) Wave[4] Velocity (Km/sec)
Rock Salt	2000-2100	2.18	0.4 (0.1-0.8)	N[2] - 1.0	58,100	0.01 (0.0003-0.17)	(4.42-4.62)
Rock Salt	2600-2700	2.18	0.5	N - 0.4	(4,900-230,000)	-	-
Anhydrite	-	2.80	-	-	-	-	-
Polyhalite	-	2.70	-	-	-	-	-
Siltstone	-	2.26	-	-	-	-	-

(1) Average H_2O content reported by Wawersik and Hannum (1979) ≈ 0.361.

(2) N - None measured.

(3) Core Labs data.

(4) P Wave velocities determined in the lab agree to 15% with those measured downhole on borehole ERDA 9 (Griswold, 1977).

The repository design process should account for the mechanical behavior of bedded salt in the following ways:

- Size pillars to account for mechanical effects expected over the repository lifetime.
- Provide room designs that keep room closure within acceptable limits.
- Design support structures and shaft linings based upon the expected behavior of the salt mass.

6.4 Thermal Effects

Investigators have proposed exponential relationships between temperature and deformation of salt masses. As an example, empirical relationships established by McClain and Starfield (1977) for Project Salt Vault data included temperature (°K) raised to the 9.5 power. Other investigators have proposed other exponential relationships (see for example, Maxwell, Wahi and Dial, 1978; Serata and Milnor, 1979). However, regardless of the properly applicable constitutive law, it has been clearly established that temperature strongly influences salt deformation resulting in reduced strength and increased ductility as temperatures rise. In view of potential temperature increases in a nuclear waste repository in bedded salt (Altenbach, 1979), thermal effects are of major importance in repository assessment.

For similar pressures, data presented by Wawersik and Hannum (1979) for WIPP salt show increased primary and secondary creep rates as temperatures rise.

In addition to the influence of temperature on the mechanical properties of salt deposits, thermal stresses will be induced as a result of the expansion of the rock mass in a confined environment. The nature of the thermal stress distribution will depend upon repository geometry, temperature distribution and the thermal/mechanical properties of the rock mass. The convective effects of circulating air, prior to back-filling, and circulating water or steam, after backfilling, may also have significant impacts. The heat balance may be significantly altered by phase changes such as water to steam (GAI, 1979a). The thermal conductivity of salt is quite temperature sensitive. The thermal conductivity of single halite crystals 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 (Birch and Clark, 1940). Therefore, at higher temperatures, salt is a less efficient conductor of heat, and models using a constant value of thermal conductivity will underestimate near-canister temperatures.

GAI (1979a) states that the thermal conductivity of bedded salt is generally greater parallel to bedding than normal to it because of the presence of thin layers of lower conductivity material within the salt. These thin layers impede heat flow normal to bedding.

Prior to decommissioning or backfilling, the flow of ventilating air through the emplacement rooms will remove significant amounts of heat. It has been stated (Ratigan and Van Sambeck, 1978) that the effects of ventilation at the midplane of the repository would be noted for up to an order of magnitude longer than the ventilation period. As an example, if the ventilation period is 30 years, the temperatures in the midplane are reduced for almost 300 years.

However, the principal advantages of ventilation will be realized prior to decommissioning and cannot be expected to significantly reduce long-term problems caused by thermal expansion and uplift (GAI, 1979a).

Bradshaw and McClain (1971) found that salt samples heated to about 280°C decrepitated (fractured violently). SAI (1976) tested a number of salt specimens and observed decrepitation for most in the range of 250 to 320°C although one specimen did not fracture up to 400°C. The generally accepted mechanism for this fracturing is pressure created by the expansion of steam formed from pore water in the salt.

Studies by Altenbach (1979) indicate that temperatures high enough to cause decrepitation will be reached in the vicinity of the waste canister. The effect would be superficial if ventilation is maintained but could extend several feet from the canister if ventilation is not maintained. Zones of decrepitated salt of this size would not materially affect the structural stability of a waste repository, but could adversely influence retrieval operations if these ever proved necessary.

The repository design and performance modeling processes should account for the thermal behavior of bedded salt in the following ways:

- If canister retrievability is required, the design must prevent temperatures in canister wells from rising high enough to result in decrepitation or include liners strong enough to prevent well failure. Data presented to date indicates that the risk of decrepitation can be minimized if repository temperatures are held below 200C. Powers and others (1978) indicate that polyhalite, present as an accessory mineral in salt, begins to break down at 170C. In minor amounts such breakdown is not likely to seriously affect salt in situ. However, thermal testing should be required to establish acceptable amounts of polyhalite in salt beds if near-canister temperatures are found to approach 170C.

- The repository thermal load must be low enough to prevent unacceptable closure or structural failure prior to decommissioning or creation of stress concentrations that could lead to long-term failure and loss of waste isolation capability. Repository design must be based on a coupled thermal/mechanical analysis.

- Borehole and shaft seals must accommodate thermal expansion and not deteriorate as a result of heating.

6.5 Radiolytic Effects

Limited data exist on the influence of radiation on the strength characteristics of salt and associated strata. Some measurements of compressive strength, yield strength, apparent elastic limit, modulus of elasticity, and creep of irradiated and non-irradiated bedded salt have been made at 20C and 200C (Gunter and Parker, 1961). These measurements 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. Agullo-Lopez and Levy (1964) exposed single salt crystals to gamma radiation and found that the irradiated samples had higher yield points and extended plastic regions.

No information is reported to exist concerning changes in thermal properties of salt as a result of irradiation (GAI, 1979a).

GAI (1979a) expressed the opinions that radiolytic effects would be limited to less than 0.5 m radius from the canister surface and would therefore be of little consequence in the structural performance of a nuclear waste repository in bedded salt. Tests should be conducted to determine whether radiolytically affected salt could be sufficiently weakened to affect retrievability.

6.6 Geotechnical Properties of Associated Strata

As discussed in the preceeding chapter, bedded salt deposits occur interbedded and interlensed with several other sedimentary rock types.

Principal among these are clay and shale beds, dolomite, limestone, anhydrite and occasionally potash salts. The presence of these rocks will influence shaft designs and may also have to be taken into account in service tunnels and haulageways depending upon details of repository design.

Most of these rock types will exhibit elastic mechanical behavior except for potash deposits which can be expected to deform similarly to bedded salt. Water-saturated clay beds may be expected to deform plastically under anticipated repository stress states and shale may also deform plastically under these conditions.

Site specific mechanical properties of other sedimentary rocks associated with bedded salt would have to be determined during geotechnical investigations conducted as part of the design process. For purposes of generic assessments, baseline mechanical properties of sedimentary rocks associated with bedded salt are listed in Table 7. It should be noted that most sedimentary rocks associated with bedded salt will show anisotropic properties; that is, their mechanical properties parallel to bedding planes will differ from those normal to bedding.

Thermal properties of sandstone, shale, carbonate rocks, anhydrite and gypsum have recently been compiled by Robertson (1979). Thermal curves are shown in Figures 27 through 34 inclusive. Data for the potash minerals sylvite and polyhalite have been compiled by Clark (1966) and Brokaw and others (1972).

TABLE 7

Listing of elastic constants for rock types associated with bedded salt

Rock Type	Young's Modulus (GPa)	Poisson's Ratio	Reference
Limestone		0.16 - 0.23	2, pp 65
	1.27 - 2.06		3, pp 134
	1.86 - 3.13		3, pp 134
	29.0 - 82.7		4, pp 280
	5.0 - 8.0	0.20 - 0.10	5, pp 77
	26.9	0.27	3, pp 373
	111	0.29	3, pp 373
	41.0		3, pp 374
	77.4	0.26	3, pp 374
	65.7	0.17	3, pp 375
Dolomites	2.0 - 3.0	0.20 - 0.08	5, pp 77
	71.0		3, pp 342
	78.5	0.30	3, pp 342
	63.1	0.16	3, pp 342
	71.7	0.17	3, pp 342
	45.8	0.46	3, pp 342
Anhydrite	72.0 - 74.0	0.30	3, pp 320
	75.0		3, pp 320
	75.8	0.27	3, pp 320
Salt	28.5	0.22	3, pp 411
	28.5	0.31	3, pp 411
	42.9 - 46.4	.21 - .30	3, pp 137

TABLE 7

Listing of elastic constants for rock types associated with bedded salt
(Continued)

Rock Type	Young's Modulus (GPa)	Poisson's Ratio	Reference
Sandstone	15.8	0.17 - 0.23	2 pp 61
	12.4 - 18.6	0.14 - 0.25	3, pp
	9.6 - 50.0		4, pp 280
	9.7		1, pp 146
	1.5 - 1.8	0.13 - 0.07	5, pp 77
	10.5		3, pp 412
	22.0	0.17	3, pp 412
	21.4	0.22	3, pp 412
Siltstone	32.6	0.23	3, pp 442
	13.1	0.12	3, pp 442
	0.72	0.27	3, pp 442
	30.6	0.13	3, pp 443
	31.0	0.42	3, pp 443
Shales and		0.19	3, pp 118
Mudstones		0.10	3, pp 118
	10.3 - 17.2		4, pp 280
	11.7 - 52.4		4, pp 280
	67.6	0.23	1, pp 146
	13.0	0.12	3, pp 436
	5.5	0.25	3, pp 437
	9.8	0.29	3, pp 439

TABLE 7: Listing of Elastic Constants for Rock Types Associated with Bedded Salt (continued)

References Cited:

(1) Jaeger, J. C., and N. G. W. Cook, Fundamentals of Rock Mechanics, Chapman and Hall, 1976.

(2) Krynine, D. P., and W. R. Judd, Principles of Engineering Geology and Geotechnics, McGraw Hill Book Company, 1957.

(3) Lama, R. D., and V. S. Vutukuri, Mechanical Properties of Rocks, Volume II, Series on Soil and Rock Mechanics Vol. 3, No. 1; Trans. Tech. Publications, 1978.

(4) Obert, L., and W. I. Duvall, Rock Mechanics and the Design of Structures in Rock, John Wiley and Sons, Inc., 1967.

(5) Szechy, K., The Art of Tunneling, Akademiai Kiado Budapest, 1966.

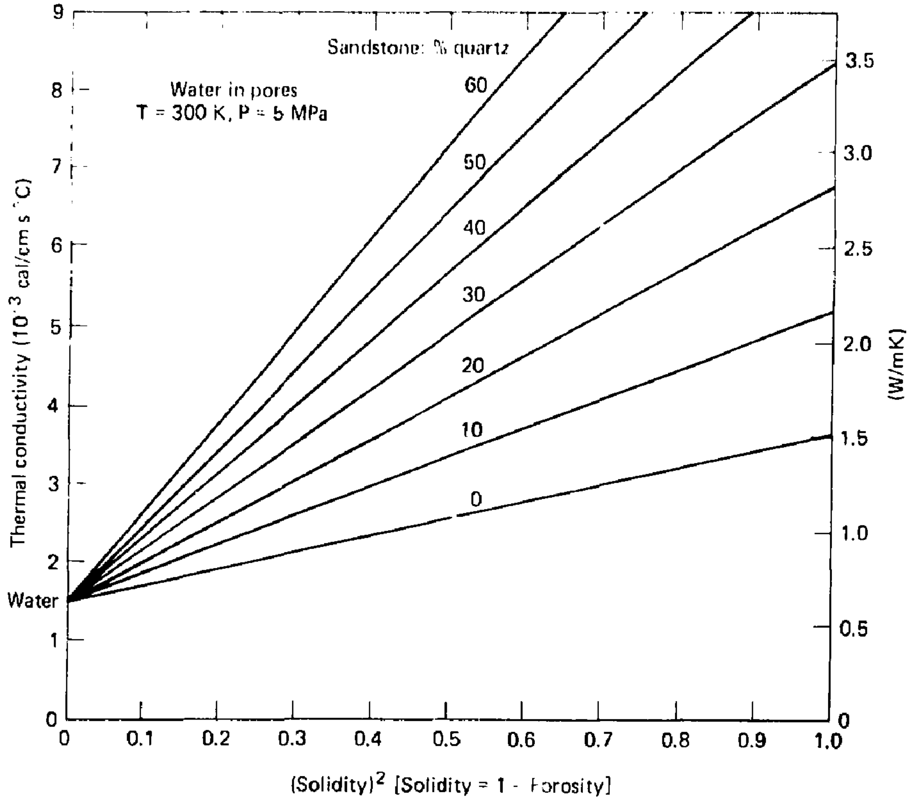


Figure 27 Thermal conductivity of sandstones and shales with respect to temperature (after Robertson, 1979).

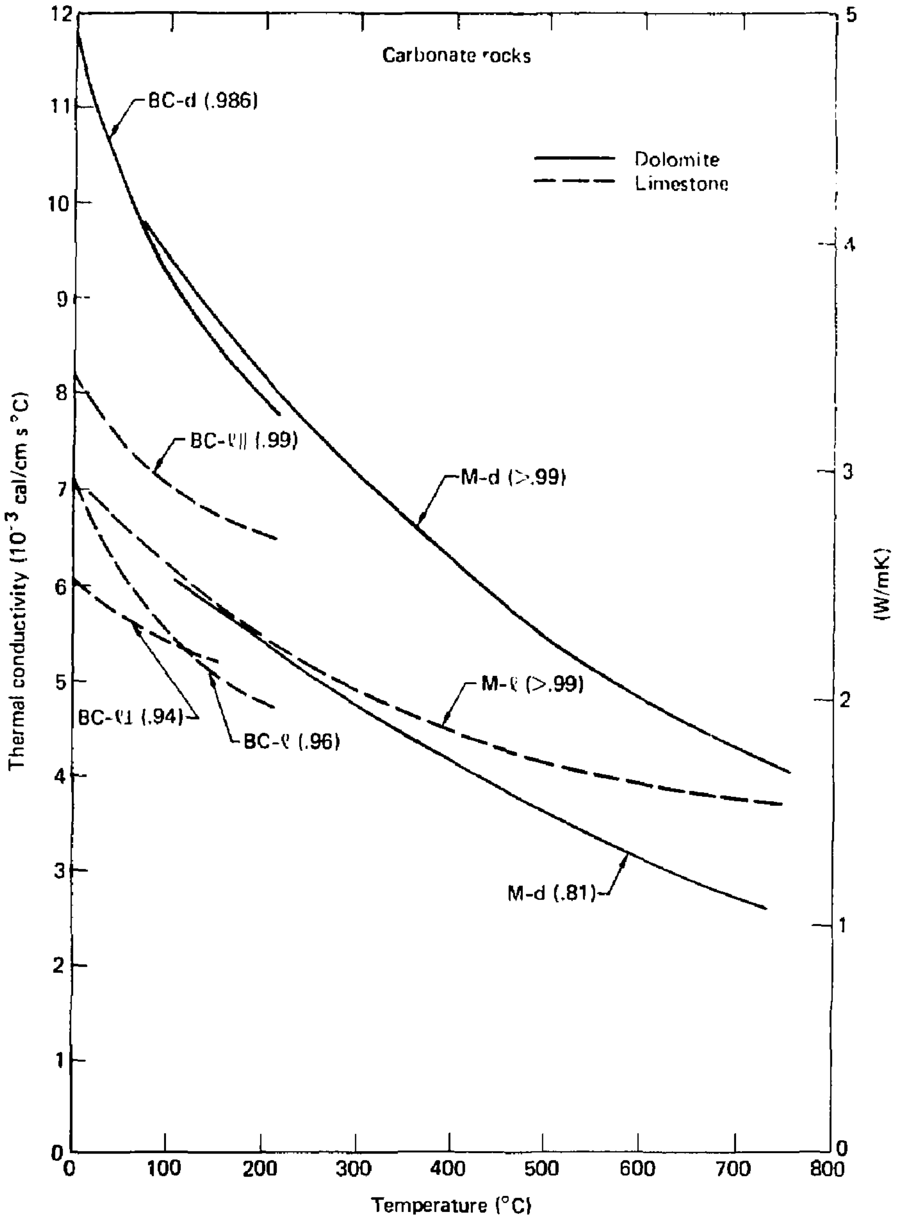


Figure 28 Thermal conductivities of carbonate rocks with respect to temperature (after Robertson, 1979).

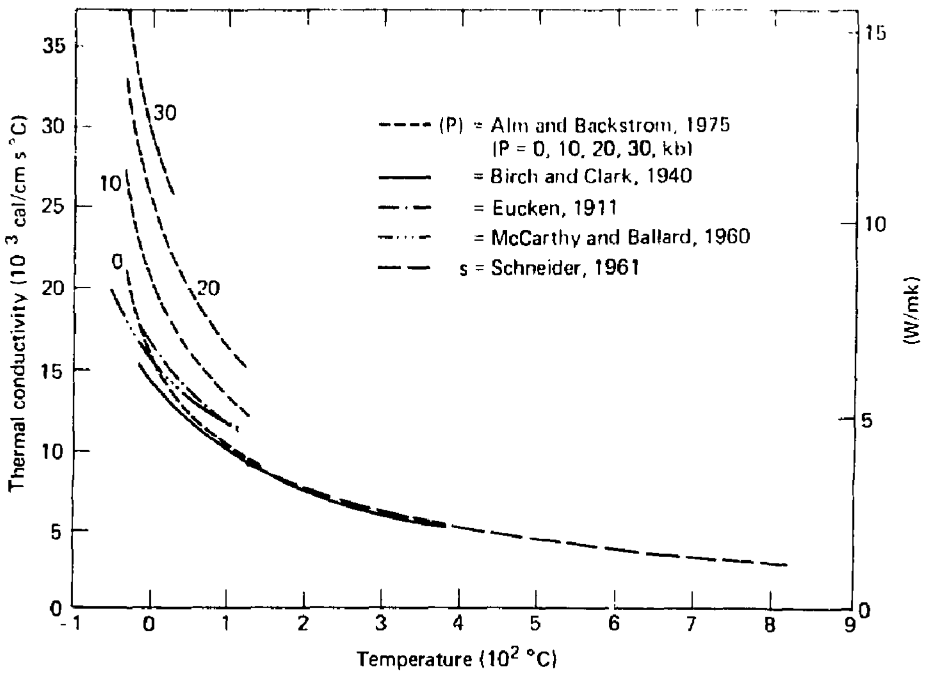


Figure 29 Thermal conductivity of single crystal salt showing temperature and pressure effects (after Robertson, 1979).

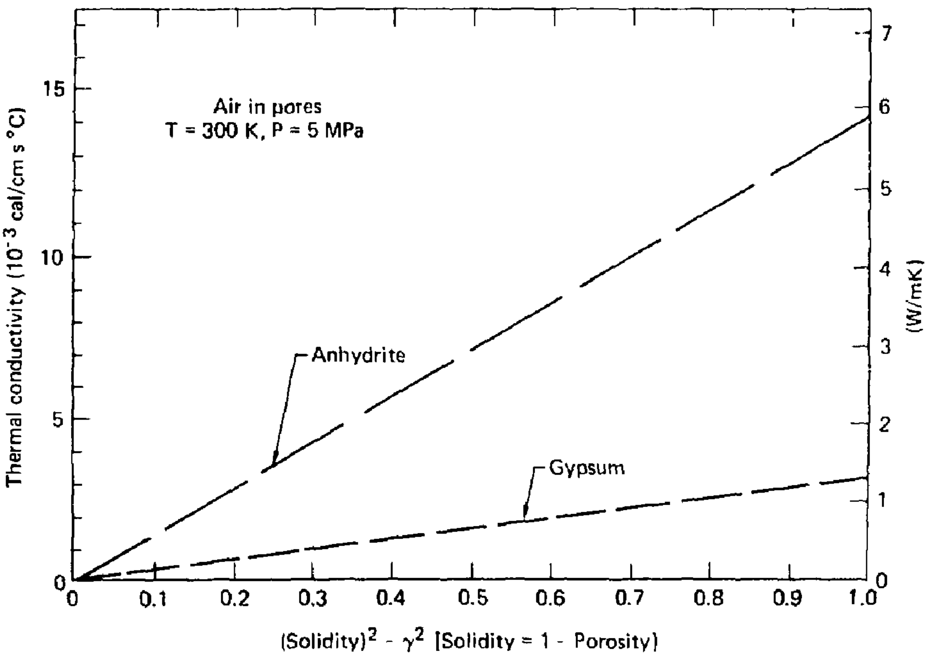


Figure 30 Thermal conductivity of anhydrite and gypsum vs. solidity (after Robertson, 1979).

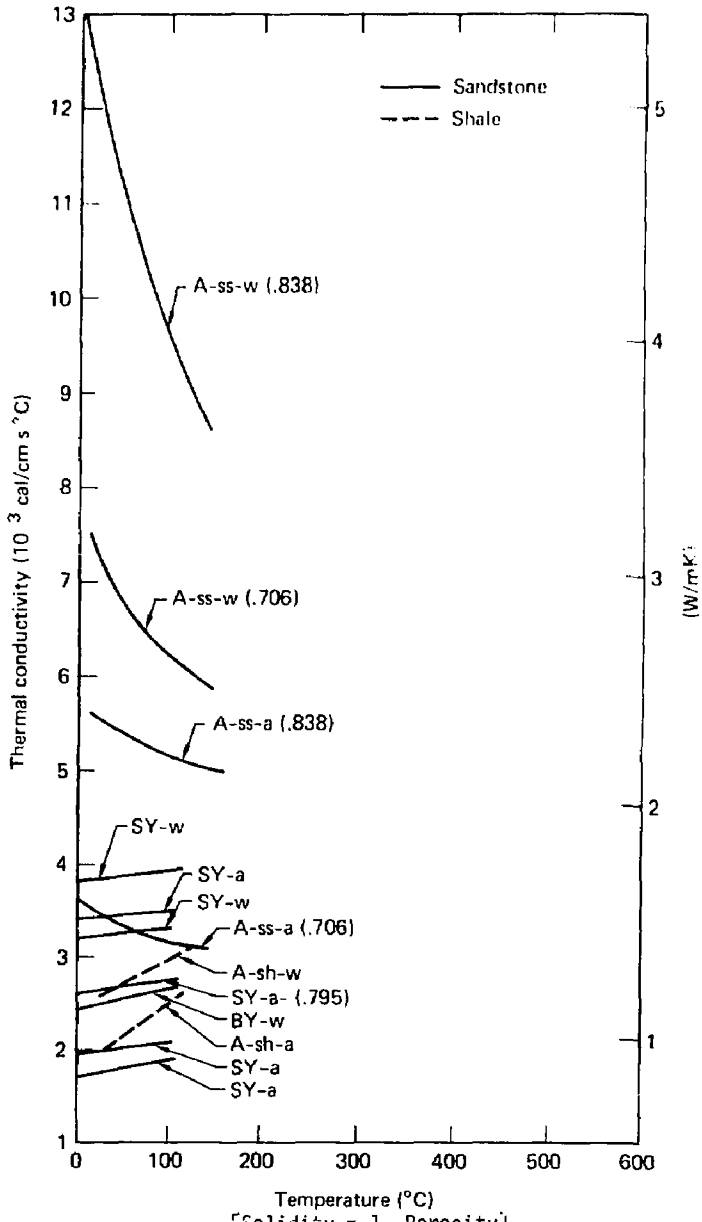


Figure 31 Thermal conductivity of shale and the effects of quartz and clay content (after Robertson, 1979; see pp. 14-15 of Robertson (1979) for the correction factor needed to use this table).

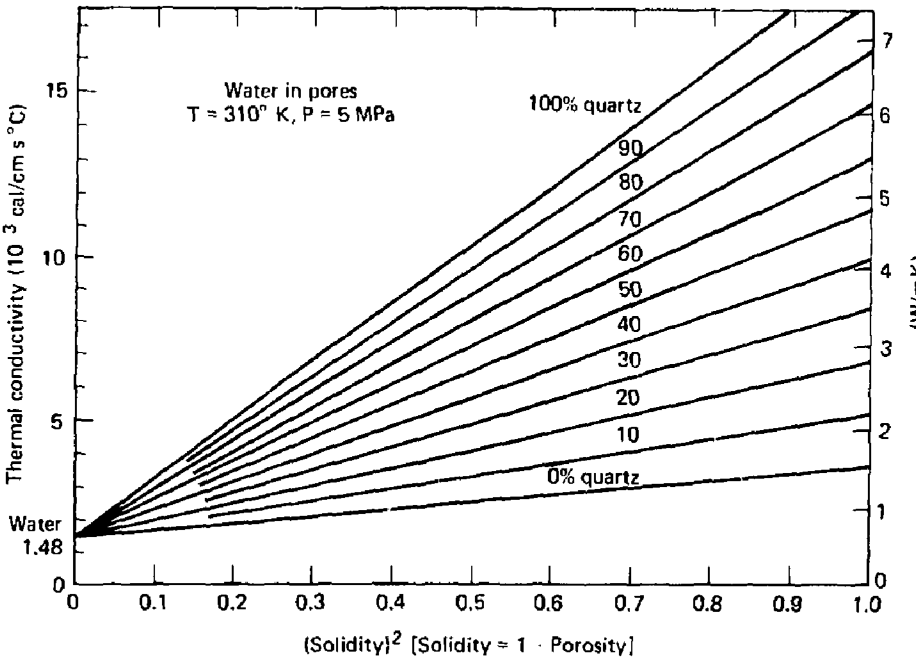


Figure 32 Thermal conductivity of sandstone with water in the pores showing effects of porosity and quartz content (after Robertson, 1979).

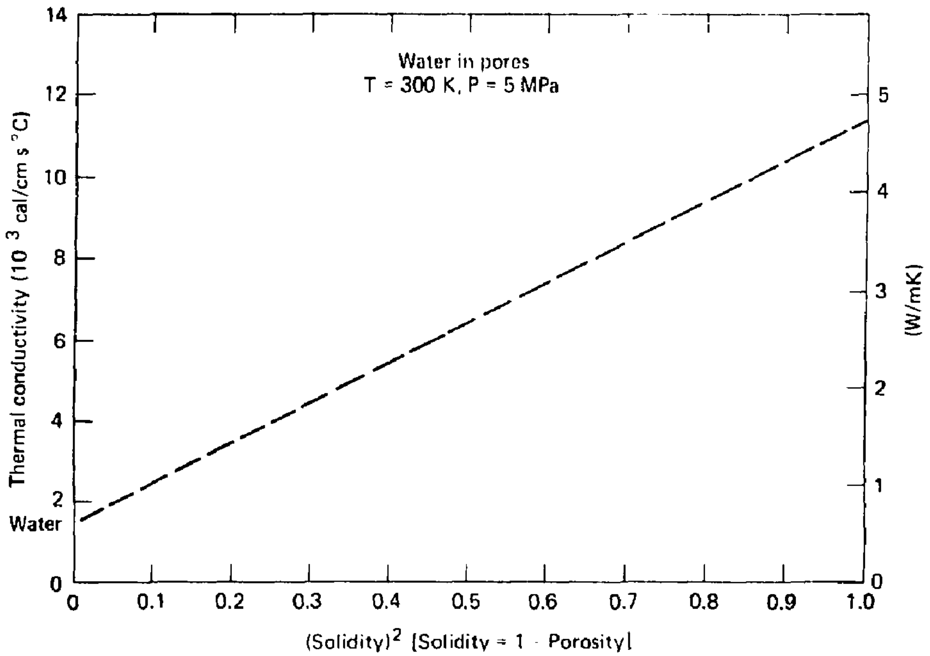


Figure 33 Thermal conductivity of dolomite vs. solidity (after Robertson, 1979).

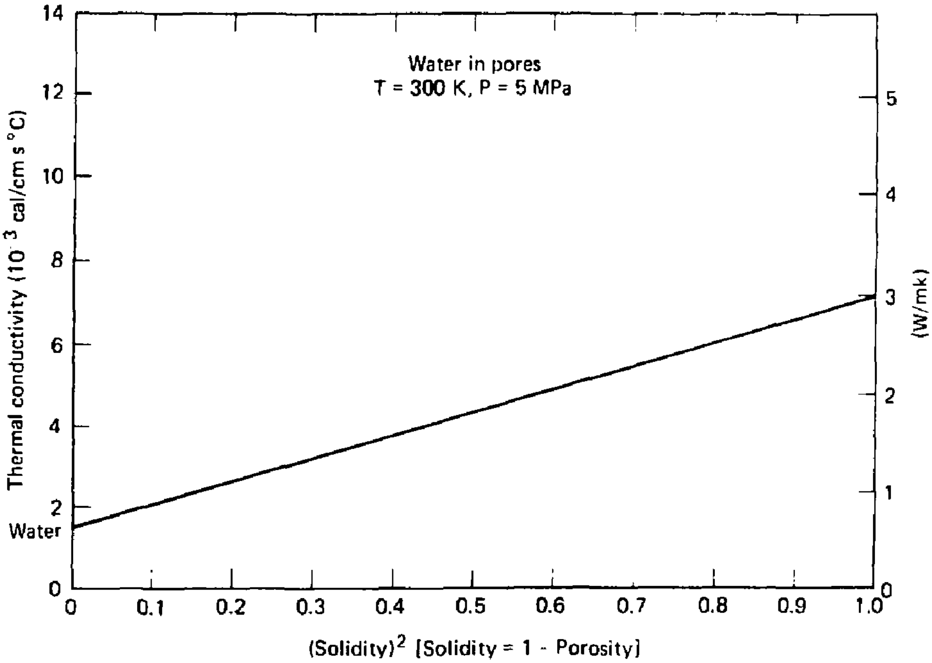


Figure 34 Thermal conductivity of limestone vs. solidity (after Robertson, 1979).

The thermal conductivity and coefficient of linear expansion of salt are approximately five times greater than those of shale and, therefore, the potential exists for uneven temperature distributions and thermally induced stresses along salt-shale contacts within the repository. These conditions could contribute significantly to room and pillar instability as a result of shearing along the bedding contacts or fracturing in the shale interbeds. Mechanical and thermal properties of other rock types within the zone of influence of the repository would have to be measured during geotechnical investigations of the repository site. In situ heater tests should include some testing of composite rock masses appropriately instrumented to measure movements along bedding planes or other discontinuities as a result of rising temperatures. These should be extended by laboratory testing of undisturbed rock cores containing planar features. The tests should be performed under confining pressures anticipated to prevail in situ after repository excavation. Since heat buildups outside of the near proximity to canisters will be slow, some long-term temperature rise tests should be performed as well as short-term tests in which upper bounds are obtained by allowing temperatures to rise rapidly. This data would then have to be used during the detailed thermal/mechanical analysis required as an element in the repository design process.

7.0 GEOCHEMICAL FACTORS

7.1 Introduction

Geochemical factors that must be considered during the design of a nuclear waste repository in bedded salt include those chemical reactions which may alter the physical characteristics of the rock mass enclosing the repository resulting in detrimental structural effects and those reactions which affect nuclide migration following canister failure. These latter reactions are largely relevant to the isolation phase following repository decommissioning but are briefly summarized in this report since some measures may be undertaken during repository design to improve subsequent nuclide retention.

7.2 Geochemical Reactions Affecting Rock Mass Properties

Certain geochemical reactions may exert significant influences on the behavior of underground facilities particularly on openings and shafts that will be in use for extended periods. Examples are described below.

Oxidation and Hydration Reactions Slaking (progressive breakdown of rock structure) and heaving of shales as a result of oxidation of sulfides to sulfates and conversion of anhydrite to gypsum with a 30-50% volume increase have been documented (Dougherty and Barsotti, 1972; Brune, 1965). Heaving of shale floors caused by sulfide oxidation and of hundreds of feet of overlying strata as a result of the anhydrite-gypsum conversion have been described (Coveney and Parizek, 1977; Brune, 1965). These reactions occur as a result of introduction of moisture into previously "dry" rock masses. Such introduction would occur through a mine ventilating system or by leakage down shafts from overlying aquifers. Delayed reactions are possible, e.g., anhydrite does not alter to gypsum above 42°C and the reaction would be inhibited near waste canisters until many years after decommissioning, although it could occur in portions of the repository remote from emplacement activities at any time. Shaft sections penetrating anhydrite strata would be particularly vulnerable with total failures of linings and shaft equipment attachments distinct possibilities.

General effects which may be experienced as a result of these reactions include reduction in rock strength, partial closure and deformation of openings, rockbursts, imposition of stresses on adjacent rock masses resulting in changes in hydrologic conditions. Either increased or decreased permeability could result.

The swelling and shrinking of certain clays and shales as a result of moisture changes have been previously described. The chemical reaction involved is simple hydration and is readily reversible. As noted previously, the compressive and tensile forces resulting from swelling and shrinking lead to physical breakdown of claystone and shale beds.

Oxidation and hydration reactions could have impacts on the operational performance of a nuclear waste repository in bedded salt. In addition to potential problems caused by failures of shaft linings or equipment attachments as noted above, progressive deterioration of pillars or unlined tunnels could result from these reactions and lead to structural nstability. Performance models could take into account the effects of hese processes by assessing the resul*s of sudden collapse events, as the failure of a shaft lining segment, or by considering the results of a slow rogressive failure such as accelerated tunnel closure. The extent to which ny particular process would pose a hazard would depend upon the site pecific presence of susceptible strata at critical locations with respect the repository.

The design process must include an assessment of probable chemical behavior of interbeds in the repository environment. Thorough sealing behind shaft linings to prevent water seepage and location of rooms and tunnels in horizons free of readily reactive shale beds represent the best means of minimizing the risk of structural deterioration as a result of chemical reactions. Asphalt and other coatings have been used to retard such deterioration.

Reactions Resulting from Presence of Radwaste Partial metamorphism of basalt by simulated radwaste has been documented (Scheetz and McCarthy, 1978) and metamorphic reactions may be found to occur in other rock types as well. Metamictization (breakdown of crystal structures by radiation) is a natural process in uranium ore bodies and probably will occur near waste canisters. Neutron activation of Na in salt is likely to occur near waste canisters. These processes may cause deterioration of rocks in the vicinity of high level wastes and influence retrievability; the degree of hazard posed by these problems is presently unknown since little is known about the extent and the rates of these reactions or their physical effects on salt masses.

7.3 Geochemical Reactions Affecting Waste Migration*

The primary geochemical control on radionuclide migration from a high-level waste repository is thought to be ion exchange. Other controls constituting the geochemical barrier are ion filtration and solubility. Retention of radionuclides by these processes may be represented in a mass transport model as a retardation factor, K_f, a measure of the relative velocity of the groundwater to the velocity expected for the radionuclides.

Although the retardation factor is primarily defined as a function of the ion exchange distribution coefficient, retardation factors used in transport models represent the combined effects of ion exchange and both reversible and irreversible absorption of charged colloidal species on surfaces. Other processes that affect radionuclide concentrations (e.g., precipitation of low solubility compounds) are not accounted for in the retardation factor.

The ion-exchange capacity of a rock is generally attributed to the clay mineral content. However, most common silicate minerals have at least some sorption capacity. As the dissolved waste moves slowly through the rock barrier, sorption will occur, but because the strength of the force holding the sorbed ions is a function of the ion's charge density, each ion will sorb to a different degree.

*The material appearing in this subsection has largely been summarized from the Geoscience Data Base Handbook for Modeling a Nuclear Waste Repository (Isherwood, 1980). It is repeated here so that this report will have continuity of thought without requiring inconvenient referral to other documents.

The extent to which sorption takes place for a particular ion is measured by the ion-exchange distribution coefficient, K_d. This assumes that the ion-exchange reaction is reversible and that equilibrium conditions exist. The distribution coefficient is defined as:

$$K_d = \frac{\dfrac{\text{mass of nuclide in solid phase}}{\text{weight of solid}}}{\dfrac{\text{Mass of nuclide in liquid phase}}{\text{volume of liquid}}} = \text{ml/g}$$

Of the many physical and chemical factors that affect the distribution coefficient, groundwater composition is probably the most important. Ions already present in the groundwater will compete with radionuclides for exchange sites, thus reducing the amount of waste that can be sorbed by the rock, especially in highly saline waters. Also, the composition of intruding groundwater will in part determine the rate of dissolution, how much is dissolved, and the extent of reprecipitation of dissolved nuclides in secondary solid phases.

Natural waters are chemically complex and variable, resulting in a correspondingly large variability in chemical parameters. Eh, pH, and concentrations of complexing ligands are very important. Ligands present in groundwater are of prime importance in determining saturation levels of nuclides in aqueous solution (e.g., the strong attraction of CO_3^{2-} for UO_2++). Equally important may be the redox capacity as defined by the concentrations of dissolved redox species, such as $O^-_{2(aq)}$, the solution pH, and the activity of the solvent (H_2O) (Isherwood, 1980).

Isherwood (1980) has noted that each unit change in pH can result in one to three orders-of-magnitude change in solubility of UO_2. A 100-mV change in Eh may leave the solubility unchanged or increase the solubility by a factor of 1,000 depending on the environment. The effects become much more pronounced at the higher oxidation states, which is why care should be taken to seal off deposited waste from atmospheric air. Water in recent contact with air would be relatively oxidizing, and therefore more corrosive toward UO_2. UO_2 is highly insoluble in nonoxidizing aqueous environments, and groundwater in a repository should contain very little dissolved oxygen at time of entry. However, it would immediately resaturate upon contact with the repository workings during the operational phase and should be expected to obtain oxygen for a period following decommissioning until the repository is resaturated.

The physical and chemical characteristics of the rock also affect the distribution coefficients. Grain size will determine the area available for surface sorption reactions. The mineral composition of the rock will determine the exchange capacity. Mineral alteration, especially the formation of clays, will change the exchange capacity. Local variations in grain size, mineral composition, or changes in the extent of mineral alteration will produce local variations in the sorption characteristics of the rock.

The retardation factor (K_f) as related to the distribution coefficient (K_d) as follows:

$$K_f = 1 + \frac{p}{\emptyset} Kd \qquad (1)$$

where p is the bulk density and $\emptyset$ is the porosity.

When there is no sorption, K_d equals 0 and the minimum value for the retardation factor is 1 (Isherwood, 1980).

Only two fission products have no sorption properties: iodine and technetium. Both exist in natural waters as negative ions, I^- and TcO_4^-. Since soils and rocks generally exhibit no anion exchange capacity (except for that sometimes shown by soil organic matter), sorption should be zero. (Natural anion exchange materials include kaolinite, apatite, and hydrous aluminum oxide. All have low anion exchange capacities and have limited distribution in rocks and soils.)

Soil experiments at Battelle Pacific Northwest Laboratories (1974) found the range of K_d's for I^- to be 0.08 to 52.6. The highest value was attributed to iron and aluminum oxide coatings on the soil particles; otherwise, I^- showed no sorption. Based on similar studies at the University of Michigan, Gast et al. (1977) reported similar K_d values for TcO_4^-. Recent experimental evidence (Barney, 1978) showed no measurable sorption of technetium on sediment samples taken at Hanford, Washington; furthermore, an earlier study of radionuclide migration at Hanford (Brown, 1967) showed that technetium migrates at about the same rate as groundwater (i.e., $K_f = 1$). Technetium K_d values were also zero over a wide range of $NaHCO_3$ concentrations in South Carolina topsoil (Routson et al., 1975).

It is evident that technetium (as TcO_4^-) has a high migration potential. However, recent work by Bondietti and Francis (1979) suggests that reducing conditions likely to exist in deep groundwaters will reduce the Tc(VII) in TcO_4^- to Tc(IV), which then precipitates as TcO_2, a very insoluble oxide. Under reducing conditions, stable concentrations of TcO_4^- will be below 2 x 10^{-7}M, the maximum concentration of ^{99}Tc permissible in drinking water, according to the International Commission on Radiological Protection.

Precipitation of TcO_2 may explain the measurable, but small, apparent K_d measured by Dosch and Lynch (1978). Using a relatively concentrated (10^{-4}M) ^{99}Tc solution, they reported a value below 5 for a clay taken from a bedded salt material encountered in a borehole near the WIPP site.

Powers and others (1978) have summarized the results of studies made to determine distribution coefficients for Tc and I using waters and rock samples judged to be representative of WIPP conditions. The results of these studies are summarized in Table 8.

The fission products with sorption characteristics that are present in high level waste are ^{90}Sr, ^{90}Y, ^{93}Zr, ^{93m}Nb, ^{126}Sn, ^{134}Cs, and ^{137}Cs. Of these, only strontium and cesium are major contributors to the waste inventory. Yttrium-90, which is in secular equilibrium with ^{90}Sr, has a half-life of only 64 hours. In 10-year-old waste, the inventory of the ^{93}Zr ^{93m}Nb pair is 2 x 10^{-5} that of the combined inventory of ^{90}Sr plus ^{137}Cs; the ^{126}Sn inventory is even less.

Table 8 Distribution Coefficients for Tc and I in WIPP Materials (from Powers and others, 1978)

Fluid	Magenta Dolomite	Culebra Dolomite	Clay(4)	Polyhalite(5)	Clay(6)	Bell Canyon Fm.
Brine A(1)	I 0-1.5 Tc do (ph range 6.5-6.9)	I < 1 Tc do (pH range 6.5-6.9)	I < 2 Tc do (ph range 6.5-7.0)	I NR(7) Tc < 1 (pH range 6.5-7.0)	I 0-3.5 Tc 3.5-4.5 (pH range 6.6-7.0)	I NR Tc NR
Brine B(2)	I < 1 Tc < 1 (ph range 6.5-7.5)	I < 1 Tc do (pH range 6.5-7.6)	I < 1 Tc do (pH range 6.5-7.7)	I NR Tc < 1 (pH range 6.5-7.2)	I NR Tc < 1 (pH range 6.7-7.4)	I NR Tc < 1 (pH range 6.5-7.4)
Soln. C(3)	I 0-1.5 Tc do (pH range 7.5-8.2)	I < 1 Tc do (pH range 7.5-8.2)	I < 1 Tc do (pH range 7.5-7.8)	I NR Tc < 1 (pH range 7.5-7.6)	I 0.5-4 Tc 0.7-1.5 (pH range 7.5-8.0)	I NR Tc < 1 (pH range 7.5-7.9)

1) Brine A: Anticipated composition of an aqueous solution in contact with potash desposit found in the vicinity of the WIPP site.
2) Brine B: Composition typical of water in contact with halite deposits in the repository horizons.
3) Solution C: "Average" composition of shallow groundwaters from the WIPP site area.
4) Clay sample from 2186.6' horizon in borehole AEC-8.
5) Polyhalite sample from 2304' horizon in borehole ERDA-9.
6) Clay sample from 2725' horizon in borehole AEC-8.
7) Not reported.

TABLE 8a

REPRESENTATIVE BRINES/SOLUTIONS FOR WIPP EXPERIMENTATION

Ion	Brine "A"[1] (mg/liter) (± 3%)	Brine "B"[2] (mg/liter) (± 3%)	Solution "C"[3] (mg/liter) (± 3%)
Na^+	42,000	115,000	100
K^+	30,000	15	5
Mg^{++}	35,000	10	200
Ca^{++}	600	900	600
Fe^{+++}	2	2	1
Sr^{++}	5	15	15
Li^+	20	-	-
Rb^+	20	1	1
Cs^+	1	1	1
Cl^-	190,000	175,000	200
SO_4^{--}	3,500	3,500	1,750
B (BO_3^{---})	1,200	10	-
HCO_3^-	700	10	100
NO_3^-	-	-	20
Br^-	400	400	-
I^-	10	10	-
pH (adjusted)	6.5	6.5	7.5
specific gravity	1.2	1.2	1.0

1) Brine A: Anticipated composition of a aqueous solution in contact with potash found in the vicinity.

2) Brine B: Composition typical of ground water in contact with halite deposits in the repository horizons.

3) Brine C: "Average" composition of shallow ground waters from the Los Mendanos area (Powers, et. al. 1978).

A representative listing of published kd values for Sr and Cs in rocks likely to be associated with a nuclear waste repository in bedded salt is given in Table 9. Additional data from the WIPP site are given in Table 10.

Based on the values shown in Tables 9 and 10, a conservative estimate for an average strontium distribution coefficient in relatively dilute groundwater is approximately 10 and the distribution coefficient for cesium is roughly an order of magnitude higher although there are considerable variations in the data. Distribution coefficients and resulting retardation factors for both strontium and cesium in simulated brines used in the WIPP experiments are substantially smaller.

The biologicaly important actinides are the products of four interrelated decay chains:

$$^{244}Cm \rightarrow {}^{240}Pu$$
$$^{243}Am \rightarrow {}^{239}Pu \rightarrow {}^{231}Pa$$
$$^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np \rightarrow {}^{233}U \rightarrow {}^{229}Th$$
$$^{242}Cm \rightarrow {}^{238}Pu \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{210}Po \rightarrow {}^{210}Pb$$

A number of actinides present in radioactive waste have similar chemical properties. Therefore, in modeling a nuclear waste repository, it is reasonable to treat the actinides as a group with a single retardation factor. The difference in retardation between different actinides is probably less than the uncertainty in the estimated average for any single actinide. As more experimental data become available, individual retardation

Table 9 Distribution coefficients for Sr and Cs (Summarized from Isherwood, 1980)

Reference	Kd ml/g Sr	Kd ml/g Cs	Conditions
Dosch and Lynch, 1978	1	1-15	Dolomite, 200 mesh, brine, pH 6.7
	3-5	7-125	Dolomite, 200 mesh, sim. groundwater, pH 7.9
	<1	<1-9	Clay, 20-45 mesh, brine, pH 6.8
	3-45	30-120	Clay, 20-45 mesh, sim. groundwater, pH 7.7
	5-22	<1	Polyhalite, 200 mesh, brine, pH 6.8
	<1	14-16	Sandstone, 200 mesh, brine, pH 7.0
	1-5	130-140	Sandstone, 200 mesh, sim. groundwater, pH 7.7
Nork and Fenske, 1970	9.19	13.5	Carbonate, >4 mm, prep. water
	8.32	309	Shaley siltstone, >4 mm, well water
	1.37	102	Sandstone, >4 mm, well water
	0.19	0.027	Salt, >4 mm, saturated salt water
Serne et al., 1977	5.6-12.4	110-2656	Dolomite, 100-325 mesh, dist. water, pH 8.3
	-0.8 to 1.0	-0.3 to 0.3	Dolomite, 100-325 mesh, brine, pH 6.5-6.9
	9.0-13.0	6540-7518	Limestone, 100-170 mesh, dist. water, pH 8.3
	-0.4 to 0.9	-0.8 to 0.2	Limestone, 100-170 mesh, brine, pH 6.5-6.9
	22-37.5	12,195-18,567	Sandstone, 100-170 mesh, dist. water, pH 8.3
	12.0-19.2	5248-6855	Sandstone, 100-325 mesh, dist. water, pH 8.3
	-0.3 to 1.1	-0.1 to 0.5	Sandstone, 100-170 mesh, brine, pH 6.5-6.9
	-0.5 to 0.7	-0.3 to 0.8	Sandstone, 100-325 mesh, brine, pH 6.5-6.9

Table 10 Distribution Coefficients for Sr and Cs in WIPP Materials (from Powers and others, 1978)

Fluid[1]	Magenta Dolomite	Culebra Dolomite	Clay[2]	Polyhalite[3]	Clay[4]	Bell Canyon Fm.
Brine A	Sr 1 Cs <1 (pH range 6.5-6.9)	Sr <1 Cs <1 (pH range 6.5-6.9)	Sr <1 Cs <1 (pH range 6.5-7.0)	Sr 5-10 Cs <1 (pH range 6.5-7.0)	Sr <1 Cs 4-9 (pH range 6.6-7.0)	Not Reported
Brine B	Sr 1 Cs <1 (pH range 6.5-7.5)	Sr 1-2 Cs 1-2 (pH range 6.5-7.6)	Sr <1 Cs 4-6 (pH range 6.5-7.7)	Sr 19-22 Cs <1 (pH range 6.5-7.2)	Sr <1 Cs 3-6 (pH range 6.7-7.4)	Sr <1 Cs 14-16 (pH range 6.5-7.4)
Sol'n C	Sr 5 Cs 4 (pH range 7.5-8.2)	Sr 4-5 Cs 7-10 (pH range 7.5-8.2)	Sr 3-6 Cs 80-120 (pH range 7.5-7.8)	Sr 35-40 Cs <1 (pH range 7.5-7.6)	Sr 30-45 Cs 34-40 (pH range 7.5-8.0)	Sr 1-5 Cs 130-140 (pH range 7.5-7.9)

1) Brine A: Anticipated composition of an aqueous solution in contact with potash deposit found in the vicinity of the WIPP site
Brine B: Composition typical of water in contact with habite deposits in the repository horizon.
Solution C: Average composition of shallow ground waters from WIPP site.
2) Clay sample from 2186.6' horizon in borehole AEC-8.
3) Polyhalite sample from 2304' horizon in borehole ERDA-9.
4) Clay sample from 2725' horizon in borehole AEC-8.

factors should be considered. The current literature suggests that the relative retardation factors for the actinides will be:

Th > Pu > Am > Np > Ra*

The actual difference between retardation factors will be a function of repository characteristics, such as rock type, flow rates, and groundwater composition.

A representative listing of published Kd values for actinides in rocks likely to be associated with a nuclear waste repository in bedded salt is given in Table 11. Additional data from the WIPP site is given in Table 12.

The K_d values given in Tables 11 and 12 vary greatly in the pH range of natural waters (5 to 8). For example, the values for americium range between 8 and 5×10^4 and for plutonium, between 20 and 3.8×10^5.

The primary reasons for this wide range of values are differences in experimental conditions and in the sorption characteristics of the rock samples. A good example of the effect of experimental conditions can be found in the work of Seitz et. al. (1978), where K_d's for americium varied between 10 (for a rock tablet) to 8.92×10^3 (for crushed rock).

*As the daughter of ^{230}Th, ^{226}Ra, an alkaline-earth element, is included with the actinides. There is evidence from deep sea cores that radium migrates faster than thorium by a factor of 10 to 100.

Table 11 Actinide distribution coefficients (summarized from Isherwood, 1980).

Reference	K_d, ml/g	
		Americium
Dosch and Lynch, 1978	290	Anhydrite, 200 mesh, brine, pH 6.5-7.9
	2200	Anhydrite, 200 mesh, sim. groundwater, pH 6.5-7.9
	310	Clay, 20-45 mesh, brine, pH 6.5-7.8
	2300	Clay, 20-45 mesh, sim. groundwater, pH 7.4-8.4
	2600	Dolomite, 200 mesh, brine, pH 6.5-7.8
	22,000	Dolomite, 200 mesh, sim. groundwater, pH 7.5-8.3
Fried, et al., 1977	($K_f = 10^4$)	Limestone, pH 6.7
Seitz, et al., 1978		Dolomite, preequilibrated water, pH 8.5, Eh = 274 mV:
	3470-8920	60-100 mesh
	653	100-325 mesh
	10-150	Rock tablet
		Limestone; preequilibrated water, pH 7.6, Eh = 277 mV:
	2230	60-100 mesh
	135-280	Rock tablet
	8-11	Sandstone, rock tablet, preequilibrated water, pH 6.8

Table 11 (continued)

Reference	K_d, ml/g	
	Neptunium	
Seitz, et al., 1978	395	Dolomite, 60-100 mesh, preequilibrated water
	27	Argillite, 60-100 mesh, preequilibrated water, Eh = 256 mV
	7540	Limestone, 60-100 mesh, preequilibrated water, pH 7.6, Eh = 277 mV
Serne, et al., 1977	22	Dolomite, 100-325 mesh, brine, pH 7.0
	27	Limestone, 100-170 mesh, brine, pH 6.9
	Plutonium	
Dosch and Lynch, 1978	6700-7700	Anhydrite, 200 mesh, brine, pH 7.9
	40,000-72,000	Clay, 20-45 mesh, brine, pH 6.8-7.9
	180,000	Clay, 20-45 mesh, sim. groundwater, pH 8.0
	2400-7300	Dolomite, 200 mesh, sim. groundwater, pH 7.9
	2100-5400	Dolomite, 200 mesh, brine, pH 7.2
Fried, et al., 1977	(K_f =3x10^4)	Limestone, Pu(IV), pH 6.7
Seitz, et al., 1978		Anhydrite, preequilibrated water, pH 7.6, Eh 275 mV:
	678-819	16-20 mesh
	946-1040	30-40 mesh
	1550-2840	50-70 mesh

Table 11 (continued)

Reference	K_d, ml/g	
		Plutonium (continued)
	13-34	Dolomite, rock tablet, preequilibrated water, pH 8.5, Eh = 273 mV
		Limestone, preequilibrated water, pH 7.6, Eh = 277 mV:
	293	60-100 mesh
	16-710	Rock tablet
	20-64	Sandstone, rock tablet, preequilibrated water, pH 6.8
		Thorium
No data for rocks presented in Isherwood, 1980. See Table 6.6 for soil and mineral data.		
		Uranium
Serne, et al., 1977	4.5	Dolomite, 100-325 mesh, brine, pH 6.9
	2.9	Limestone, 100-170 mesh, brine, pH 6.9

Table 12 Distribution Coefficients for Actinides in WIPP Materials (from Powers and others, 1978).

Fluid[1]	Magenta Dolomite	Culebra Dolomite	Clay[2]	Cowden Anhydrite[3]	Clay[4]
Brine B	Pu 5.4 x 10^3	Pu 2.1 x 10^3	Pu 4 x 10^4	Pu 6.7 x 10^3	Pu 7.2 x 10^4
	Am 3.1 x 10^2	Am 2.6 x 10^3	Am 1.1 x 10^3	Am 2.9 x 10^2	Am 310
	Cm 1.3 x 10^3	Cm 1.2 x 10^4	Cm 1.9 x 10^4	Cm 4.2 x 10^3	Cm 2.7 x 10^3
	(pH range 6.5-7.8)	(pH range 6.5-7.8)	(pH range 6.5-8.0)	(pH range 6.5-7.9)	(pH range 6.5-7.8)
Soln C	Pu 2.4 x 10^3	Pu 7.3 x 10^3	Pu 1.8 x 10^5	Pu 7.7 x 10^4	Pu 4.0 x 10^4
	Am 2.4 x 10^3	Am 2.2 x 10^4	Am 3.5 x 10^3	Am 2.2 x 10^3	Am 2.3 x 10^3
	Cm 4.2 x 10^4	Cm 1.1 x 10^5	Cm 4.2 x 10^5	Cm 1.8 x 10^5	Cm 1.6 x 10^5
	(pH range 7.5-8.2)	(pH range 7.5-8.2)	(pH range 7.5-8.4)	(pH range 7.5-8.2)	(pH range 7.4-8.4)

(1) Brine B: Composition typical of water in contact with halite deposits in the repository horizons.
Brine C: "Average" composition of shallow groundwtaers from the WIPP site area.

(2) Clay sample from 2186.6' horizon in borehole AEC-8.

(3) Sample from 2562' horizon in borehole AEC-8.

(4) Clay sample from 2725' horizon in borehole AEC-8.

Based on this range of values, an average K_d for the actinides and their daughter products is conservatively estimated at 200 to 300, which yields a retardation factor of approximately 10^4. Minimum and maximum K_d values of 10 and 10^4 give k_f's of 10^2 and 10^5. These estimated retardation factors are presently useful only for modeling a generic repository although some of this data may be ultimately used in performance modeling of the WIPP site.

To develop a standard methodology, Battelle Pacific Northwest Laboratories designed an interlaboratory controlled-sample program. The objectives of this ongoing program are (Relyea and Serne, 1979):

- To ascertain whether nine different experimenters can obtain the same results for the adsorption of cesium, strontium, and plutonium, using common rocks, standard solutions, and a prescribed method.
- To compare the results obtained by individual laboratories using different experimental methodologies.
- To resolve any differences found or to determine what conversions can be made to compare results from one method with those of another.

Based on initial results, distribution coefficients measured at different laboratories for cesium and strontium in brine agreed for both limestone and basalt rock samples. Consistent results were also found for cesium and strontium in the basalt groundwater. However, in the limestone groundwater, results for cesium varied over three orders of magnitude, and those for strontium varied by one order of magnitude. Observed values for plutonium typically varied by two to three orders of magnitude in all systems studied.

It was thought that adsorption of plutonium by container walls and by collodial particles caused much of the variation in the K_d's for plutonium. However, direct measurement of the plutonium adsorbed by the rock (rather than measurement of the difference between influent and effluent activities) failed to reduce the variability.

These results, together with an analysis of the methods actually used in each laboratory, indicate that several uncontrolled factors may have affected the results. The uncontrolled factors were:

- Method of tracer addition to the solution.
- Solution-to-rock ratio.
- Initial tracer concentration in the influent solution.
- Particle size distribution.
- Solid-solution separation method.
- Sample containers.
- Temperature.

Experimental evidence shows that retardation factors are functions of rock type, pH, water composition, flow rates, etc.; however, the interrelationships between these parameters and the mechanism by which they quantitatively influence retardation are largely unknown. We can only estimate values for the relative velocities of the waste and groundwater, based on laboratory experiments. When we use these estimated values in a mass transport model, we must recognize that, until laboratory experiments are correlated with in situ conditions, the uncertainty in predictions will be high. Future data base improvements will require that the retardation behavior of individual radionuclides be understood under a wide range of environmental conditions.

Two other geochemical controls on radionuclide migration are ion filtration and low solubility. Their relative importance in protecting the biosphere from contamination will depend on the physical and chemical properties of the system (Isherwood, 1980).

Pure salt has virtually no exchange capacity. However, sorption may occur in salt beds containing detrital clays or altered silicate detritus. For example, sorption studies of samples taken from salt beds containing minor amounts of clay in the Salado Formation of the Permian Basin during studies of the WIPP site showed an exchange capacity for Sr, Am, Pu, and Cm, but not for Cs (Dosch and Lynch, 1978).

In rock units adjacent to the salt layer it is probable that the high NaCl content of the groundwater will saturate the exchange sites so that sorption will be limited. The extent to which saturation affects radionuclide sorption will depend on the affinity of the exchange site for the radionuclide species relative to the sodium ion.

Isherwood (1980) has provided discussions of the composition and dissolution of spent fuel by groundwater in a salt repository. These discussions are peripheral to the design of a nuclear waste repository in bedded salt and are therefore not repeated here.

However, it should be noted that the thermal environment in a nuclear waste repository is an important consideration since reaction mechanisms, rates and final equilibrium states are all functions of temperature. Isherwood (1980) has noted that data above 25C are scarce but that since techniques are available for the estimation of thermodynamic properties at elevated temperatures, the evaluation of temperature effects on the solubilities of the UO_2 fuel matrix and its contents of fission products and actinides appears feasible. It is known that uranium solubility would decrease with increase in temperature to at least 100°C, because the thermodynamic stability of uranyl carbonate complexes, which account nearly quantitatively for total dissolved uranium in most groundwaters, declines over this range. Isherwood (1980) stated that a more detailed evaluation of temperature effects should be made, and would add greatly to the scope and value of dissolution modeling.

The design process and performance modeling effort must consider probable chemical reactions between nuclear waste and the environment since these are fundamental to nuclear waste isolation. Specific items to be considered include the following:

- Repository excavation and operations should facilitate the ultimate use of excavated materials to create backfills designed to maximize retardation. As an example, the feasibility of a zoned backfill should be thoroughly evaluated. Such a backfill might consist of a blanket of bentonite or other highly sorptive material placed nearest the waste canisters, with a mixture of excavated shale and impure salt used to backfill the remaining room volumes. Relatively pure salt would be reserved for use as tunnel backfill or in other areas remote from waste. If such a backfill sequence was found to provide improved retardation, the repository design would have to permit segregation of materials during excavation and long-term storage of these materials in separate piles.

- The effects of various thermal loadings on waste-host rock reactions must be thoroughly evaluated and repository temperatures must not be permitted to rise high enough to greatly accelerate geochemical reactions.

- Borehole and shaft seals must be resistant to breakdown by waste products. Ideally, seal materials should have sorbtive properties.

- The geochemical environment at a particular repository site must be carefully characterized and values for distribution coefficients, retardation factors, and solubility of ionic species determined for the specific geochemical environment established. The performance model developed must closely simulate the physical environment of the site and evaluate the geochemistry in that framework.

Consideration is being given to the improvement of the nuclide isolation capabilities of waste repositories through use of sorptive materials in backfills and other engineered barriers. Some studies on soils, clays and other minerals that may simulate backfill materials have been made. Representative published Kd values for these materials are presented in Table 13. These data may be useful in generic modeling of the geochemical performance of certain types of engineered barriers.

Table 1[illegible]. Distribution coefficients for various sorptive elements in soils, clays and certain minerals

Reference	K_d ml/g	Conditions
	Cesium	
Baetsle and Djonghe, 1962	22-314	Quartz sand, pH 7.7
Brown, 1967	300	Hanford sediments
Godse, et al., 1967	617-1053	Soil, pH 6.8
Hajek and Knoll, 1966	189-420	Soils
Inoue, 1967	250-1000	Soils, Ca groundwater
Nork, et al., 1971	121-3,165	Alluvium, 0.5-4mm, groundwater
Parsons, 1962	100	Sands
Goldberg, et al., 1962	12,000-17,800	Tuff, 100-200 mesh, prep. groundwater
Dlouhy 1967	800-1000	Tuff
	Strontium	
Baetsle and Djonghe, 1962	1.7-3.8	Quartz sand, pH 7.7.
Brown, 1967	50	Hanford sediments
Godse, et al., 1967	143-282	Soil, pH 6.8
Hajek and Knoll, 1966	19-43	Soils
Inoue, 1967	9.4-71	Soils, Ca groundwater
Nork, et al., 1971	48-2454	Alluvium 0.5-4mm, groundwater

Table [illegible] (continued)

[illegible]	K_d, ml/g	Conditions
[illegible], 1962	[illegible]-43	Sands
[illegible], et al., 19[illegible]	[illegible]-3480	Tuff, 100-200 mesh, prep groundwater
[illegible], 1962	[illegible]-25	Tuff
	Americium	
[illegible] and [illegible], 1966	1	Sand, 5N NO_3^-, oil, org., pH 3
	280	Sand, 5N NO_3^-, oil, org., pH 7
	500	Sand, sludge, pH 7
Routson, et al., 1975	>1200	Desert sand, 0.001M Ca, pH 2.5-3.1
	>1200	Desert sand, 0.2M Ca, pH 2.5-3.1
	67	Sandy clay, 0.002M Ca, pH 2.5-3.1
	1	Sandy clay, 0.2M Ca, pH 2.5-3.1
	1.6	Sandy clay, 3M Na, pH 2.5-3.1
	280	Sandy clay, 0.015M Na, pH 2.5-3.1
Van Dalen, et al., 1975	50,000	Illite/kaolinite, 90% sat. NaCl, pH 7-8
	400	River sand, 90% sat. NaCl, pH 7-8
	Neptunium	
Dahlman, et al., 1976	320	Clay soil, 5mM $Ca(NO_3)_2$, pH 6.5
Routson, et al., 1975	2.37	Sand, 0.002M Ca, pH 2.5-3.1
	0.36	Sand, 0.2M Ca, pH 2.5-3.1

Table 13 (continued)

Reference	K_d ml/g	Conditions
	[illegible]	Sand, 0.[illegible]M [illegible], pH [illegible]-3.1
	3.[illegible]	Sand, 3.0M Na pH 2.5-3.1
	0.2[illegible]	Sandy clay, [illegible]M [illegible]a, pH [illegible]-3.1
	0.16	Sandy clay, [illegible]M [illegible]a, pH 2.5-3.1
	0.7	Sandy clay, 0.015M Na, pH 2.[illegible]-3.1
	0.4	Sandy clay, 3.0M Na, pH 2.5-3.1
Seitz, et al., 1978	1280	Apatite, 60-100 mesh, preequilibrated water
	8	Tuff, 60-100 mesh, preequilibrated water, pH 7.9, Eh - 282 mV
	Plutonium	
Dahlman, et a[illegible] [illegible]976	300,000	Clay soil, Pu(IV), 5mM Ca, pH 6.5
Dursuma and Pa[illegible], 1974	10,000-90,000	Mediterranean sediment
Fried and Friedman, 1976	(K_f = 10^4)	Tuff, Pu(IV), pH 6.7
	(K_f = 300)	Tuff, Pu(VI), pH 6.7
Gast, et al., 1977	100,000 to 170,000	Soil clays, Pu(IV), 5mM ca, pH 6.5
	75,000	Soil clays, Pu(VI), 5mM Ca, pH 6.5
	21,000	Montmorillonite, Pu(IV) 5mM Ca, pH 6.5
Glover, et al., 1976	35-14,000	17 soil samples, 10^{-6}, 10^{-7}, 10^{-8}M Pu
Hajek and Knoll, 1966	(K_f = 104)	Surface soil, groundwater
Hetherington, et al, 1975	20,00-48,000	5% clay, 50% silt, 45% sand

Table 13 (continued)

Reference	K_d ml/g	Conditions
Miner, et al., 1974	>430	Soils
Mo and Lowman, 19[illegible]	16,000-380,000	Calcareous sediment
Noshkin, et al., 1976	250,000	Av value for Enewetak groundwater particulates
Pillai and Mathew, 1976	90,000	Av value for suspended silt
	Thorium	
Bondietti, et al., 1976	160,000	Silt loam, Ca sat. clay, pH 6.5
	400,000	Montmorillontie, Ca sat. clay, pH 6.5
Dahlman, et al., 1976	160,000	Clay soil, 5m$\underline{M}$ $Ca(NO_3)_2$, pH 6.5
Nishiwaki, et al., 1972	40-130	Med. sand pH 8.15
	310-470	Very fine sand, pH 8.15
	2700-10,000	Silt/clay, pH 8.15
Rancon, 1973	8	Schist soil, 1 g/liter Th, pH 3.2
	60	Schist soil, 0.1 g/liter Th, pH 3.2
	120	Illite, 1 g/liter Th, pH 3.2
	1000	Illite, .1 g/liter Th, pH 3.2
	>100,000	Illite, 0.1 g/liter Th, pH >6
	Uranium	
Bondietti, et al., 1976	62,000	Silt loam, U(VI), Ca sat., pH 6.5
Dahlman, et al., 1976	4400	Clay soil, U(VI), 5m$\underline{M}$ $Ca(NO_3)_2$, pH 6.5

Table 33 (continued)

Reference	K_d, ml/g	Conditions
Rancon, 1973	300	clay soil, 1 ppm [illegible], pH 5.6
	2000	clay soil, 1 ppm [illegible], pH 10
	270	clay soil, 1 ppm UO^{2+}, pH 12

Uncertainties in the retardation factors result from both the uncertainties related to modeling a generic site when no direct measurements of the rock properties have been made and the experimental uncertainties in K_d measurements. In light of these uncertainties, we must ask whether K_d's determined in the laboratory actually represent the retardation factors in the field. The first uncertainty arises in part because there are no reliable in situ measurement techniques for adsorption. The second is complicated by the fact that even laboratory measurements (especially those from the 1960s) do not share a common methodology. For example, the K_d's reported in Tables 9, 11 and 13 were obtained using a number of different techniques. In the earlier papers from the 1960s, samples and solutions were generally not characterized, and the experimental conditions were left unexplained. This makes it impossible to assess the uncertainty in the K_d's or to compare values for various rock types.

8.0 PHYSICAL REPOSITORY SYSTEM

8.1 Introduction

The purpose of a reference design concept is to establish a baseline from which performance assessments may be made. The important features of the physical repository system needed for performance assessment are the geometrical arrangement of the repository, the waste inventory and emplacement scheme, the ventilation system design, and the engineered barriers that may be used to enhance containment. Added to these physical aspects must be a statement of the philosophy upon which the concept is based.

The underlying philosophy for the repository design concept presented is discussed below.

- Concurrence of mining and emplacement operations will allow for early waste storage without the requirement of mining the entire repository.

- Waste emplacement should take place in a retreating mode, that is, placement operations occur first at the farthest extent of the repository. This concept, together with peripheral confinement air return drifts allows the maximum amount of underground exploration and will define the boundaries of the repository at an early stage in its development.

- Complete separation of mining and waste emplacement operations and the air supply and return systems that are required for those operations.

- Shaft placement at one end of the repository serves two purposes:
    (1) Shafts and shaft stations are removed from the effects of mining and waste heat loading.
    (2) Shafts are located at the upstream end of the regional hydrologic system, thereby ensuring that no waste that may be ultimately dissolved by groundwater will be provided with a direct pathway up the shafts to an overlying aquifer.

8.2 General Layout

The physical repository system described below is based upon the design by Kaiser Engineers for the Department of Energy (Kaiser Engineers, 1978), modified to include the concept of concurrent mining and waste emplacement in a retreating mode of operation. As with any design concept, this geometry is subject to modification as specific sites are chosen and exploratory testing is performed to evaluate the site and physical properties of the repository horizon and overlying strata. Modifications may also be required as a consequence of analyses based on the use of actual material and other physical data encountered in a specific site.

The repository is divided into two major areas; the waste storage area and the shaft pillar area. The waste storage area occupies a nominal 2000 acres and the shaft pillar area requires an additional 52 acres. The shaft pillar is at one end of the storage area and contains four shafts in line, transverse to the long axis of the storage area.

Five main airways connect the shaft pillar area to the storage area. The storage area is rectangular in shape and contains 1[illegible] storage rooms on both sides of the central airways. Peripheral confinement air return drifts occur on each side of the storage area. Each half of the storage area of the repository may be constructed and operated with complete independence. Figure 35 shows a schematic layout of the repository. An expanded partial layout of the repository is shown in Figure 36.

8.3 Shafts

Four shafts will be constructed within the shaft pillar area, 1000 feet from the main storage area. Shaft construction will be by conventional drilling and blasting techniques. Shafts passing through an aquifer or water bearing zone will require sealing of that particular stratum. The conventional method of accomplishment is to drill holes around the proposed shaft location and pump grout or chemical sealants into the strata. Figure 37 illustrates the method (Koplik,et al, 1979). All shafts are lined with concrete of a one foot minimum thickness. The diameter of a shaft depends upon the sizes of equipment and materials to be transported and the quantity of ventilation air required for mining or waste heat removal.

> Shaft No. 1 Mining air supply and men and materials transport. This shaft will be 22 feet inside diameter and will contain a men and material cage and a service cage. It will serve as the primary entrance and exit for men and materials to the floor level of the repository. It will also supply fresh air for all mining and support areas not involved with waste handling.

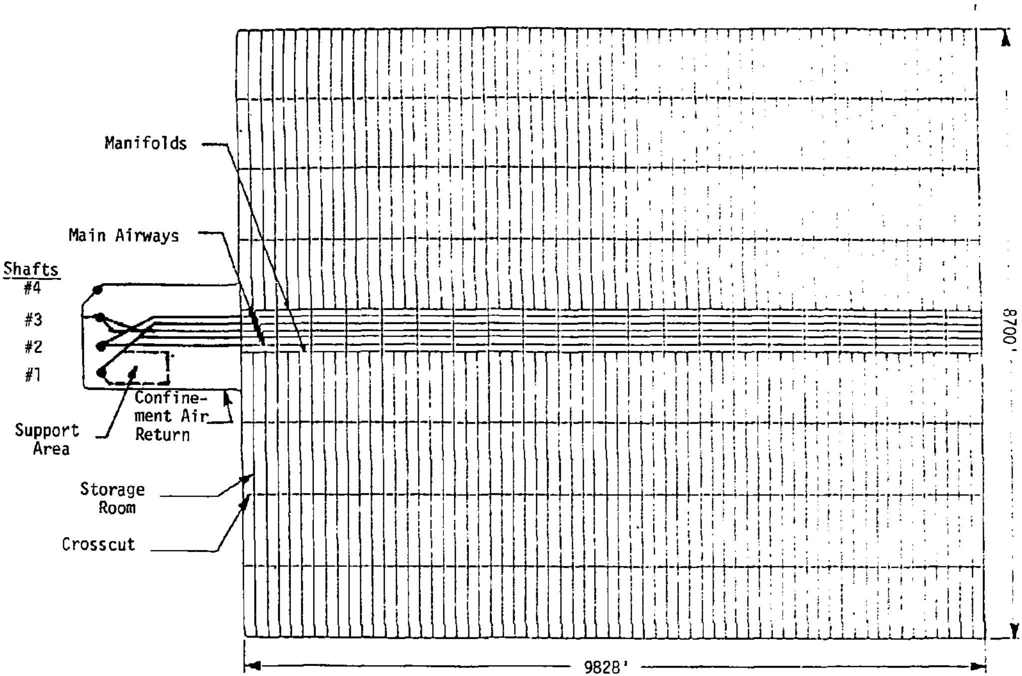


Figure 35 Schematic layout of repository.

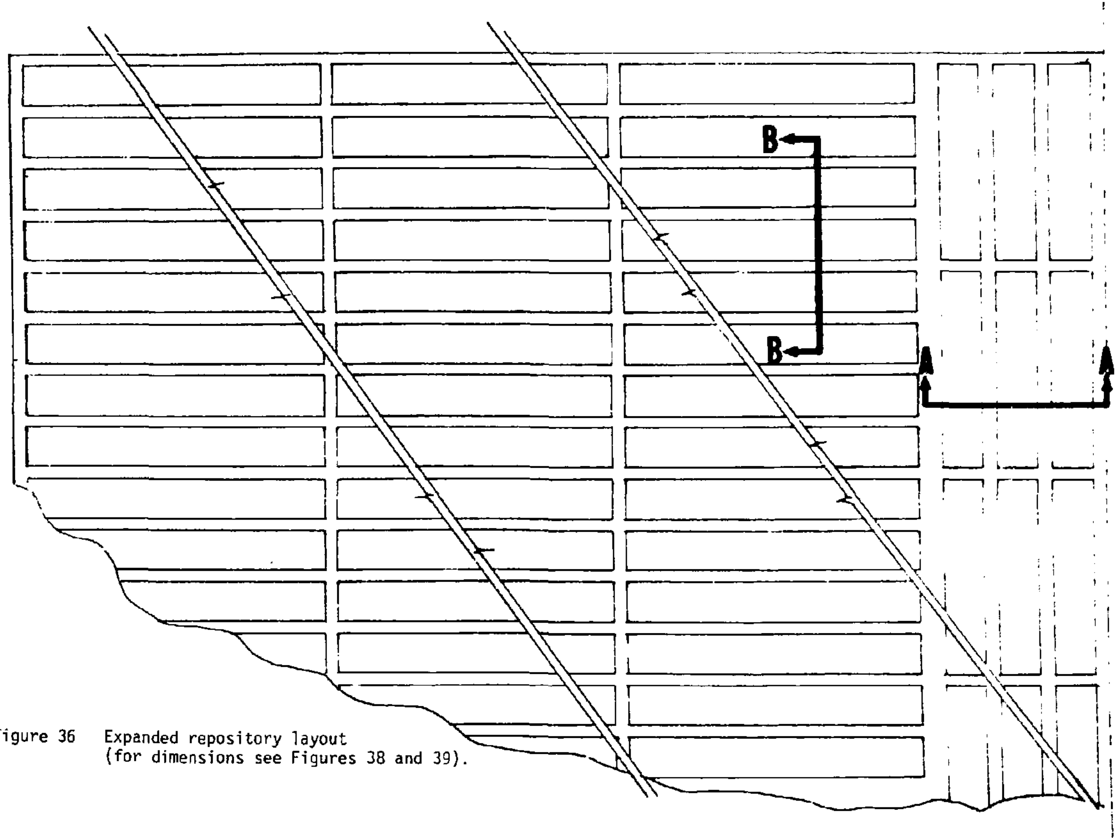


Figure 36 Expanded repository layout
(for dimensions see Figures 38 and 39).

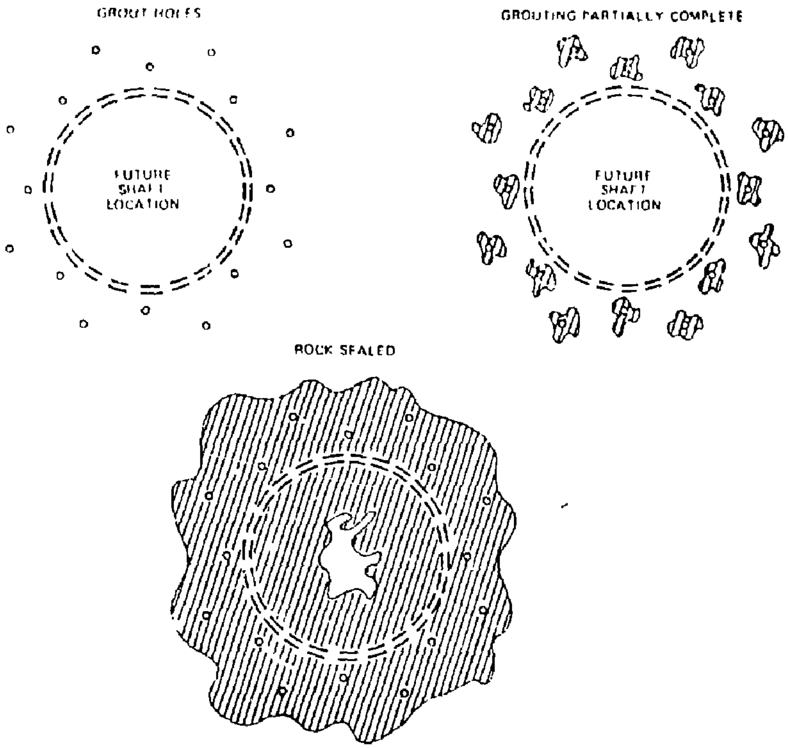


Figure 37 Illustration of pre-grouting prior to sinking shaft thorugh water bearing zone

Shaft No. 2 Mining air exhaust and salt removal. This shaft will be 20 feet (12' KE) in diameter and will serve to remove mined salt with its installed skips and to exhaust air from the mine development operations. Backfill material will be transported from the surface through this shaft when the repository is to be decommissioned.

Shaft No. 3 Confinement air supply and waste handling. This shaft will be 30 feet in diameter and will supply air to the waste storage rooms. It will contain an inside casing through which two waste handling cages will travel. It will also be equipped with an inspection cage for periodic examination of the waste cage casing.

Shaft No. 4 Confinement air exhaust. This shaft will be 30 feet in diameter and will return air from the storage rooms to a filter house at the surface. No regular passage of men or materials will occur in this shaft, but it will be equipped with an inspection cage.

8.4 Shaft Pillar Area

The shaft pillar at the end of the repository contains the four shafts, waste handling areas, mined salt removal areas, ventilation control, maintenance and shop areas, offices and first aid station.

The areas around shafts No. 1 and 2 will contain all underground facilities not involved with waste handling, while the areas around shafts No. 3 and 4 will be restricted to waste handling and confinement air supply and exhaust.

Shaft No. 3 will have a station at an elevation about the repository floor level leading to an inclined drift for the admission of waste and confinement air. The waste handling cages will open into a compartment separated from the main airway by double airlocks and will be connected to the confinment return airway.

Shaft No. 2 will have a station at an elevation above the level of the No. 3 shaft station containing surge bins, mined salt removal equipment and mine exhaust air.

All shaft stations will be lined with reinforced concrete.

8.5 Main Airways

There will be five main airways and two manifold drifts leading to the repository storage area and two peripheral confinement air return airways. All airways and manifolds will be 20 feet high. As with shaft sizes, airway dimensions are based on requirements for machinery and material transporter dimensions as well as ventilation requirements. The central airway will be 60 feet wide and will serve the purposes of confinement air supply and waste transport. Two construction air supply drifts, 25 feet wide will be separated from the confinement supply airways by 70 foot pillars and will serve to supply fresh air for repository development as well as being the main route for men and materials.

Two mine exhaust airways, 25 feet wide, will be separated from the repository supply airways by 70 foot pillars and will exhaust air from the repository development operations and provide conveyor transport of mined salt. A manifold drift, 40 feet wide will be driven next to the repository return airways, separated by 70 foot pillars. This manifold will be the area from which all storage rooms are driven. A common crosscut will occur at every fifth storage room. The confinement air return drifts at the repository perimeter will be 20 feet wide. Figure 38a shows a cross-section through the airway and manifold system.

8.6 Storage Rooms

Storage rooms will be driven on each side of and at right angles to the central airways, beginning at the manifold drifts. The storage rooms will be 4000 feet long on 90 foot centers. There will be a total of 220 rooms, 18 feet wide and 25 feet high, separated by 72 foot wide pillars. This arrangement will yield a storage room extraction ratio of twenty percent. The two rooms and the shaft end of the repository are used for confinement air return. At 1000 foot intervals along each room, crosscuts 10 feet high and 18 feet wide will be constructed. These crosscuts serve as safety exits and cross ventilation during mining and storage. Figure 38b shows a typical cross section through the storage rooms.

8.7 Exploratory Boreholes

The only exploratory boreholes that will be allowed within the repository boundaries are those that may be drilled at the proposed shaft locations. Other boreholes may exist outside the repository boundary,

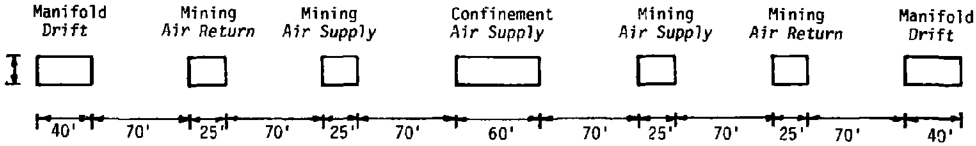


Figure 38a Cross section of main airways and manifolds (Section A-A of Figure 36)

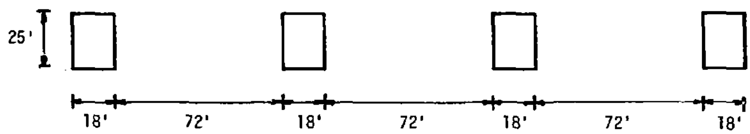


Figure 38b Cross section of waste storage rooms (Section B-B of Figure 36)

but their number and location must be determined from an analysis of their effect on the long term hydrological transport of radionuclides from the repository. Until such an assessment of the long term consequences of boreholes is made, it is not possible to define either their number or location.

8.8 Excavation Methods

The excavation of the main airways, manifolds and storage rooms will be performed by continuous miners with a ripping cutter head. The dimensions that can be cut from such a machine are generally less than 12 feet high and 20 feet wide, thus multiple passes will be required (Koplik et al, 1979). The inclined portions of the airways connected to shaft nos. 2 and 3 will be contructed by drilling and blasting.

The scheduling of mining operations is complex and should be done with the aid of a mining simulation computer code.

The rate of advance for continuous mining equipment may be taken as approximately 140 feet per eight hour shift for an 18 by 11.3 foot opening.

This is equivalent to about 2000 tons per machine per shift (Kaiser Engineers, 1978). The mining machines are equipped with extendible conveyors which transfer the mined salt to the mine return airways where it is transferred to the main conveyors leading to the salt surge bin area in the shaft pillar.

8.9 Waste Types and Characteristics

The repository design concept presented in this report is intended for the storage of spent unreprocessed reactor fuel and transuranic contaminated waste from the nuclear industry.

8.9.1 Spent Fuel

It is assumed that the spent fuel arrives at the repository in canisters containing either one PWR or two BWR fuel assemblies and that all fuel assemblies are aged ten years after removal from the reactor.

The canisters will be 14-1/2 inches outside diameter and 16 feet long.

Table 14 shows the thermal output of light water reactor fuel assemblies as a function of decay time (Kaiser Engineers, 1978).

Tables 15 through 18 list the radionuclide inventory of spent fuel components as a function of decay time (DOE, 1979).

It is further assumed that the PWR assemblies will comprise 40 percent of the total and BWR assemblies will comprise 60 percent of the total to be stored in the repository.

8.9.2 Transuranic Contaminated Waste (TRU)

It is assumed that all TRU waste received will be immobilized in concrete in 55 gallon (208L) steel drums. The variety of TRU waste that can be emplaced in the repository is immense; there are not only various radioisotopes and radiation fields, but also an indefinite combination of physical forms, conditions and chemical compositions. There has

TABLE 14

Thermal power and gamma power of LWR fuel assembly
as a function of decay time

Decay Time		Total Thermal Power* (kW)		Gamma Power Portion of Total Thermal Power (kW)	
Days	Years	PWR	BWR	PWR	BWR
120	1/3	11.1	3.29	4.40	1.29
160	44	9.27	2.77	3.46	1.03
250	2/3	6.77	2.04	2.26	.69
365	1	5.08	1.54	1.61	.50
731	2	2.73	.85	.97	.31
1,095	3	1.75	.56	.67	.22
1,826	5	.96	.32	.42	.14
2,557	7	.71	.24	.29	.099
3,653	10	.58	.19	.21	.072
36,530	100	.133	.0471	.019	.0063
365,300	1,000	.0254	.00944	.000036	.000012
3,653,000	10,000	.00637	.00241	.000018	.0000060

*Total thermal power includes alpha, beta, and gamma power based on ORIGEN computer runs for the following conditions.

	PWR	BWR
Exposure (MWd/mtu)	33,000	27,500
Average Specific Power (MW/mtu)	30	20.7
Mass of uranium per assembly (mtu)	0.461	0.189

TABLE 15

Activation product inventory in reference fuel assembly hardware,[a] as a function of decay time, all fuel cycle modes

Radionuclide	Ci/MTHM for Various Decay Periods[b] 0.5 yr	1.5 yr	3.5 yr	6.5 yr	10^1 yr	10^2 yr	10^3 yr	10^4 yr	10^5 yr	10^6 yr
^{14}C	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	2.0×10^{-2}	1.0×10^{-7}	
^{35}S	8.0×10^{-2}	4.0×10^{-3}	1.0×10^{-5}	2.0×10^{-9}						
^{45}Ca	1.0×10^{-2}	3.0×10^{-3}	1.0×10^{-4}	1.0×10^{-6}	3.0×10^{-9}					
^{46}Sc	8.0×10^{-1}	4.0×10^{-2}	9.0×10^{-5}	1.0×10^{-8}						
^{54}Mn	3.0×10^{2}	2.0×10^{2}	3.0×10^{1}	2.0	8.0×10^{-2}					
^{55}Fe	6.0×10^{3}	4.0×10^{3}	2.5×10^{3}	1.0×10^{3}	4.0×10^{2}	1.0×10^{-8}				
^{58}Co	2.0×10^{3}	2.0	4.0×10^{-2}	1.0×10^{-6}						
^{60}Co	5.0×10^{3}	4.0×10^{3}	3.0×10^{3}	2.0×10^{3}	1.0×10^{3}	7.0×10^{-3}				
^{59}Ni	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0	1.0	3.0×10^{-4}
^{63}Ni	4.0×10^{2}	4.0×10^{2}	4.0×10^{2}	4.0×10^{2}	4.0×10^{1}	2.0×10^{2}	2.0×10^{-1}			
^{65}Zn	2.0×10^{1}	6.0	8.0×10^{-5}	4.0×10^{-2}	6.0×10^{-4}					
^{90}Sr	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	9.0×10^{-4}	9.0×10^{-4}	9.0×10^{-5}				
^{90}Y	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-3}	9.0×10^{-4}	9.0×10^{-4}	9.0×10^{-5}				
^{94}Nb	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	3.0×10^{-6}	
^{93}Mo	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	6.0×10^{-3}	1.0×10^{-3}		
^{99}Tc	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	7.0×10^{-3}	5.0×10^{-3}	2.6×10^{-4}
^{113m}Cd	4.0	4.0	3.0	2.0	2.0	3.0×10^{-2}				
^{125}Sb	4.0×10^{1}	2.0×10^{1}	2.0×10^{1}	8.0	2.0					
^{125m}Te	2.0×10^{1}	1.0×10^{1}	7.0	3.0	1.0					
^{181}W	4.0×10^{-4}	7.0×10^{-5}	2.0×10^{-6}	9.0×10^{-9}						
Total	1.3×10^{4}	8.7×10^{3}	5.5×10^{3}	3.4×10^{3}	1.8×10^{3}	2.0×10^{2}	3.3	2.0	1.0	5.6×10^{-4}
Total thermal watts	6.8×10^{1}	5.8×10^{1}	4.4×10^{1}	2.9×10^{1}	1.7×10^{1}	3.2×10^{-2}	1.2×10^{-4}	5.9×10^{-5}	4.0×10^{-5}	2.2×10^{-5}

a. Hardware components are 302-304 stainless steel, Inconel and Nicrobraz-50.
b. Periods are measured from reactor discharge.

TABLE 16

Activation product inventory in reference zircaloy cladding hulls as a function of decay time

Radionuclide	Ci/MTHM for Various Decay Periods[a]									
	0.5 yr	1.5 yr	3.5 yr	6.5 yr	10^1 yr	10^2 yr	10^3 yr	10^4 yr	10^5 yr	10^6 yr
^{14}C	6.0×10^{-2}	6.0×10^{-2}	6.0×10^{-2}	6.0×10^{-2}	6.0×10^{-2}	6.0×10^{-2}	5.0×10^{-2}	2.0×10^{-2}	1.0×10^{-7}	
^{35}S	2.0×10^{-1}	9.0×10^{-3}	3.0×10^{-5}	6.0×10^{-9}						
^{54}Mn	4.0	2.0	3.0×10^{-1}	2.0×10^{-2}	8.0×10^{-4}					
^{55}Fe	1.0×10^{2}	9.0×10^{1}	5.0×10^{1}	2.0×10^{1}	[illegible]					
^{58}Co	6.9×10^{1}	2.0	2.0×10^{-3}	4.0×10^{-8}						
^{60}Co	2.0×10^{2}	1.0×10^{2}	1.0×10^{2}	8.0×10^{1}	4.0×10^{1}	3.0×10^{-4}				
^{59}Ni	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	1.0×10^{-2}	1.0×10^{-6}
^{63}Ni	5.0	4.0	4.0	4.0	4.0	2.0	2.0×10^{-3}			
^{93}Zr	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	6.0×10^{-2}
^{95}Zr	4.0×10^{3}	8.0×10^{1}	3.0×10^{-2}	3.0×10^{-7}						
^{93m}Nb	9.0×10^{3}	1.0×10^{-2}	2.0×10^{-2}	3.0×10^{-2}	4.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	6.0×10^{-2}
^{95}Nb	7.0×10^{3}	2.0×10^{2}	7.0×10^{-2}	6.0×10^{-7}						
^{113m}Cd	7.0×10^{-3}	5.0×10^{-3}	5.0×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	4.0×10^{-5}				
^{119m}Sn	1.0×10^{1}	5.0	6.0×10^{-1}	3.0×10^{-2}	5.0×10^{-4}					
^{121m}Sn	3.0×10^{-1}	3.0×10^{-1}	3.0×10^{-1}	3.0×10^{-1}	3.0×10^{-1}	1.0×10^{-1}	4.0×10^{-5}			
^{123}Sn	2.0×10^{-1}	2.0×10^{-2}	3.0×10^{-4}	8.0×10^{-7}						
^{181}W	1.0×10^{-3}	2.0×10^{-4}	5.0×10^{-6}	2.0×10^{-8}						
Total	1.1×10^{4}	4.8×10^{2}	1.6×10^{2}	1.0×10^{2}	5.3×10^{1}	3.7×10^{-1}	2.6×10^{-1}	2.3×10^{-1}	1.9×10^{-1}	1.2×10^{-1}
Total thermal watts	3.9	2.3	1.8	1.2	3.3×10^{-1}	3.2×10^{-4}	2.5×10^{-5}	1.6×10^{-5}	1.0×10^{-5}	6.9×10^{-6}

a. Periods are measured from reactor discharge.

TABLE 17

Fission products in reference [illegible] fuel as a function of decay time

Isotope	Ci/MTHM for Various Decay Periods[a]									
	0.5 yr	1.5 yr	3.5 yr	6.5 yr	10^{1} yr	10^{2} yr	10^{3} yr	10^{4} yr	10^{5} yr	10^{6} yr
^{3}H	4.4×10^{2}	4.2×10^{2}	3.7×10^{2}	3.1×10^{2}	2.5×10^{2}	1.6				
^{14}C[b]	7.4×10^{-1}	7.4×10^{-1}	7.4×10^{-1}	7.4×10^{-1}	7.4×10^{-1}	7.3×10^{-1}	6.5×10^{-1}	2.2×10^{-1}	4.2×10^{-6}	
^{79}Se	3.5×10^{-1}	3.5×10^{-1}	3.5×10^{-1}	3.5×10^{-1}	3.5×10^{-1}	3.5×10^{-1}	3.5×10^{-1}	3.2×10^{-1}	1.2×10^{-1}	[illegible]$.7 \times 10^{-6}$
^{85}Kr	9.5×10^{3}	8.9×10^{3}	7.9×10^{3}	6.5×10^{3}	5.0×10^{3}	1.6×10^{1}				
^{87}Rb	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}	1.7×10^{-5}
^{89}Sr	5.5×10^{4}	4.2×10^{2}	2.5×10^{-2}	1.1×10^{-8}						
^{90}Sr	6.7×10^{4}	6.5×10^{4}	6.3×10^{4}	5.8×10^{4}	5.2×10^{4}	5.7×10^{3}	1.3×10^{-6}			
^{90}Y	6.7×10^{4}	6.5×10^{4}	6.3×10^{4}	5.8×10^{4}	5.7×10^{4}	5.7×10^{3}	1.3×10^{-6}			
^{91}Y	9.5×10^{4}	1.3×10^{3}	2.4×10^{-1}	5.8×10^{-7}						
^{93}Zr	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.6	1.1
^{95}Zr	1.7×10^{5}	3.4×10^{3}	1.4	1.2×10^{-5}						
^{93m}Nb	1.7×10^{-1}	2.5×10^{-1}	3.9×10^{-1}	5.7×10^{-1}	7.7×10^{-1}	1.7	1.7	1.7	1.6	1.1
^{95m}Nb	3.6×10^{3}	7.3×10^{1}	3.0×10^{-2}	2.6×10^{-7}						
^{95}Nb	3.3×10^{5}	7.6×10^{3}	3.2	2.7×10^{-5}						
^{99}Tc	1.3×10^{1}	1.3×10^{1}	1.3×10^{1}	1.3×10^{1}	1.3×10^{1}	1.3×10^{1}	1.3×10^{1}	1.2×10^{1}	9.2	4.9×10^{-1}
^{103}Ru	4.3×10^{4}	7.2×10^{1}	2.0×10^{-4}	9.5×10^{-13}						
^{106}Ru	3.4×10^{5}	1.7×10^{5}	4.2×10^{4}	5.3×10^{3}	3.4×10^{2}					
^{103m}Rh	4.3×10^{4}	7.2×10^{1}	2.0×10^{-4}	9.5×10^{-13}						
^{106}Rh	3.4×10^{5}	1.7×10^{5}	4.2×10^{4}	5.3×10^{3}	3.4×10^{2}					
^{107}Pd	9.2×10^{-2}	9.9×10^{-2}	9.8×10^{-2}	9.8×10^{-2}	9.9×10^{-2}	9.9×10^{-2}	9.9×10^{-2}	9.9×10^{-2}	9.8×10^{-2}	9.0×10^{-2}
^{110m}Ag	1.8×10^{3}	6.6×10^{2}	8.8×10^{1}	4.4	8.1×10^{-7}					
^{110}Ag	2.3×10^{2}	8.6×10^{1}	1.1×10^{1}	5.7×10^{-1}	1.0×10^{-2}					
^{113m}Cd	1.2×10^{1}	1.1×10^{1}	7.2	6.2	7.0	8.2×10^{-2}				
^{119m}Sn	8.6	3.1	4.1×10^{-1}	2.0×10^{-2}	3.4×10^{-4}					
^{121m}Sn	4.6×10^{-4}	4.6×10^{-4}	4.4×10^{-4}	4.3×10^{-4}	4.2×10^{-4}	1.9×10^{-4}	5.1×10^{-8}			
^{123}Sn	2.7×10^{3}	3.6×10^{2}	6.3	1.4×10^{-7}	4.4×10^{-6}					
^{126}Sn	4.8×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	4.8×10^{-1}	4.5×10^{-1}	2.4×10^{-1}	$4.[illegible] \times 10^{-4}$

a. Periods are measured from reactor discharge.
b. Not a fission product, ^{14}C is formed by neutron activation of ^{14}N impurity in fuel.

TABLE 18

Actinides and daughters in reference spent fuel as a function of decay time

Isotope	Ci/MTHM for Various Decay Periods[a]									
	0.5 yr	1.5 yr	3.5 yr	6.5 yr	10^1 yr	10^2 yr	10^3 yr	10^4 yr	10^5 yr	10^6 yr
^{210}Pb (b)					7.0×10^{-10}	1.7×10^{-6}	1.9×10^{-3}	[illegible]	[illegible]	[illegible]
^{226}Ra (c)					[illegible] $\times 10^{-9}$	3.4×10^{-6}	[illegible]	[illegible]	4.1×10^{-1}	[illegible]
^{227}Ac (d)					[illegible] $\times 10^{-6}$	2.6×10^{-5}	3.5×10^{-4}	3.4×10^{-3}	[illegible]	[illegible]
^{228}Th (e)	[illegible] $\times 10^{-3}$	2.5×10^{-3}	5.7×10^{-3}	9.7×10^{-3}	1.3×10^{-2}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{229}Th (f)					2.0×10^{-8}	9.0×10^{-7}	1.7×10^{-5}	[illegible]	[illegible]	[illegible]
^{230}Th					4.1×10^{-6}	7.2×10^{-5}	[illegible]	[illegible]	[illegible]	[illegible]
^{231}Th	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.7×10^{-2}	1.9×10^{-2}	[illegible]	[illegible]
^{232}Th (g)					1.1×10^{-10}	1.1×10^{-9}	1.1×10^{-8}	1.3×10^{-7}	[illegible] $\times 10^{-6}$	[illegible]
^{234}Th	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	[illegible]	[illegible]	[illegible]
^{231}Pa	1.8×10^{-6}	2.1×10^{-6}	2.8×10^{-6}	[illegible] $\times 10^{-6}$	5.3×10^{-6}	3.7×10^{-5}	[illegible] $\times 10^{-4}$	[illegible]	[illegible]	[illegible]
^{233}Pa	3.1×10^{-1}	3.1×10^{-1}	3.1×10^{-1}	3.1×10^{-1}	3.1×10^{-1}	4.1×10^{-1}	9.5×10^{-1}	[illegible]	[illegible]	[illegible]
^{234m}Pa	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	[illegible]	[illegible]	[illegible]
^{234}Pa	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}	[illegible]	[illegible]	[illegible]
^{232}U	4.2×10^{-3}	6.7×10^{-3}	1.0×10^{-2}	1.3×10^{-2}	1.4×10^{-2}	6.2×10[illegible]	1.1×10^{-6}			
^{233}U	2.3×10^{-5}	2.5×10^{-5}	2.8×10^{-5}	3.2×10^{-5}	3.8×10^{-5}	1.8×10^{-4}	3.0×10^{-3}	[illegible]	[illegible]	[illegible]
^{234}U	1.5×10^{-2}	2.1×10^{-2}	2.3×10^{-2}	[illegible] $\times 10^{-2}$	7.4×10^{-2}	4.4×10^{-1}	8.0×10^{-1}	[illegible]	[illegible]	[illegible]
^{235}U	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	[illegible]	[illegible]	[illegible]	[illegible]

a. Periods are measured from reactor discharge.

b. Activities of ^{210}Bi and ^{210}Po are the same as ^{210}Pb.

c. Activities of ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po are the same as ^{226}Ra.

d. Activities of ^{227}Th, ^{223}Ra, ^{219}Rn, ^{215}Po, ^{211}Pb, ^{211}Bi and ^{207}Tl are the same as [illegible]Ac.

e. Activities of ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{212}Bi are the same as ^{228}Th. ^{208}Tl is 36 [illegible] of ^{228}Th [illegible]

f. Activities of ^{225}Ra, ^{225}Ac, ^{221}Fr, ^{217}At, ^{213}Bi and ^{209}Pb are the same as ^{229}Th. [illegible] is [illegible] of [illegible]

g. Activities of ^{228}Ra and ^{228}Ac are the same as ^{232}Th.

TABLE 13 (continued)

Isotope	Ci/MTHM for Various Decay Periods[a] 0.5 yr	1.5 yr	3.5 yr	6.5 yr	10^1 yr	10^2 yr	[illegible] yr	[illegible] yr	[illegible] yr	[illegible] yr
^{236}U	2.2×10^{-1}	2.2×10^{-1}	2.2×10^{-1}	2.2×10^{-1}	2.2×10^{-1}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{237}U	2.8	2.7	2.4	2.1	1.7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{238}U	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	3.2×10^{-1}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{237}Np	3.1×10^{-1}	3.1×10^{-1}	3.1×10^{-1}	3.1×10^{-1}	3.1×10^{-1}	[illegible]	[illegible]			[illegible]
^{239}Np	1.4×10^{1}	1.4×10^{1}	1.4×10^{1}	1.4×10^{1}	1.4×10^{1}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{236}Pu	2.9×10^{-1}	2.3×10^{-1}	1.4×10^{-1}	6.8×10^{-2}	2.6×10^{-2}					
^{238}Pu	2.1×10^{3}	2.1×10^{3}	2.1×10^{3}	2.1×10^{3}	2.6×10^{3}	[illegible]				
^{239}Pu	2.9×10^{2}	2.9×10^{2}	2.9×10^{2}	2.9×10^{2}	2.9×10^{2}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{240}Pu	4.5×10^{2}	4.5×10^{2}	4.5×10^{2}	4.5×10^{2}	4.5 × [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{241}Pu	1.1×10^{5}	1.1×10^{5}	9.2×10^{4}	8.4×10^{4}	6.9×10^{4}	[illegible]	[illegible]	[illegible]	[illegible]	
^{242}Pu	1.6	1.6	1.6	1.6	1.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
^{241}Am	2.0×10^{2}	3.7×10^{2}	6.9×10^{2}	1.1×10^{3}	1.6×10^{3}	[illegible]	[illegible]	[illegible]	[illegible]	
^{242m}Am	1.1×10^{1}	1.1×10^{1}	1.1×10^{1}	1.0×10^{1}	1.0×10^{1}	[illegible]	[illegible]			
^{242}Am	1.1×10^{1}	1.1×10^{1}	1.1×10^{1}	1.0×10^{1}	1.0×10^{1}	[illegible]	[illegible]			
^{243}Am	1.4×10^{1}	1.4×10^{1}	1.4×10^{1}	1.4×10^{1}	1.4×10^{1}	[illegible]	[illegible]		[illegible]	[illegible]
^{242}Cm	1.7×10^{4}	3.6×10^{3}	1.7×10^{2}	1.0×10^{1}	8.5	[illegible]	[illegible]			
^{243}Cm	4.0	3.9	3.8	3.5	3.7	[illegible]	[illegible]			
^{244}Cm	1.3×10^{3}	1.3×10^{3}	1.2×10^{3}	1.0×10^{3}	9.0×10^{2}	[illegible]				
^{245}Cm	1.8×10^{-1}	1.8×10^{-1}	1.8×10^{-1}	1.8×10^{-1}	1.8×10^{-1}	[illegible]	[illegible]	[illegible]	[illegible]	
^{246}Cm	3.5×10^{-2}	3.5×10^{-2}	3.4×10^{-2}	3.4×10^{-2}	3.5×10^{-2}	[illegible]	[illegible]	[illegible]	[illegible]	
^{249}Bk	1.1×10^{-3}	5.0×10^{-4}	9.9×10^{-5}	8.9×10^{-6}	3.5 × [illegible]					
^{249}Cf	1.9×10^{-6}	3.4×10^{-6}	4.4×10^{-6}	4.6×10^{-6}	4.6×10^{-6}	[illegible]	[illegible]			
^{250}Cf	1.7×10^{-5}	1.6×10^{-5}	1.4×10^{-5}	1.2×10^{-5}	9.9×10^{-6}	[illegible]				
^{252}Cf	2.0×10^{-5}	1.5×10^{-5}	9.0×10^{-6}	4.1×10^{-6}	1.4×10^{-6}					
Total	1.3×10^{5}	1.1×10^{5}	1.0×10^{5}	8.9×10^{4}	7.5×10^{4}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Total Thermal Watts	7.7×10^{2}	2.9×10^{2}	1.7×10^{2}	1.7×10^{2}	1.8×10^{2}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

a. Periods are measured from reactor discharge.

been no standard developed for a TRU waste form, nor is there any agreement about its definition with respect to activity on the basis of weight or volume.

The current regulatory position is based upon a requirement for retrievable storage of TRU having an activity of 10 nanocuries per gram or above.

Table 19 lists characteristics of TRU isotopes (TERA, 1979).

8.10 <u>Waste Emplacement, Density, and Inventory</u>

The mixture of waste types in a repository can be quite arbitrary. There is no single preferred proportions of spent fuel and TRU waste. For this design concept, it will be assumed that five percent of the total storage area is reserved for TRU waste, the remainder being used for spent fuel in the ratio of 60/40 BWR to PWR assemblies.

For this design, it is assumed that spent fuel is emplaced in sleeved holes drilled into the storage room floor. The holes will be cased with a carbon steel sleeve, 20 inches in inside diameter with a wall thickness of 2 inches.

The low-level waste drums will be palletized and banded, stored two pallets high in the storage rooms.

8.10.1 <u>Spent Fuel Spacing</u>

The spacing of waste canisters in the storage room floors is highly dependent upon the ventilation and the thermomechanical response of the storage room. Without thorough analysis using sophisticated

TABLE 19

All α-emitting TRU isotopes

with half-life greater than 100 days

Isotope	$T_{1/2}$ (yr)	$T(SF)_{1/2}$ (yr)	Thermal Neutron Cross Sections (barn)	Specific Activity (g/Ci)	(SF) Activity (fission/sec-g)	ν (SF)	Parent	Daughter
$^{233}_{92}U$	1.62×10^{5}		$\sigma_c = 49$ $\sigma_f = 524$	1.05×10^{2}	~ 0		^{233}Pa ^{233}Np	^{229}Th
$^{237}_{93}Np$	2.14×10^{6}	$>10^{18}$	$\sigma_c = 170$ $\sigma_f = 0.019$	1.42×10^{3}	$<5.6 \times 10^{-5}$		^{237}U ^{241}Am ^{237}Pu	^{233}Pa
$^{236}_{94}Pu$	2.85×10^{0}	3.5×10^{9}	$\sigma_f = 170$	1.88×10^{-3}	1.6×10^{4}		^{240}Cm ^{236}Np	^{232}U
$^{238}_{94}Pu$	8.64×10^{1}	4.9×10^{10}	$\sigma_c = 500$ $\sigma_f = 16.8$	5.75×10^{-2}	1.13×10^{3}	2.26	^{238}Np ^{238}Am ^{242}Cm	[illegible]
$^{239}_{94}Pu$	2.44×10^{4}	5.5×10^{15}	$\sigma_c = 274$ $\sigma_f = 741$	1.63×10^{1}	1.00×10^{-2}	[illegible]	^{239}Np ^{243}Cm ^{239}Am	^{235m}U
$^{240}_{94}Pu$	6.58×10^{3}	1.34×10^{11}	$\sigma_c = 286$ $\sigma_f = <0.08$	4.4×10^{0}	4.1×10^{2}	[illegible]	^{244}Cm ^{240}Np ^{240}Am	^{236}U
$^{242}_{94}Pu$	3.79×10^{5}	7.1×10^{10}	$\sigma_c = 19$ $\sigma_f = <0.2$	2.57×10^{2}	7.7×10^{2}	2.16	^{246}Cm ^{242}Am	^{238}U
$^{244}_{94}Pu$	$\sim 7.6 \times 10^{7}$	2.5×10^{10}	$\sigma_c = 1.8$	$\sim 5.2 \times 10^{4}$	2.7×10^{3}		^{248}Cm	^{240}U F.P.
^{241}Am	4.58×10^{2}	2×10^{14}	$\sigma_c = 700$ ^{242}Am $\sigma_c = 100$ ^{242m}Am $\sigma_f = 3.0$	3.08×10^{-3}	$2.$[illegible]$ \times 10^{-1}$	2.3	^{241}Pu ^{245}Bk ^{241}Cm	^{237}Np
$^{242m}_{95}Am$	1.52×10^{2}		$\sigma_c = 2000$ $\sigma_f = 6000$	1.03×10^{-1}			[illegible]	[illegible] ^{238}Np
$^{243}_{95}Am$	7.95×10^{3}		$\sigma_c = 74$ $\sigma_f = <0.07$	5.40×10^{0}			^{243}Pu ^{247}Bk	^{239}Np
$^{242}_{96}Cm$	4.45×10^{-1}	7.2×10^{6}	$\sigma_c = 20$ $\sigma_f < 5$	3.01×10^{-4}	7.58×10^{6}		^{242}Am ^{246}Cf	^{238}Pu F.P.
$^{243}_{96}Cm$	3.2×10^{1}		$\sigma_c = 250$ $\sigma_f = 660$	2.2×10^{-2}			^{243}Bk	^{239}Pu

TABLE 19 (continued)

Isotope	$T_{1/2}$ (yr)	$T(SF)_{1/2}$ (yr)	Thermal Neutron Cross Sections (barn)	Specific Activity (g/Ci)	(SF) Activity (fission/sec-g)	ν (SF)	Parent	Daughter
$^{233}_{92}U$	1.62×10^{5}		$\sigma_c = 49$ $\sigma_f = 524$	1.05×10^{2}	[illegible]		^{233}Pa ^{233}Np	^{229}Th
$^{237}_{93}Np$	2.14×10^{6}	$>10^{18}$	$\sigma_c = 170$ $\sigma_f = 0.019$	1.42×10^{3}	$<5.6 \times 10^{-5}$		^{237}U ^{241}Am ^{237}Pu	^{233}Pa
$^{236}_{94}Pu$	2.85×10^{0}	3.5×10^{9}	$\sigma_f = 170$	1.88×10^{-3}	[illegible] $\times 10^{4}$		^{240}Cm ^{236}Np	^{232}U
$^{238}_{94}Pu$	8.64×10^{1}	4.9×10^{10}	$\sigma_c = 500$ $\sigma_f = 16.5$	5.75×10^{-2}	1.13×10^{3}	2.26	^{238}Np ^{238}Am ^{242}Cm	^{234}U
$^{239}_{94}Pu$	2.44×10^{4}	5.5×10^{15}	$\sigma_c = 274$ $\sigma_f = 742$	1.63×10^{1}	1.00×10^{-2}	2.2	^{239}Np ^{243}Cm ^{239}Am	^{235m}U
$^{240}_{94}Pu$	6.58×10^{3}	1.34×10^{11}	$\sigma_c = 286$ $\sigma_f = <0.08$	4.4×10^{0}	4.1×10^{2}	2.17	^{244}Cm ^{240}Np ^{240}Am	^{236}U
$^{242}_{94}Pu$	3.79×10^{5}	7.1×10^{10}	$\sigma_c = 19$ $\sigma_f = <0.2$	2.57×10^{2}	7.2×10^{2}	2.16	^{246}Cm ^{242}Am	^{238}U
$^{244}_{94}Pu$	$\sim 7.6 \times 10^{7}$	2.5×10^{10}	$\sigma_c = 1.8$	$\sim 5.2 \times 10^{4}$	2.7×10^{3}		^{248}Cm	^{240}U F.P.
^{241}Am	4.58×10^{2}	2×10^{14}	$\sigma_c = 700$ ^{242}Am $\sigma_c = 100$ ^{242m}Am $\sigma_f = 3.0$	3.05×10^{-3}	[illegible]	[illegible]	^{241}Pu ^{245}Bk ^{241}Cm	^{237}Np
$^{242m}_{95}Am$	1.52×10^{2}		$\sigma_c = 2000$ $\sigma_f = 6000$	1.03×10^{-1}			—[a]	^{242}Am ^{238}Np
$^{243}_{95}Am$	7.95×10^{3}		$\sigma_c = 74$ $\sigma_f = <0.07$	5.40×10^{0}			^{243}Pu ^{247}Bk	^{239}Np
$^{242}_{96}Cm$	4.45×10^{-1}	7.2×10^{6}	$\sigma_c = 20$ $\sigma_f < 5$	3.01×10^{-3}	7.58×10^{6}		^{242}Am ^{246}Cf	^{238}Pu F.P.
$^{243}_{96}Cm$	3.2×10^{1}		$\sigma_c = 250$ $\sigma_f = 660$	2.2×10^{-2}			^{243}Bk	^{239}Pu

numerical models and actual thermal and mechanical properties from the particular repository site, the following assumed spacing is based upon the suggested criteria of 36 KW per acre of storage area (Russell, 1979). It is further assumed that a single row of canisters will occupy each room.

Canister Type	No. of Rooms	Canister Spacing	No. of Canisters
PWR	141	7.75 feet	71,769
BWR	68	4.94 feet	54,264

8.10.2 TRU Waste Emplacement

Since five percent of the repository storage rooms are for the storage of TRU waste, 11 rooms will be required. With the assumption of palletized 55 gallon (208 liter) drums in a 2 by 3 by 2 high configuration and the vertical stacking of two pallets, each room would contain 6000 barrels.

8.10.3 Radionuclide Inventory

The total inventory of radionuclides can be obtained by taking the product of the number of assemblies of spent fuel, their mass of heavy metal, and the activities presented in Tables 8-2 through 8-5. For ten year old assemblies, the figures are below:

Assembly	Activation Products	Fission Products	Actinides
PWR	6.131×10^{7}	8.933×10^{9}	2.481×10^{9}
BWR	3.801×10^{7}	5.538×10^{9}	1.538×10^{9}
TOTAL	9.932×10^{7}	1.447×10^{10}	4.019×10^{9}

Total Inventory = 1.859×10^{10} curies

The inventory of radionuclides in the spent fuel at any time may be obtained in the same way using the same method described above. The actual inventory will be made up of wastes of various ages. If the reference fuel is 10 years old as it is placed in the repository and the repository takes 40 years to fill then at any year n the repository will contain approximately 1/40th of its entire capacity of waste that is 10 years old, 1/40th will be 11 years old, 1/40th 12 years old etc. to the oldest waste in the repository being n+10 years old. When the repository is full at 40 years the oldest waste is 50 years and the average waste is 30 years old. For a repository which had been filled at a steady rate with waste that was 10 years out of the reactor as it is emplaced, the inventory of radionuclides at that time will be about 85 percent of that listed above.

In order to establish an inventory for TRU wastes, the following assumptions have been used:

(a) Concrete immobilization with concrete density of 2.0 gm/cm^3.

(b) TRU loading in concrete is 10 weight percent.

(c) All TRU has been reduced to a level of 10 nanocuries per gram.

For the total of 66,000 barrels of TRU waste, the inventory is 27.46 curies.

8.11 Subsurface Waste Handling

High-level waste enclosed by transfer casks will be removed from the hoist at the waste handling station at the base of shaft No. 3 by a machine operating within the airlocked compartments. The high-level waste transfer casks will be rotated to a horizontal position, loaded on transporters, and moved to storage areas. All waste movement takes place in the drifts associated with this shaft. When the high-level waste is transported to the storage room, the transfer cask will be returned to the vertical position and the waste inserted into the sleeved holes in the storage room floor. After the canister is placed, a concrete shield plug will be inserted into the top of the sleeve. The sequence of waste placement will start near the confinement exhaust airway and retreat towards the repository centerline.

TRU waste will be removed from the waste cage and placed on a transporter with a forklift equipped with barrel grabs. The drums will be placed on non-combustible pallets on the transporter in a two by three pattern, two tiers high, with the tiers separated by a metal plate and banded. The palletized drums will be transported to the storage rooms and stored two pallets high and two pallets wide.

8.12 Engineered Barriers

Engineered barriers will provide the only man-controlled means to either prevent or to slow down the migration of radionuclides from the repository. Four types of possible engineered barriers are readily apparent.

(1) A chemical buffer such as a zeolite, could be placed between the waste canister and the storage hole sleeve. Such a barrier would have highly sorptive properties for radionuclides and could retard their migration after the canister has been breached and the waste has dissolved.

(2) The material used for backfilling the repository at decommissioning could contain a low permeability, highly sorptive material such as a bentonite clay. Such compositions also tend to swell in the presence of water, which could act to provide a tight seal against the storage room or airway walls. A careful analysis of the local hydrological system and the complex geochemical interactions is needed to design the backfill material and placement operations.

(3) Physical barriers could be constructed within the repository drifts or storage rooms. These could act as seals to prevent or delay water flow to or from the waste storage areas. Carefully designed and placed plugs, particularly between the shaft pillar and the storage rooms could extend the time before the storage area would become saturated and water would reach the waste. Analysis might show that a series of plugs and/or plugs at each storage room would also be effective in extending the time before water reaches the waste.

(4) In a geologic medium such as bedded salt, one of the most likely sources of water inflow will be in the shaft area. Carefully designed and monitored seals around the shafts in aquifer locations are necessary. The seals should be designed to match the media with respect to mechanical and chemical compatability. Well designed seals could significantly extend the time before water enters the repository and will also act to prevent radionuclide transport out of the repository through the use of chemically retardant materials.

Until analyses of hydrology and transport on the repository scale are performed, no quantitative statements can be made regarding engineered barriers. For example, a tailored backfill material intended to retard radionuclide migration might serve no purpose unless it can be shown that dissolved waste will, in fact, be directed through the backfill.

Complete and competent analysis must be performed to quantitatively assess the effectiveness of engineered barriers.

9.0 STRUCTURAL PERFORMANCE

9.1 Introduction

The structural performance of a repository depends upon repository depths, the initial stress state, deformability and thermomechanical response of the geologic media, the waste heat loading, and the mine design. The deformations that can be expected will include roof s g, floor heave, and pillar widening within the storage rooms. Stability problems include roof falls and pillar slabbing.

The requirement suggested in the proposed regulation 10CFR60 that waste can be retrieved for a period of 50 years after termination of emplacement suggests a total time for the repository to remain open of around 150 years. At present, no analysis has been performed and no material testing has been done to assess the possibility of attaining such a requirement.

Only the combined effort of advanced state of the art thermal and thermomechanical analyses using material properties from a specific site and experimental results from a repository proving mine can predict the thermomechanical response of a repository for the time period required.

9.2 Thermomechanical Response

9.2.1 Room Closure

Room closure calculations have been performed for several heat loadings, depths, and extraction ratios (Russel, 1979; Koplik et al., 1979; Kaiser Engineers, 1978). The methods used and the material models employed are questionable, but may be reasonable estimates for design concepts. Results reported for the design of Kaiser Engineers show 21 inches of closure at 25 years for a repository in bedded salt having an 8.1 percent extraction ratio. The analytical method used was the integration of the differential equations of motion from the Project Salt Vault experiments.

The degree of room closure is determined by the creep characteristics of the salt, the in situ stress state, the salt temperature, and the shape of the room opening. As previously mentioned, the salt temperature is a function of the waste heat loading and the removal of heat by the ventilation system.

Figure 39 shows the canister surface and room floor temperatures for both a ventilated and non-ventilated storage room (Cheung and Otsuki 1980). based on a waste heat loading of 36 Kw/acre. Figure 40 shows the response of the floor temperature to ventilation after several elapsed times of no ventilation. While the temperatures do not seem to be a major concern, analyses must be performed to estimate the room closure that would accompany such temperature responses.

9.2.2 Pillar Stability

The stability of pillars separating rooms and airways is related to the pillar aspect ratio (height to width), room shape, and the presence or absence of clay or shale beds in the salt.

Such beds occurring at the top or bottom of a room serve to reduce the strength of the pillar and can cause buckling of the floor or slabbing of the roof.

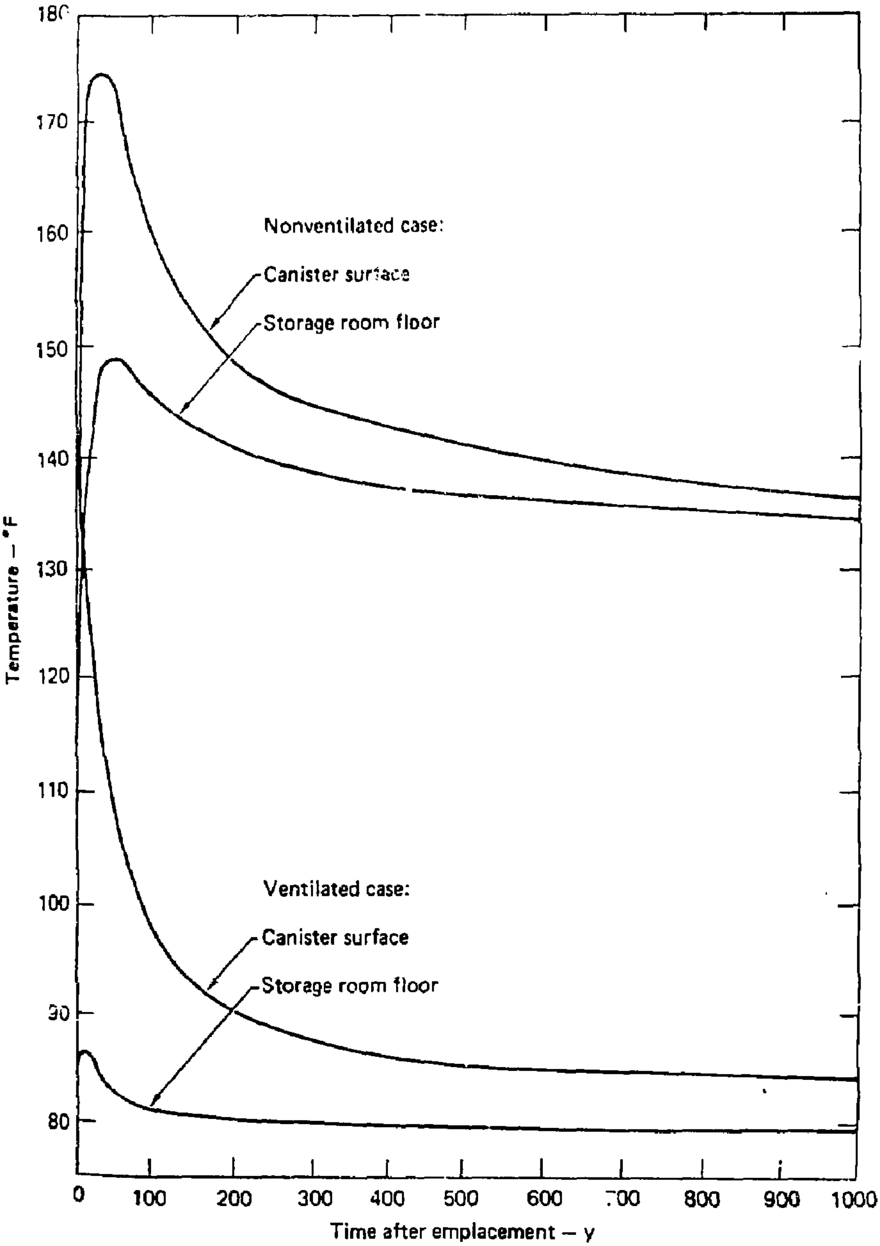


Figure 39 Canister surface and storage room floor temperature histories for both ventialted (with 79 F air at 10,000 cfm) and unventilated cases.

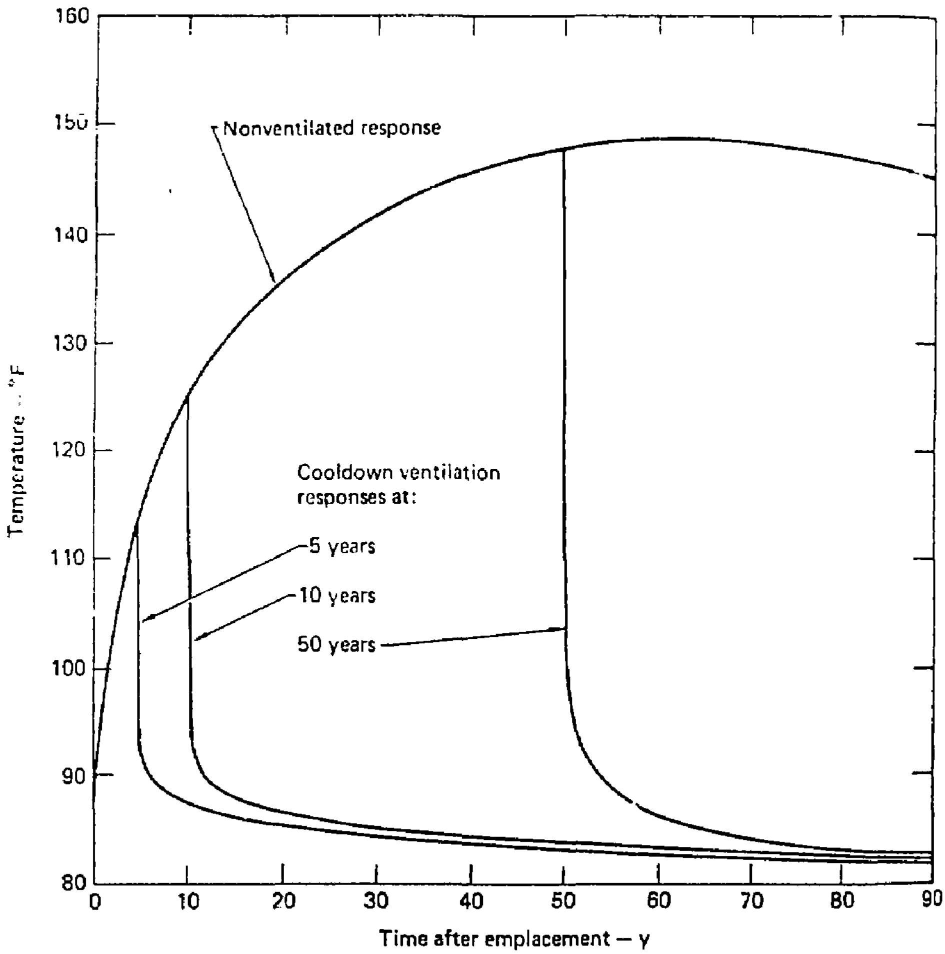


FIGURE 40. Storage room floor temperature histories representing cool-down (10,000 cfm of 79 F air) from an unventilated state after 5, 10, and 50 years.

Analyses, using the in situ shear stiffness of interbeds combined with the ability to redesign the mine to avoid such beds at critical locations could be reasonably expected to reduce the impact of these beds and determine the correct room shape and pillar size at a particular site.

9.2.3 Far-Field Effects

Effects in the geologic media resulting from the heat of emplaced waste will occur in times greater than those of repository operations. The results of these deformations include surface uplift, surface temperature rise, and aquifer temperature changes. In addition, deformations could occur in the area of shaft aquifer seals, and tensile and shearing stresses may be developed in aquitards separating the repository horizon from an aquifer. If sufficient tension is developed, the possibility of fracturing and the creation of a possible hydrological pathway exists.

9.2.4 Scale Effects and Structural Modeling

Most structural modeling efforts have focused on a single storage room bounded by planes of symmetry or on very large scale models such that repository details are not included. An additional usual assumption is that of instantaneous and identical waste emplacement. These assumptions overlook the inherent three dimensional nature and temporal variations of loads on an actual repository.

It is unlikely that a single thermal and structural model of a repository can ever be constructed with sufficient detail to understand the many aspects of structural performance.

Waste emplacement will occur over several tens of years. It will therefore be necessary to examine the effect of time dependent emplacement on room closure, room and pillar stability, and long term deformation of the geologic media.

Several scales or sizes of problems must be studied and carefully integrated with appropriate and compatible boundary conditions.

The use of boundary conditions as coordinating variables between different size problems has been discussed by Dettinger, et al. (1980).

10.0 OPERATIONAL PHASE PERFORMANCE

10.1 Introduction

The analysis of repository performance during the operational phase will require extensive numerical modeling and has not yet been thoroughly examined. Manpower loading and placement, human factors, ventilation system response, gaseous and particulate radionuclide transport, structural response and radiation shielding are the major areas that must be examined prior to definitive understanding of the operational safety and environmental effects of repository operation.

10.2 Repository Operations

One of the underlying philosophies of this design concept is that of concurrence of mining and waste emplacement operations. Waste will be emplaced beginning at the outer repository boundary and will retreat towards the shaft areas. In addition to allowing maximum exploration of the repository horizon, this retreating mode of operations will assure that mining operations and personnel will not be required to traverse areas in which waste handling operations are taking place.

10.3 Ventilation System Air Flow Quantities and Velocities

A key factor in the concept of concurrent mining and placement operations is the ventilation system design and its ability to insure that air streams from those concurrent operations are separate.

During concurrent operations, stoppings are constructed to prevent air stream mixing. Figure 41 shows schematically where stoppings are erected.

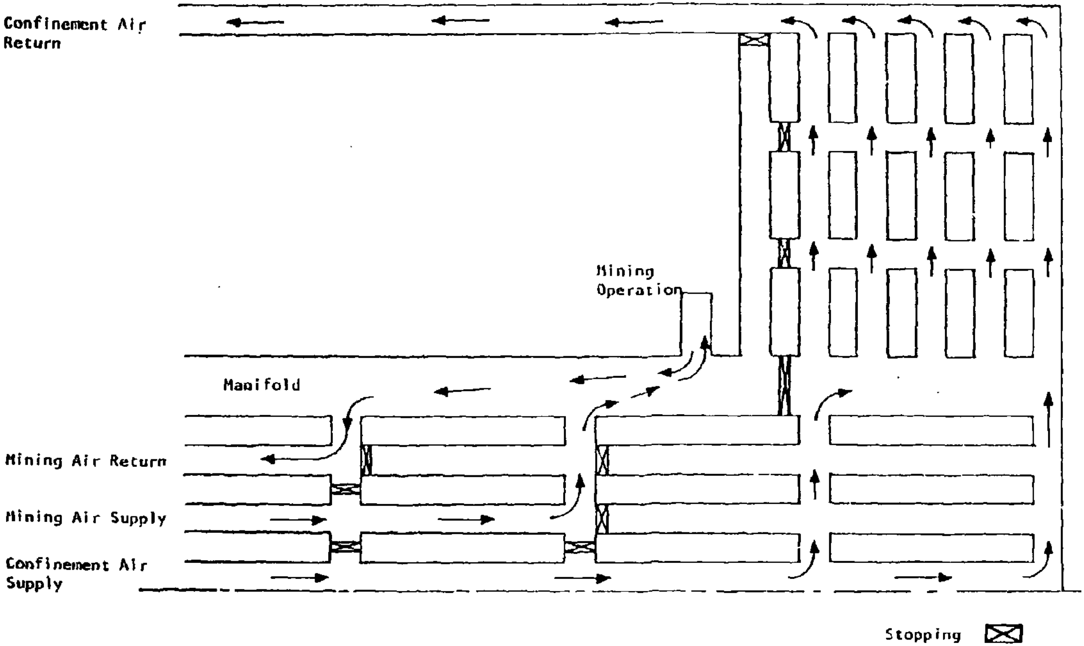


FIGURE 41. Schematic diagram showing stopping placement during mining

The confinement air exhaust system is operated at the lowest pressure in the overall ventilation system. This insures that any leakage will direct air to the confinement exhaust system. Confinement air is normally vented to atmosphere, but a radiation monitoring system will activate a damper system to direct this air through a bank of high efficiency particulate air (HEPA) filters when radiation is detected in the air stream.

10.3.1 Air Flow Quantities and Velocities

The quantity of air required for storage of waste is given by Cheung and Otsuki (1980) as 10,000 cubic feet per minute (cfm) per storage room. The flow rates and velocities for confinement air are shown below.

Location	Flow (cfm)	Velocity (ft/min)
Storage Room	10,000	22
Supply Airway	2,090,000	1742
Supply Shaft	2,090,000	3326
Exhaust Airway	1,045,000	2612
Exhaust Shaft	2,090,000	2956

It should be noted that these values are maximum and assume continuous ventilation of all spent fuel storage areas. It is assumed that storage rooms for TRU waste will require no ventilation.

Results of thermal calculations presented in Chapter 9 (Cheung and Otsuki (1980) suggest based solely on thermal considerations that the possibility exists that no ventilation may be required even for the spent fuel storage areas. Thermomechanical analysis must be performed to assess the structural response of the repository for the case of no ventilation.

The airflow requirements for extraction operations depend directly upon the rate of repository development, which will determine the number of mining machines and construction personnel.

It is assumed that 1,000,000 cubic feet per minute will be a maximum requirement for repository development, support areas at the shaft pillar, and construction dust control. On this assumption, the flow rates and velocities are shown below.

Location	Flow (cfm)	Velocity (ft/min)
Supply Shaft	1,000,000	2630
Airways	400,000	640
Support Areas	200,000	variable
Exhaust Shaft	1,000,000	3182

A significant problem may be encountered by the requirement of the high ventiltion rates suggested by Cheung and Otsuki (1980). Airway velocities are seen to be as high as 2600 feet per minute. According to Carpenter, et al., (1980), current mine practive is to limit air velocity in unlined airways to 500 feet per minute to ensure that dust from walls is not made airborne. In addition, higher velocities mean greatly increased pressure losses and short transit times for contaminants in the air stream. A possible solution to the dust problem might be spraying airway walls with a resinous compound.

10.4 Shaft Conveyances

Concrete head frames will be constructed over each shaft. All hoists will be tower mounted. The types of hoists are listed below:

Shaft No.	Conveyance	Hoist Type
1	Inspection	single drum, counterweight
	Men and Materials	multi-rope friction
2	Mined rock removal	double drum
3	Waste handling	multi-drum
	Inspection	single drum
4	Inspection	single drum

The waste handling conveyance must be equipped with positive position indication and a thorough system of interlocks to ensure the safety of loading and unloading operations. Safety dogs or similar mechanisms should be built into the shaft system to arrest the cage in a free-fall situation (Carpenter, et al, 1980).

The waste handling cage (Shaft No. 3) speed will be in the range of 200 to 400 feet per minute, therefore, particular attention must be paid to the design of its braking system.

10.5 Waste Handling Machinery

Spent fuel canisters are received at the shaft station in shielded transfer casks. At this station, the transfer casks are removed from the waste hoist cage, rotated, and placed on a transfer cask transporter.

The transporter then leaves the double airlocked waste handling station and proceeds to the storage room.

When the transporter is correctly positioned at the storage hole, the concrete shield plug will be removed and moved out of position. The transfer cask will be rotated to the vertical position, and a floor shield plate will be positioned over the hole. The end of the transfer cask will be opened, the canister lowered into the sleeve, the shield plate removed, and the concrete plug replaced.

The transfer cask will then return to the horizontal position and the transporter will return to the shaft station.

A thorough analysis of accidental occurrences and a complete shielding analysis of the transfer cask and transporter will be required to limit occupational exposure.

10.6 Receival Rates

The rate of receival of spent fuel canisters at the repository will largely be determined by the rate at which they can be transported to the repository surface facility and by the economics of repository operation. The rates of underground receival in the Kaiser design vary from 2,800 to 11,000 canisters per year.

The underground handling machinery will most likely not be a limiting factor in determining waste receival rates. A total emplacement time of from 17 to 25 years is a reasonable estimate for this repository.

10.7 Retrieval System

The design concept presented here is intended to allow for the possibility of waste retrieval for a period of 50 years after emplacement. Two factors will control the design of the system required for retrieving the waste: the condition of the waste canister, and the thermomechanical response of the storage room and storage sleeve.

Only a thorough analysis of these aspects will determine whether retrieval can be a simple reversal of the emplacement operation or if remining and the design of highly specialized equipment will be necessary.

10.8 Shielding

10.8.1 Waste Transfer Cask

The main body of the transfer cask is fabricated from three concentric steel cylinders: the outer and intermediate cylinders of carbon steel, the inner cylinder of stainless steel. The annulus between the inner and intermediate cylinders contains 6.16 inches of lead. The annulus between the intermediate and outer cylinders is filled with polyethylene. The radiation dose at the outer surface will be 25 mrem/h or less (Kaiser Engineers, 1978).

10.8.2 Storage Hole Shield Plug

The shield plug will be constructed of ordinary concrete, 44 inches long. The estimated dose rate is less than 1.2 mrem/h (Kaiser Engineers, 1978).

10.9 Dewatering

The shafts will likely intercept aquifers between the surface and repository horizon. Shaft liners can be constructed that are relatively impermeable using watertight concrete and grouts. Drain holes and a water collecting ring are normally used to prevent pressure buildup behind the shaft liner.

It has been stated (Koplik, et al., 1979) that normal leakage rates encountered in the salt mining industry are usually less than 20 gallons per minute. Larger flow rates can be accommodated with the inclusion of sumps in the shaft design.

The rate of inflow will depend upon the regional hydrology and the competence of the seal. Site exploration and in situ testing of seals is the only approach to definitive control of seal leakage rates.

Since this design concept requires complete peripheral exploration before waste storage begins, the possibility of flooding due to unknown water or brine pockets is greatly reduced.

10.10 Support Facilities

A nuclear waste repository demands some support facilities not required in a conventional mine. The following sections will discuss only those special features that will be required.

10.10.1 Fire Protection

Since the geologic medium is soluble in water, all fire extinguishing must be accomplished using dry chemicals. A mobile fire protection unit must be provided and all vehicles must be equipped with built-in fire protection systems. *Ventilation flow reversal, sometimes employed for smoke control should not be permitted.*

10.10.2 Power Supply

The electrical power supply to the repository should be taken underground using a duplicate feed system located in separate shafts to preclude the possibility of major shaft accidents resulting in total failure of electrical supply.

10.10.3 Decontamination System

Special powered vehicles containing decontamination equipment should be provided. Decontamination techniques will include scooping, vacuuming, mopping, and resin spraying. All decontaminated material will be placed in shielded containers and returned to the surface.

10.10.4 Communication Systems

Extensive telephone and high-quality radio links should be provided at all locations.

10.10.5 Radiation Monitoring

Monitors capable of detecting gaseous and particulate radioactive materials should be installed in each storage room, all airways, and the shaft pillar system.

10.10.6 *Instrumentation*

Extensive instrumentation will be installed in the repository. The types of instrumentation are listed below; their number and locations depend upon either experimental requirements, safety requirements, or systems control.

- Rock mechanics behavior
- Ventilation differential pressure
- Temperature (rock, air)
- Air velocity
- Relative humidity
- Seismic activity

11.0 OPERATIONAL ACCIDENT SCENARIOS

11.1 Introduction

A nuclear waste repository in bedded salt will include all of the equipment and operations normally found in an underground salt or potash mine plus the equipment and operations uniquely associated with nuclear waste emplacement and/or retrieval operations. Therefore, the potential exists for both mining-related and radioactive materials handing accidents within an operating repository. It should be noted that those accidents involving radioactive materials are of greatest interest to NRC. Other accidents are industrial in nature and can best be evaluated by OSHA or the Bureau of Mines based upon their regulatory and technical expertise.

Accidents may be classified according to their consequences, mode of occurrence or area and operations affected. Each of these classifications are presented and briefly discussed in following sections. The classification of accidents by consequences is presented in general terms while classifications based on mode of occurrence and area and operations affected are presented with specific reference to a nuclear waste repository in bedded salt.

The final section of this chapter presents a discussion of ways in which the design process may anticipate accidents and reduce hazards during subsequent repository operations.

11.2 Accident Classification According to Consequences

Five general types of accidents have been identified based upon their consequences (Koplik and others, 1979). These are:

- Type A - Accident could result in damage to equipment or environment only. No radioactive materials involved.
- Type B - Accident could result in injury or death. No radioactive materials involved.
- Type C - Accident could result in release of radioactive materials but with no danger to man.
- Type D - Accident could result in release of radioactive materials with possible effects on those present within the site only.
- Type E - Accident could result in release of radioactive materials with possible effect on public safety.

Accidents in categories A and B would be covered by existing federal or state mining regulations. Accidents in categories C, D, and E could result in radiation release, and therefore, would require the development of appropriate NRC regulations and enforcement policies.

11.3 Accident Classifications According to Mode of Occurrence and Repository Operations

Koplik and others (1979) have summarized accident statistics obtained from the Mine Safety and Health Administration (MSHA) for underground non-metal mines including salt and potash mines. The MSHA statistics reproduced in Table 20 indicate that the main cause of fatal accidents in this mining environment is unexpected geological or hydrological hazards with fire/suffocation and materials haulage also providing significant contributions. These factors and other materials handling accidents are the dominant causes of non-fatal accidents.

TABLE 20
Distribution of accidents by category

Category	Average Number of Accidents (in %)			
	Fatal		Nonfatal	
	1966-70	1973-76	1966-70	1973-76
Falls of ground, water inrush, rock burst	32.1	27.8	14.3	11.2
Haulage	12.8	5.6	16.4	13.5
Machinery	2.6	5.6	13.6	18.5
Material Handling	0.8	2.8	25.1	22.8
Falling Material	6.1	8.3	4.4	2.1
Electrical	3.5	13.9	1.5	1.2
Explosives	3.4	8.3	1.1	1.3
Fire-Suffocation	37.0	13.9	4.1	0.3
Miscellaneous	1.7	13.9	19.5	29.1

Source: Koplik and others (1979).

Additional data are available based on accident statistics from the coal-mining industry. This information is believed to be appropriate because mining equipment and geologic conditions in coal mines bear many similarities to equipment and conditions anticipated during non-radiologic operations in a nuclear waste repository in bedded salt. This information is unique in that it provides a breakdown by occupation of accident injury data that have been normalized in terms of work exposure.

It is therefore possible to use this information to make a reasonable estimate of a repository in bedded salt based on job classifications developed for DOE in Y/OWI/TM-36/9 (Parsons,Brinckerhoff, Quade & Douglas, Inc., 1978). The resulting estimates are presented in Table 21.

Based upon analogies between occupations, rough estimates have also been made for injury accidents associated with nuclear waste-handling operations. These data are presented in Table 22.

In order to develop a capability to evaluate repository performance in terms of the short-term risk of radioactive release as a result of accidents, two accident matrices have been developed. The first matrix diagram, Figure 42, classifies accidents with reference to failure events and work activity.[1] The second matrix, Figure 43 classifies accidents in terms of work activity and operating areas or locations. These matrices are not intended to be definitive since future plans for repository designs, equipment and operational procedures will affect them and other accident scenarios may be identified in the future.

1. A failure event as used in this discussion is the occurrence of an unplanned or unexpected event. Thus, the breakdown on a piece of mining equipment would not be a failure event since it is expected to happen during normal operations. A roof fall would be a failure event if it occurred during waste emplacement operations, but would not be a failure event during excavation operations.

TABLE 21 Estimated non-radiological occupational hazard effects by job classification mining operation.

Type	General Activity	Man Shifts* Per Day	Estimated Occupational Hazard** Effects Per Year FTL	N-F Dis.	Accidents
Foreman	Supervising Mining at Face	12	0.01	0.7	1.8
Continuous Miner Operators and Helpers	Operation of Face Equipment	24	0.04	2.0	4.0
Face Mechanics	Maintenance of Face Equipment	24	0.04	2.0	5.6
Conveyor Tenders	Operation of Extensive Haulage Conveyors	30	0.01	2.9	5.1
Truck Drivers	Haulage of Material	21	0.02	2.2	4.[illegible]
Loader Operators	Face Cleanup	12	0.04	1.4	2.7
Shaft Superintendents	Supervising	3	--	--	0.2
Bin Tenders	Loading Pocket and Hoist Operations	6	0.02	2.6	7.3
Skip Tenders		3	0.02	2.6	7.3
Cage Tenders		3	0.02	2.6	7.3
Signal Men		9	0.02	2.6	7.3
Helpers		12	0.02	2.6	7.3
Hoistmen	Hoisting of Waste	3	0.02	2.6	7.3
Surface Truck Drivers	Surface Waste Disposal	29	0.04	1.7	3.6
Surface Dozer	Surface Waste Disposal	29	0.04	1.7	3.6
Maintenance Men	Roadway and Ventilation Maintenance	30	0.02	2.9	5.9

* TM-36/8, Appendix B

** Based on 300 day work year. Effects/yr. = 300 x 8 x Man Shifts/Day x Injury Rate/10^6 Man Hours

TABLE 21 Continued

Type	General Activity	Man Shifts* Per Day	Estimated Occupational Hazard** Effects Per Year FTL	N-F Dis.	Accidents
Electricians	Electrical Repair	30	0.02	3.6	7.9
Mechanics	Shop Repair	45	0.02	4.1	12.4
Mechanic	Hoise Maintenance	9	--	0.8	1.9
Utility Men Laborer	Miscellaneous	57	0.06	8.2	14.7
Clerical	Clerical	56	0.01	2.0	4.0
Foreman	Supervising and Drilling Operations	17	0.03	0.6	1.9
Drill Operators and Helpers	Drilling	84	0.13	16.1	29.6
Mechanics	Machine Repair and Maintenance	110	0.11	9.2	25.4
Conveyor Tenders	Backfill Operations	30	0.01	2.9	5.1
Dozer Operator	Backfill Operations	6	--	0.3	0.6
Engineers	Production Management	57	0.05	2.1	5.1
Office Workers	Accounting, Etc.	81	--	1.4	5.5
TOTAL - CYCLE II MINING OPERATION		803	0.667	69.7	154.7

TABLE 22 Estimated occupational hazard effects by job classification breakdown - underground water storage operation.

Type	General Activity	Man Shifts Per Day	Estimated Occupational Hazards* Effects Per Year FTL	N-F Dis.	Accidents
LLW Shaft Crew	Handling LLW in Shaft Area	3			
Forklift Drivers	Move LLW From Shaft to Rooms	4			
Room Laborers	Handle LLW in Rooms	4			
Mechanics	Equipment Maintenance	2			
PWR/BWR Shaft Crew	Handling PWR/BWR in Shaft Area	12			
Transporter Operators	Move PWR/BWR From Shaft to Rooms	16			
Mechanics	Transporter Maintenance	8			
Laborers	Labor in Rooms	8			
Crusher Crew	Crusher Operations	4			
Mechanics	Maintenance	5			
TOTAL - UNDERGROUND WASTE STORAGE OPERATION		66	0.05	4.8	11.1

* Data not subdivided as to craft. Data developed based on analogies between occupations in relevant non-metallic mining operations and anticipated personnel in a nuclear waste repository.

The letters A, B, C, D and E appearing in the matrix diagrams are the designators for the various accident consequences described in the previous section.

11.4 Accident Scenarios and Design Process Criteria

Each of the cells in the accident matrices presented in Figures 42 and 43 defines an accident scenario. The scenario may be identified by Matrix A (Figure 42) or Matrix B (Figure 43) and two grid numbers. Thus, scenario A1,1 refers to an accident resulting from an electrical failure during the transport of men.

The various accident scenarios defined in Figures 18 and 19 are further described in the following paragraphs along with examples of design criteria that may be specified to minimize the attendant hazards.

Accidents:

A1,1: Electrical failure during transport of men. Likelihood is minimized by having secondary electrical supply and standby power generation systems. No radioactive materials involved. No material or human damage expected.

A1,2: Electrical failure during transport of material. Same as A1,1.

A1,3: Electrical failure during transport of waste. Very low likelihood of secondary and standby power also failing. Heat build-up in the areas around a canister will have to be dissipated by increased airflow. Low danger of damage and of escape of radioactive materials into biosphere if duration of failure is excessive.

MATRIX A

WORK ACTIVITY

FAILURE EVENT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19		FAILURE FREQUENCY
1 Electric Failure	A	A	C		A					C	C			A		C	C		A		Low (For Test)
2 Mechanical Failure	E	A	C					C		C	C						C				Low
3 Impact of Meteor	E	E	C	E	E	E	E	E	E	C	C	E	E	E	E	C	D	E	B		Remote
4 Gas Inflow	E	E	C	E	B	E	B	B	E	C	C	B	E	E	B	C	C	E	B		Remote
5 Roof Fall	E	E	C	E	E	E		E	E	D	C	E	E	E	E	C	C	E	E		Frequent
6 Haulage Accident	E	E	D					D						E			D		E		Frequent
7 Transporter Failure			C								D					D	C				Low
8 Canister Failure			E								D					D	D				Remote
9 Drum Failure			C							D	D ✓					D	D				Low
10 Explosive Misfire				E	E																Low
11 Seal Failure	D	D	D						D	D	D		D		D						Frequent
12 Ventilation Failure	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B		Remote/Low
13 HEPA Filter Failure			C							C	C					C	C				Low
14 Premature Room Closure																A		A			Medium
15 Human Failure	B	B	C	B	B	B	B	B	B	D	D	B	B	E	D	D	D	B	B		Medium
16 Communications Failure			C								D						D				Remote
Vehicle Fire			R							D	D					D	D				Low

FIGURE 42 Accident matrix linking failure events and work activities

MATRIX B — WORK ACTIVITY	LOCATION - OPERATING AREAS											
	HOISTS		HEADFRAMES		SHAFTS		SHAFT BOTTOM		Ventilation	STORAGE ROOMS		ACCESS CORRIDORS
	Waste Handling	Production /Service	Waste Handling	Production /Service	Waste Handling	Production /Service	Waste Handling	Production /Service	Airways	Waste Handling	Mining Production /Service	
Transport Men		E				E						
Transport Material		A				E		E				5
Transport Waste	E		E		E		D			D		
Ground Support						E			E	D	B	
[illegible]									E	E	E	
[illegible]								E			B	E
Crusher-Set								B				
Backfill [illegible]										D		D
Drill Holes											E	
LLW Emplacement										C		C
LW Emplacement										D		D
Exploratory Drilling										E	B	E
Construction Of Seals (Stoppings)									B	B		B
Maintenance		E		E		B		B		B	B	B
Removal Of Seals										D		D
Retrieval										D		
Transport Of Retrieved Waste										D		D
Backfill										B		
Repair		B		B		B		B		B	B	

FIGURE 43 Accident matrix linking work activities and locations

A1,5: Electrical failure during continuous miner operation. Likelihood - not infrequent. No radioactive materials involved. Consequences - Class A. Damage to continuous miner could occur from roof falls since it could not be retreated to under supported roof due to the power failure.

A1,10: Electrical failure during LLW emplacement. The immediate consequence is a loss of lighting in the storage rooms. This could lead to collisions, the dropping of drums and then to the release of low level radioactivity into the immediate surroundings of the drums. Likelihood is low since each vehicle has its own independent lighting system.

A1,11: Electrical failure during HLW emplacement. Similar to A1,10. Higher levels of release of radioactivity.

A1,12: Electrical failure during maintenance activities. Loss of lighting. No radioactive materials involved. No material or human effects expected unless compounded by human error since all workers underground are provided with cap lamps which are adequate for lighting of immediate surroundings.

A1,19: Electrical failure during repair activities. Same as A1,12.

Design Criteria for Mitigating Above Hazards:

1. Presence of standby power system with maximum allowable time for repair of standby power generation system or of main electrical system not to exceed a specified number of hours.

2. Canistered waste hoist should be connected to standby power generation system for possible use in an emergency, OR the design should provide for an increase in airflow in the canistered waste shaft, adequate to cool the canister to acceptable temperatures.

Accidents

A2,1: Mechanical failure during transport of men. Rope failure, brake failure, etc. Normal safety mechanisms should minimize risk to human life. Design criteria adequately covered by existing mine standards.

A2,2: Mechanical failure during material transport. No risk of radioactive release or to human life. A remote possibility of a collision between a stalled muck hauling vehicle and a transporter could be designed against by requiring separate transportation routes for canister transport.

A2,3: Mechanical failure during transport of radioactive waste. Possible radioactive release with effects on those present within the site only.

A2,8: Mechanical failure during haulage of backfill material to storage rooms. A possibility exists of a collision between a stalled vehicle and a transporter carrying canistered waste which could result in the release of radioactive materials. Normal traffic control procedures would minimize the risk.

A2,10 & 11: Mechanical failure during waste emplacement could result in damage to the drums or canisters and consequent release of radionuclides.

A2,16: Mechanical failure during retrieval. Same as A2,11. Added possibility that canister has been damaged during storage or as a result of retrieval operations.

A2,17: Mechanical failure during transport of retrieved waste. Similar to A2,3 and A2,16.

Design Criteria for Mitigating Above Hazards:

1. Specifications for canistered waste shaft and transportation to include maximum speeds, braking distances and redundant (dual) braking systems.

2. Transporter may need the capability of manual release of the canister so as to permit transfer to another transporter. Special mobile equipment to effect the transfer may need to be developed.

3. Require dual (back-up) systems for critical components of the vehicles that carry radioactive waste. Specify that drums and canisters should be able to withstand without rupture, shock load levels that may be expected as a result of an accident.

4. The repository design process should include a traffic analysis study so that potential cross-over or congestion points can be

recognized. A signal system may need to be developed and vehicle-to-vehicle communication provided.

Accidents

A3,1-19: Inrush of water: The primary risk is to human life with some risk of radioactive release if activities such as emplacement of waste are effected. The likelihood is low and the risk may be minimized by employing standard operating procedures to contain sudden inrushes of water during exploratory drilling and development. The long-term effect of such an inrush would be more critical to the long term containment capabilities of the repository.

A4,1-19: Gas inflow: The consequences of a gas inflow are similar to those of a water inflow with the added danger that there is a risk of an explosion that would result in the release of radionuclides to the atmosphere. The likelihood of such an event is remote if the repository site has been carefully selected. It may be necessary to follow standard procedures used in gassy mines during the early stages of repository development until the absence of gas at the site has been proven.

Design Criteria for Mitigating Above Hazards

1. Standards such as 30CFR 75.1701 - Abandoned areas, adjacent mines; drilling of boreholes - may need to be developed to minimize the possibility of mining into a brine laden cavity. A program for surveilance and reporting of water quantities

in seepage areas must be developed to assure that increased flows resulting from salt dissolution are promptly detected.

2. The mine layout will have to be such that any inrush of water may be rapidly contained within the same panel through use of water doors between independent working areas.

3. The ventilation system will have to have the capacity to rapidly exhaust suffocating gasses such as CO_2 and N_2 and to direct extra air into affected areas.

Accidents

A5,1-19: Roof falls: These are the most frequent accidents underground and roof falls are nearly always the largest single cause of death in underground mines. Consequences are human death and injury and damage to material and equipment. The possibility of radioactive release exists if the work activity involves the handling of nuclear waste.

Design Criteria for Mitigating Above Hazards

1. The construction of drums and canisters should specify that they should be capable of withstanding a typical roof fall without rupture. An adequate system of roof and rib support should minimize the frequency of roof falls. Existing mine standards may need to be revised to be specific for the control of the bedded salt roof.

2. Seismic design criteria need to be specified.

Accidents:

A6,1-19: Haulage accidents, collisions, etc.

A7,1-19: Transporter failure. See A6 and A2,3.

A8,1-19: Canister failure during transport: Design of the canister should make the probability of such an accident extremely remote. The sequence of events that could lead to the la ge release of radionuclides would be a rope failure during waste handling operations followed by failure of all the braking mechanisms resulting in the canister and cage falling down the shaft. Proper mair.'enance and inspection procedures will minimize the probability of such an occurrence. Shaft and rope inspection procedures used in mines may need to be revised for use in repositcries.

A8,11: Canister failure during emplacement operations. Similar to A6.

A8,16 & 17: Canister failure during retrieval operations: There is a good possibility that the canister could be corroded or wedged in the hole at the time of retrieval. Release of radionuclides during retrieval operations could result. S:,ecific techniques to evaluate the integrity of the canisters prior to retrieval will need to be developed.

A9,1-19: Drum failure: Similar to A8, except that the level of possible release of radioactivity would be much lower than that for canister failure. The extremely improbable sequence of canister/drum failure followed by a failure of the HEPA filters could result in contamination of the biosphere.

Design Criteria for Mitigating Above Hazards:

1. Transporters, drums and canisters to be developed such that containment of radionuclides is assured even under accidental shock loading.

2. Associated measures and standards for the handling, disposal, and retrieval of damaged canisters will need to be developed.

3. Risk analyses of the probability of linked or sequential accidents will need to be made.

Accidents:

A10,4 & 5: Explosive misfires: Very minor use of explosives is expected during the construction and operation of a repository in bedded salt.

Design Criteria for Mitigating Above Hazards:

None specified beyond specification of usual safety standards in handling of explosives.

Accidents:

A11,1-19: Seal failures: Closure in a room where waste has been emplaced could cause the failure of the seal (barrier) that separates the storage room from the fresh airway for emplacement operations. Contamination of the fresh airway with radionuclides could result if a canister in the room has been breached. Since mining operations are provided with fresh air by a separate fresh airway, no danger to the mining side of the repository need be expected.

Design Criteria for Mitigating Above Hazards:

1. Monitoring of the storage room environment after emplacement will be required during operation. The storage rooms should be maintained at a negative air pressure relative to fresh airways so that any leakage would always be from the airways into the rooms and to the placement exhaust. Special seals with particular stiffness and deformability characteristics may need to be developed for use in a repository. The seals will have to be designed to withstand significant corridor closures without losing integrity.

Accidents:

A12,1-19: Ventilation failures: A total failure of the ventilation system would occur as a result of an electrical power outage and failure to activate the standby power generation system. No radioactive release is expected but a prolonged ventilation outage would result in an increased repository temperature.

Local ventilation failures could occur as a result of the failure of barriers and the resulting leakage and recirculation. A vehicle fire in a main airway and human error in shutting off airflow to a working area are examples of other events that could lead to ventilation failure.

A large roof fall in the exhaust corridors could also result in ventilation failure. Periodic inspection and maintenance of these airways would minimize the possibility of such an occurrence. Special procedures to minimize exposure to radiation during such inspections may need to be developed.

Design Criteria for Mitigating Above Hazards:

1. Emergency evacuation systems and procedures will need to be mandated particularly with respect to those working in areas containing nuclear waste.

2. The ventilation system will have to include sufficient capacity to cool the repository back to specified working temperatures following an outage.

3. Remote air quality monitoring devices will need to be installed at all working areas. Operation of critical ventilation doors may be controlled remotely by authorized personnel only. Transporters of canistered waste should be equipped with automatic fire suppression systems.

4. Impact tests of ventilation pipes, underground blower units, etc., should be conducted as part of the design process and impact resistant systems designed and constructed.

Accidents:

A13,1-19: HEPA filter failures: The HEPA filters could lose their filtering efficiency if they are not renewed periodically. This would be true for the filters at the exhaust shaft as well as those underground at the canistered waste shaft. Release of radionuclides to the biosphere would be possible if there was an accident underground that caused release into the mine environment.

Design Criteria for Mitigating Above Hazards:

1. Proof testing of filter systems should be required during the design process.

2. Standards should be developed for changing and disposing of spent filters and for monitoring to identify premature losses of filter efficiency.

Accidents:

A14,1-19: Premature room closure as a result of creep could make it impossible to retrieve canistered waste. Backfilling over the waste may also not be possible. A certain amount of such loss due to room closure should reasonably be expected in a repository in bedded salt. No accident risks evolve from primary or secondary creep phenomena. Structural failures would result in areas experiencing tertiary creep; in the worst cases, these would be similar to roof falls.

Design Criteria for Mitigating Above Hazards:

1. A thermal/mechanical analysis will be necessary as part of the design process. Periodic monitoring must be specified to assure that structural performance is as envisioned during repository design.

Accidents:

A15,1-19: Human Failures: A risk to human life as a result of human failure is associated with every activity in a repository. Only those activities associated with the handling or storage of nuclear waste carry a risk of release of radioactive materials as a result of human errors.

Design Criteria for Mitigating Above Hazards:

1. Standards for the training and certification of all workers, particularly those involved in the handling of nuclear waste must be developed as part of the design process.

2. The design of appropriate safety interlocks will need to be specified for all machinery involved in the handling of nuclear wastes.

Accidents:

A16,3,11,17: Communications failures: A release of radionuclides could result from the misunderstanding of signals during the lowering and raising of nuclear waste. The probability of release would be extremely low since the canister or drum would also have to be ruptured as a result of the accident. Container design has already been discussed in A8 and A9.

Design Criteria for Mitigating Above Hazards:

1. Training of workers should include use of communications systems during normal and extraordinary circumstances.

2. Backup systems for use during emergencies must be included in the repository design.

Accidents:

A17,1-19: A vehicle fire during the transport and handling of nuclear waste could result in the release of radionuclides into the mine environment. Contamination of the fresh air supply with noxious gases could effect the health and safety of all persons downstream.

Design Criteria for Mitigation of Above Hazards:

1. All transporters should be equipped with automatic fire suppression equipment.

2. Ventilation layouts should have built-in design capabilities that would permit the speedy isolation of any part of the repository from the others and permit circulation of additional air to rapidly exhaust smoke and fumes.

Accidents:

B1,2 & 1,6: Accidents during the transport of men from surface to the underground shaft station. No radioactive materials are involved. Likelihood - low. Accidents could be caused by rope failure, mechanical failure, etc. Design criteria covered by existing mine standards.

B2,2, 2,6, 2,8, & 2,12: Accidents during the transport of material. No radioactive materials are involved (except in the case of a collision with a transporter carrying radioactive waste. Such an event is normally designed against by traffic control procedures). Likelihood - medium.

B3,1, 3,3, 3,5, 3,7 & 3,10: Accidents during the transport and handling of nuclear waste. Typical accidents could be dropping canister down the shaft, damaging canister during transfer operations, collisions, roof falls, vehicle fire, etc. Likelihood - not infrequent.

Design Criteria for Mitigation of Above Hazards:

1. Develop repository traffic flow analyses and traffic control plans.

2. Specify canister design requirements. Require safety interlocks during all transfer operations. Specify transporter design requirements.

Accidents:

B4,6 & 4,11: Roof and rib falls, shaft liner failure, premature closures, etc. Accidents would not result in any release of radionuclides. Likelihood - frequent/low. Existing mine standards are adequate.

B4,9: Roof fall in ventilation airways. No release of radionuclides need be expected. Operational activities may need to be curtailed. Likelihood - medium.

B4,10: Roof fall during placement operations. Some danger of escape of radionuclides from damaged drums. Likelihood - low if standard procedures of roof inspection and sealing in work areas are followed.

Design Criteria for Mitigation of Above Hazards:

1. Perform detailed thermal/mechanical and structural analyses during repository design. Specify inspection procedures and monitoring to identify excessive closure rates.

2. Revise existing mine standards to specify inspection procedures in return airways.

Accidents:

B5,9, 5,10, & 5,11: Accidents during continuous miner operation. Likelihood - frequent. No radioactive materials involved. Safe operative procedures adequately covered in existing mine standards.

B6,8, 6,11, & 6,12: Haulage accidents. See A6.

B7,8: Accident at crusher station such as worker falling into ore bin. No radioactive material involved. Safety procedures adequately described in 30 CFR.

B8,10, & 8,12: Haulage accident during backfill operations. Some risk of collisions with transporters carrying radioactive waste.

B9,11: Accident during drilling of canister holes. No radioactive material involved. Normal mine safety procedures may be followed.

Design Criteria for Mitigation of Above Hazards:

1. Specify training and certification programs for all equipment operators.

2. Specify operational and traffic control to minimize risks.

Accidents:

B10,10 & 10,12: Accident during LLW emplacement. See A9,3 and A9,10.

B11,10, & 11,12: Accident during HLW emplacement. See A8,3, and A8,11.

B12,10, 12,11 & 12,12: Accident during exploratory drilling. See A3 and A4.

B13,10 & 13,12: Accidents during construction of ventilation barriers. Adequately covered in 30 CFR.

B14,-: Accidents during aintenance activities. See A-,14.

B15,10, 15,12, 16,10, 17,10 & 17,12: Accidents during retrieval operations. See A-,16 and A-,17.

B19,-: Accidents during repair operations. See A-,19.

Design Criteria for Mitigation of Above Hazards:

As previously listed.

Accident:

B18,10: Accidents during backfill operations. No danger of release of radioactive materials. Some occupational risk of exposure to radioactivity.

Design Criteria for Mitigation of Above Hazard:

1. Standards specifying backfill operational procedures in waste storage rooms will need to be developed.

12.0 POST SEALING PERFORMANCE ANALYSIS

12.1 Introduction

The purpose of this chapter is to present numerical values of parameters to be used in analyzing the performance of a repository, to discuss the basis upon which those numerical values are chosen, and to discuss the regulatory constraints as presented in the Advance Notice of Proposed Rulemaking (10CFR60) of May 13, 1980.

The prediction of repository performance in its post-sealing phase must necessarily rely upon numerical models. It is through such models that insight may be developed regarding the relative importance of processes and parameters and that an examination of the sensitivity to variations in parameters may be made.

While it is true that no single model now exists of the complete repository system the use of simple models is required for the understanding of repository performance.

12.2 Regulatory Constraints

In this section we will present excerpts from the Advance Notice of Rulemaking (10CFR60) of May 13, 1980 and discuss their relationships with the prediction of repository performance in the post closure phase.

In discussing the nature of the problem regarding a geologic repository, the proposed 10CFR60 states:

> *The operational life of a geologic repository for the disposal of HLW quite naturally divides into three periods-the period of*

construction and emplacement of the wastes: the period during which the shortlived fission products dominate the hazard posed by the wastes; and the long term during which the hazard is dominated by the very long-lived isotopes including the actinides. The technical criteria must reflect the different physical conditions of the repository during these periods and be responsive to the specific nature of the hazard posed by the wastes.

The second period begins following closure of the repository, and will persist for the time that the relatively short-lived fission products dominate the hazard. During this time there will be substantial heat output from the wastes which if not properly accommodated by site selection and engineering could compromise the integrity of the repository. In addition, the chemical species and makeup of the emplaced wastes are rapidly changing due to radioactive decay. Criteria applicable to this period will focus on selecting sites and generating designs to accommodate these two major features.

By the time the short-lived fission products no longer dominate the hazard, the wastes are no longer generating significant amounts of heat. Moreover, the short-lived elements have for the most part decayed away and the chemical properaties of the waste have greatly stabilized - generally dominated by the actinides. However, for this final period it would be imprudent to rely on engineering to contain the emplaced wastes; and final protection is achieved by the ability of the geologic setting to inhibit migration of the wastes leached from the waste form in a controlled manner. Properties which affect leaching of the waste and which affect transport of the wastes such as fractures, porosity, sorption, hydraulic gradient, and thermal gradient, and determination of the long-term stability of the geologic setting will dominate the criteria addressed to this period.

Some of the considerations for the development of technical criteria for the disposal of high level waste in geologic repositories are presented below from the proposed 10CFR60:

(1) Systems Approach. The term "systems approach" relates to the set of natural and engineered barriers which would function to contain and isolate the waste from the biosphere for the periods of time required, to increase the degree of the Commission's confidence that indeed such containment and isolation would be achieved, or to permit appropriate and conservative analyses to be performed which would form the decision basis.

It is evident that for a geologic repository, the geologic setting must be one barrier. In considering whether there should other barriers, a key question which needs to be answered is whether it is prudent, in view of the nature of the problems and the uncertainties involved, to rely on the geologic setting alone to accomplish the functions stated above. The state-of-the-art in the earth sciences is such that all of the uncertainties associated with these functions cannot be resolved through consideration of the geologic setting.

It is appropriate, therefore, to consider how engineering-in the broadest sense of anything used to effect a purpose - might be used to compensate for, reduce, or eliminate at least some of the uncertainties inherent in reliance on the geologic setting alone. Engineering can be used to narrow the extent of geologic processes which need to be considered in the rulemaking and licensing processes; that is engineering can be used to bound and/or diminish the importance of certain geologic processes. Engineering also can be used to make the containment of emplaced waste as insensitive as possible to potential changes in the geologic environment. For example, the use of buffering materials to retain radionuclides is one possible way to compensate for uncertainties in the sorption capabilities of a particular medium and site.

Given the nature of the problems, as discussed earlier, the Commission staff has identified the following as composing the set of three primary barriers of the waste disposal system: the geologic setting; the design and configuration of the repository, including the waste emplacement scheme and engineered barriers; and the waste package.

(2) Use of Minimum Performance Standards for Major Regulatory Elements. Determining the expected evolution of a geologic repository in time is the key to understanding the consequences of emplacing wastes in a repository. Such expectations of the effects of pertubations and changes, both natural and man-caused to the hydrologic environment, serves to identify the kinds of events, including institutional failures, which might cause a radioactive release to the biosphere. Assessment of such events that reasonably can be assumed to occur and their likely consequences permits the identification of the "credible" events which should be considered in the design of the repository and evaluated in rulemaking and licensing decisions: Identification of these "credible" events permits development of performance requirements for both the natural and engineered barriers to assure that such events are avoided where possible for their consequences mitigated when these performance requirements are met. Such describes the deterministic approach the Commission staff has been taking in development of the performance requirements for HLW disposal in geologic repositories, and defense-in-depth approach to provide assurance and confidence that the EPA standard can be met.

(3) The Nature of the Major Regulatory Elements. The regulatory elements selected should be either important to safety, that is, contain and isolate the waste from the biosphere for the period of time required, or contribute to confidence in the functioning of the repository system or individual components. As discussed above, the repository is conceived as a system of multiple barriers, both natural and engineered. The two most important attributes of the natural barriers, are that the site should be geologically simple and stable so that the site can be easily understood and so that there can be confidence that the ability of the site to contain and isolate the wastes will remain viable for long times.

The three most important attributes of the engineered barriers must be their compatibility with the geologic and hydrologic characteristics of the site so that the engineered barriers will have the least adverse impact on the site's ability to retain the emplaced wastes; their insensitivity to any changes in the site characteristics so that there can be confidence in the predictability of their performance over timer and their ability to complement the performance of the site so as to increase confidence in overall repository performance to supplement the performance of the site-where possible-to increase the overall margin of safety.

Perhaps one of the most important considerations regarding the performance of a geologic repository is stated in 10CFR60 as part of the nature of the problem; that is, the fact that both the physical processes and the parameters important to those processes are uncertain:

If there is to be confidence that wastes disposed in a geologic repository will not pose a significant hazard to the health and safety of future populations, then two factors which pose fundamental difficulties must be addressed satisfactorily. First, geologic disposal is an entirely new enterprise - no experience exists with geologic disposal. Second, there will be no opportunity to observe behavior over the long term - the decisions to close the repository in effect will be a statement of its expected behavior based upon inference, deduction, and extrapolation from results of tests and experiments carried out for a comparatively short period and upon predictions of future geologic, hydrologic, and climatologic conditions based upon observations of the past. These facts impose very definite constraints as to how confidence is achieved that the expectation of behavior will match actual behavior over the long term. These constraints fairly clearly define the items of uncertainty which arise because qualitative descriptions and models necessarily approximate nature rather than exactly describe or predict nature; uncertainties which arise, because the data used as input to those descriptions and

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(b) Required barriers. In the design and construction of a geologic repository, the Department shall utilize (1) an engineered system including waste package and an underground facility, and (2) the geologic environment.

(c) Performance of required barriers and engineered systems. (1) Waste Packages[2]. The Department shall design waste packages so that there is reasonable assurance that radionuclides will be contained for at least the first 1,000 years after decommissioning and for as long thereafter as is reasonably achievable given expected processes and events as well as various water flow conditions including full or partial saturation of the underground facility.

(2) Underground facility. The Department shall design the underground facility to provide reasonable assurance of the following:

(i) An environment for the waste packages that promotes the achievement of 60.111(c)(1) above under conditions resulting from expected processes and events.

(ii) Containment of all radionuclides for the first 1,000 years after decommissioning of the geologic repository operations area and as long thereafter as is reasonably achievable, assuming expected events and processes and that some of the waste dissolves soon after decommissioning.

(3) Overall performance of the engineered system after containment. The Department shall design the engineered system to provide reasonable assurance that:

(i) Starting 1,000 years after decommissioning of the geologic repository operations area, the radionuclides present in HLW will be released from the underground facility at an annual rate that is as low as reasonably achievable and is in no case greater than an annual rate of one part in one hundred thousand of the total activity present in HLW within the underground facility 1,000 years after decommissioning assuming expected processes and events.

(ii) Starting at decommissioning radionuclides present in TRU waste will be released at a rate that is as low as reasonably achievable and is in no case greater than one part in one hundred thousand of the total activity present in TRU waste within the underground facility at the time of decommissioning assuming expected processes and events.

(4) Performance of the geologic environment. (i) The Department shall provide reasonable assurance that the degree of stability exhibited by the geologic environment at present will not significantly decrease over the long term.

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[2] Sections 60.111(c)(1) and 60.111(c)(2) apply only to HLW.

(ii) The Department shall provide reasonable assurance that the site exhibits properties which promote isolation and that their capability to inhibit the migration of radionuclides will not significantly decrease over the long term.

(iii) The Department shall provide reasonable assurance that the hydrologic and geochemical properties of the host rock and surrounding confining units will provide radionuclide travel times to the accessible environment of at least 1,000 years assuming expected processes and events.

The only method of determining the probability of meeting the above mentioned numerical criteria is through the use of numerical models. The best of expert opinion will not serve to quantify the performance of a geologic waste repository. With the use of highly sophisticated numerical models and relevant physical measurements, quantitative performance may be determined.

Uncertainties will exist in both the models and in the data used in those models. Expert opinion will serve to assist in the determination of data and model uncertainties, but again will not be of use in determining the extent to which those uncertainties will propagate throughout the repository system performance analysis.

If assurance must be given that a repository will perform within specified numerical limits, there exists no option other than the development of complete, competent models and data, used by investigators who understand the physical system as well as the limitations of their tools.

12.3 Selection of Parameters for Repository Performance Modeling

In the sections that follow, we present parameter values to be used in the prediction of the performance of a geologic repository. The values are taken from the open literature and represent what we consider to be reasonable estimates that may be used for preliminary models.

Corresponding values that will be presented to NRC in support of a license application will be site specific and may differ from the values suggested here; therefore, results obtained from the parameters suggested here will be of value primarily in understanding the nature of the results that may be obtained in modeling repository performance.

12.4 Geologic Parameters

12.4.1 Generic Stratigraphy for Performance Modeling

As discussed in Chapter 1, while each of the bedded salt-bearing sedimentary basins in the coterminous United States has its own distinct geologic characteristics, these basins may be placed into three groups for purposes of generic performance modeling. These groups are the following:

- Basins in which predominantly carbonate sedimentation preceeded and followed deposition of the salt-bearing sequence.
- Basins in which clastic sedimentation is predominant.
- Continental basins of Tertiary and Quaternary age in which thick but laterally restricted salt deposits appear to have formed by cyclic filling and evaporation of playa lakes.

Studies to date for potential repository sites have focused on sedimentary basins of the first two types since these contain laterally extensive salt deposits and appear to provide the most tectonically stable environments.

For purposes of generic far-field performance modeling, the generalized stratigraphy of the Michigan Basin (Figure 8 repeated as Figure 44) and the southeastern New Mexico area (Figure 7 repeated as Figure 45) have been selected

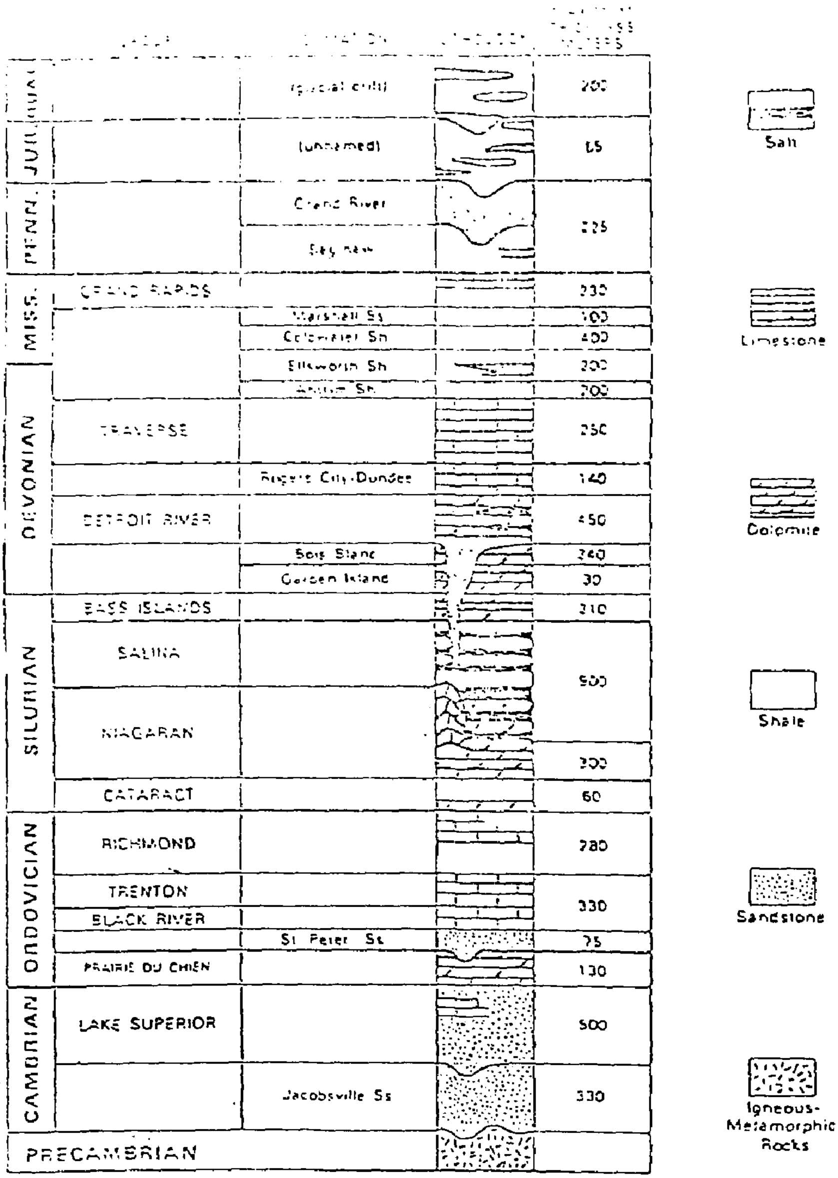
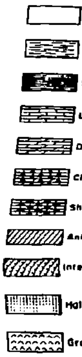
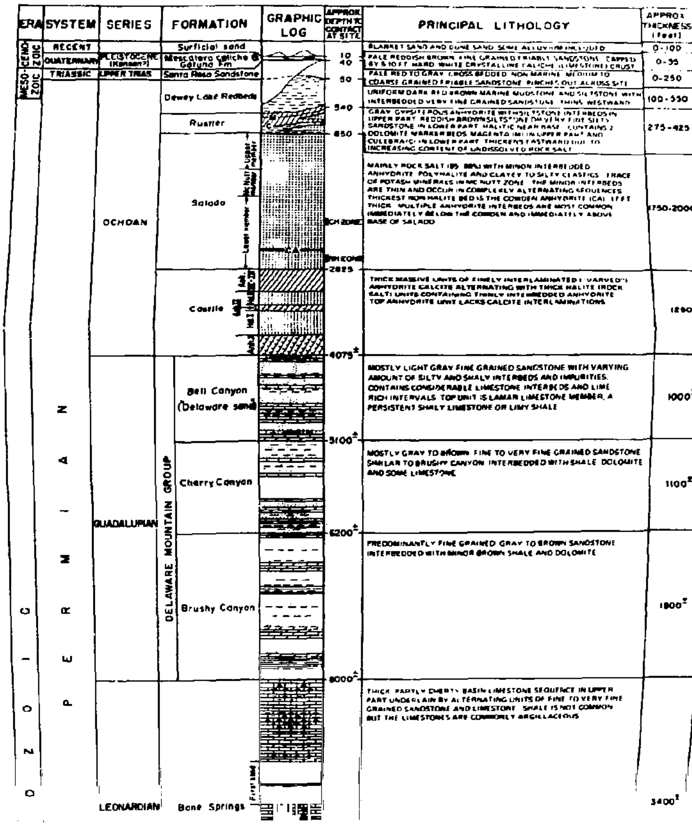


FIG.44 Stratigraphic succession in Michigan Basin (after Michigan Geological Society, 1964).

EXPLANATION

LITHOLOGIC SYMBOLS





REFERENCES:

1. Anderson, 1978
2. Anderson, et al, 1972
3. Brokaw, et al, 1972
4. Foster, 1974
5. Griswold, 1977
6. Meyer, 1966
7. Sipes, Williamson and Aycock, 1976

NOTE:

For complete citations, refer to reference list for chapter 4

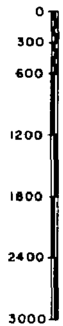
Granitic rocks

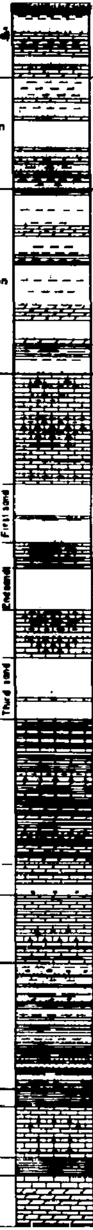
REFERENCES:

1. Anderson, 1978
2. Anderson, et al, 1972
3. Brokaw, et al, 1972
4. Foster, 1974
5. Griswold, 1977
6. Meyer, 1966
7. Sipes, Williamson and Aycock, 1976

NOTE:

For complete citations, refer to reference list for chapter 4





Era	System	Series	Group	Formation	Depth	Description	Thickness
PALEOZOIC	PERMIAN	GUADALUPIAN	DELAWARE MOUNTAIN GROUP	Bell Canyon (Delaware sand)	5100±	CONTAINS CONSIDERABLE LIMESTONE INTERBEDS AND LIME-RICH INTERVALS TOP UNIT IS LAMAR LIMESTONE MEMBER A PERSISTENT SHALY LIMESTONE OR LIMY SHALE	1000±
				Cherry Canyon	6200±	MOSTLY GRAY TO BROWN FINE TO VERY FINE GRAINED SANDSTONE SIMILAR TO BRUSHY CANYON INTERBEDDED WITH SHALE DOLOMITE AND SOME LIMESTONE	1100±
				Brushy Canyon	8000±	PREDOMINANTLY FINE GRAINED GRAY TO BROWN SANDSTONE INTERBEDDED WITH MINOR BROWN SHALE AND DOLOMITE	1800±
		LEONARDIAN		Bone Springs (First sand, Second sand, Third sand)	11400±	THICK PARTLY CHERTY BASIN LIMESTONE SEQUENCE IN UPPER PART UNDERLAIN BY ALTERNATING UNITS OF FINE TO VERY FINE GRAINED SANDSTONE AND LIMESTONE SHALE IS NOT COMMON BUT THE LIMESTONES ARE COMMONLY ARGILLACEOUS	3400±
		WOLFCAMPIAN		"Wolfcamp"	12800±	DARK COLORED BASIN LIMESTONE AND DOLOMITE WITH INTERBEDDED SHALE SANDSTONE IS SCARCE SHALE AND CARBONATE CONTENT ROUGHLY EQUAL MAY CONTAIN A FEW HUNDRED FEET OF LITHOLOGICALLY SIMILAR UPPER PENNSYLVANIAN STRATA (CISCO AND CANYON EQUIVALENTS)	1400±
	?	?		?			
	PENNSYLVANIAN	DESMOINESIAN? DERRYAN?		Strawn	13100±	DOMINANTLY LIMESTONE WITH SOME CHERT AND INTERBEDDED SHALE IN UPPER PART DOMINANTLY LIGHT GRAY MEDIUM TO CONGLOMERATIC SAND IN LOWER PART	300±
		MORROWAN?		Atoka	13800±	PRINCIPALLY LIMESTONE CHERTY IN MIDDLE PART ALTERNATING WITH DARK SHALE	650±
				Morrow	15000± (UNCONFORMITY)	MOSTLY FINE TO COARSE OR CONGLOMERATIC SANDSTONE WITH DARK GRAY SHALE SOMEWHAT LIMY SEQUENCE NEAR TOP INTERBEDDED WITH SANDSTONE IS REFERRED TO AS MORROW LIME	1250
	MISSISSIPPIAN	UPPER MISS.		Barnett Shale		LIGHT YELLOWISH BROWN LOCALLY CHERTY LIMESTONE OVERLAIN BY DARK BROWN SHALE (BARNETT)	650±
		LOWER MISS.			15600±		
	DEVONIAN	UPPER DEV.		Woodford Shale	15800± (UNCONFORMITY)	BLACK ORGANIC SHALE PYRITIC	175
						LIGHT COLORED CHERTY DOLOMITE CONTAINS TWO LIMESTONE INTERVALS IN UPPER HALF OF SECTION	

SITE GE

SOUTHWESTER

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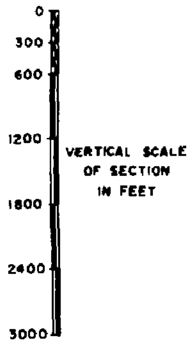
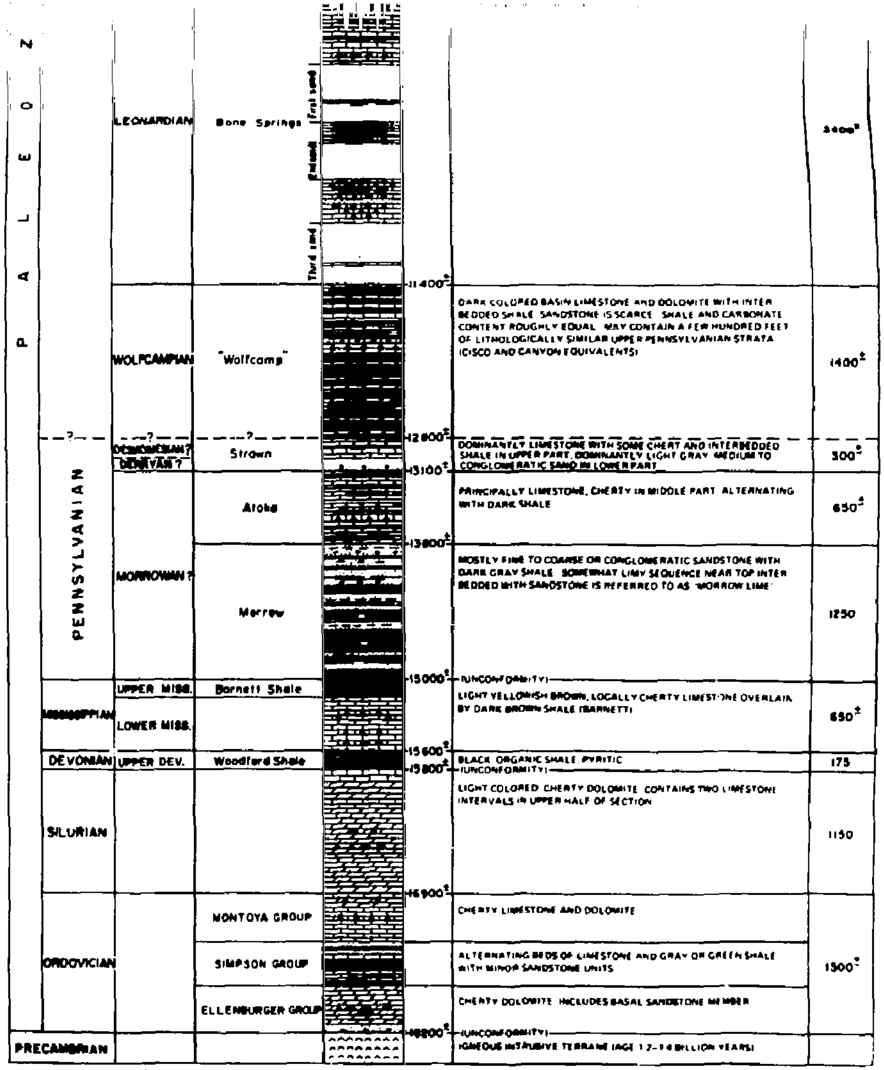
NOTE:

For complete citations, refer to reference list for chapter 4





SITE GEOLOGIC COLUMN

SOUTHWESTERN NEW MEXICO (WIPP) SITE

FIG. 45

(From Powers and others 1978)

as representative of the carbonate and clastic settings respectively. These stratigraphic section show the complexities of real sedimentary sequences. As noted in Chapter 1, some simplifying assumptions will be necessary before they can be used in performance models. Such simplifications must be made by a technically qualified group which includes the geologic, geomechanical and modeling disciplines.

Figure 46 presents the detailed log of a portion of borehole ERDA-9 cored by the U.S. Geological Survey at the southeastern New Mexico (WIPP) site (Powers and Others, 1978). The portion of the core log selected extends from the 1700-2510 foot (520-766 meter) depth and is offered as representative of a near-field stratigraphic sequence through a potential nuclear waste repository horizon. The sequence presented extends about 100 m above and below a potential host horizon at the WIPP site.

As Figure 45 illustrates, while a potential repository horizon and its enclosing strata can consist of relatively pure halite [(1)], various interbeds will be present and must receive consideration during performance modeling. As with far-field modeling, their incorporation will be a matter of informed judgement requiring input from several professional disciplines.

Representative values for the thicknesses of potential repository horizons in bedded salt range from 60 m, the minimum acceptable (Wagoner and Steinborn, 1979) to 100 m. A few thicker salt sequences may be found.

Available data indicate that for near field modeling bedded salt deposits may be regarded as laterally homogeneous. For far-field modeling, effective lateral homogeneity should be assumed over distances of as little as

(1) Powers and others (1978) indicate that the argillic fraction of the halite beds shown on the log is small and usually amounts to only a few percent of the total rock weight.

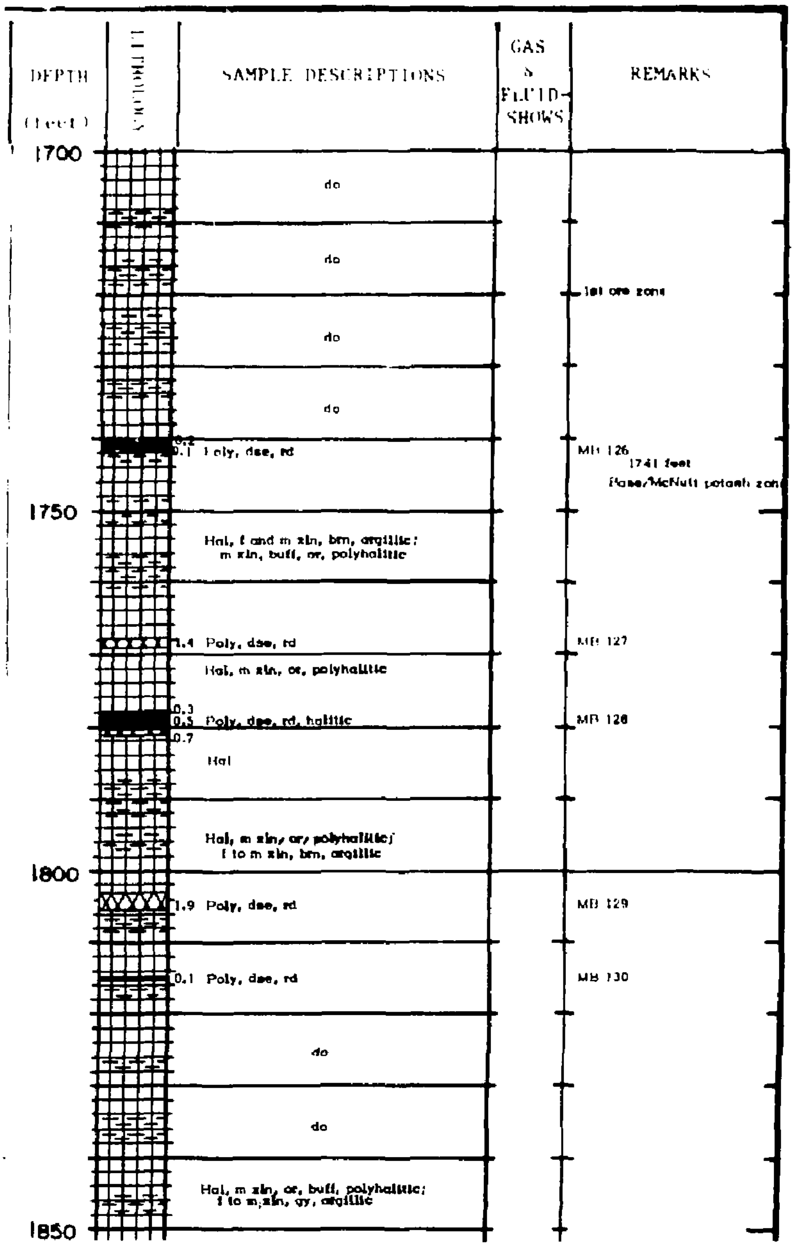


FIG. 46: Detailed stratigraphy through potential repository horizon (Powers and others, 1978)

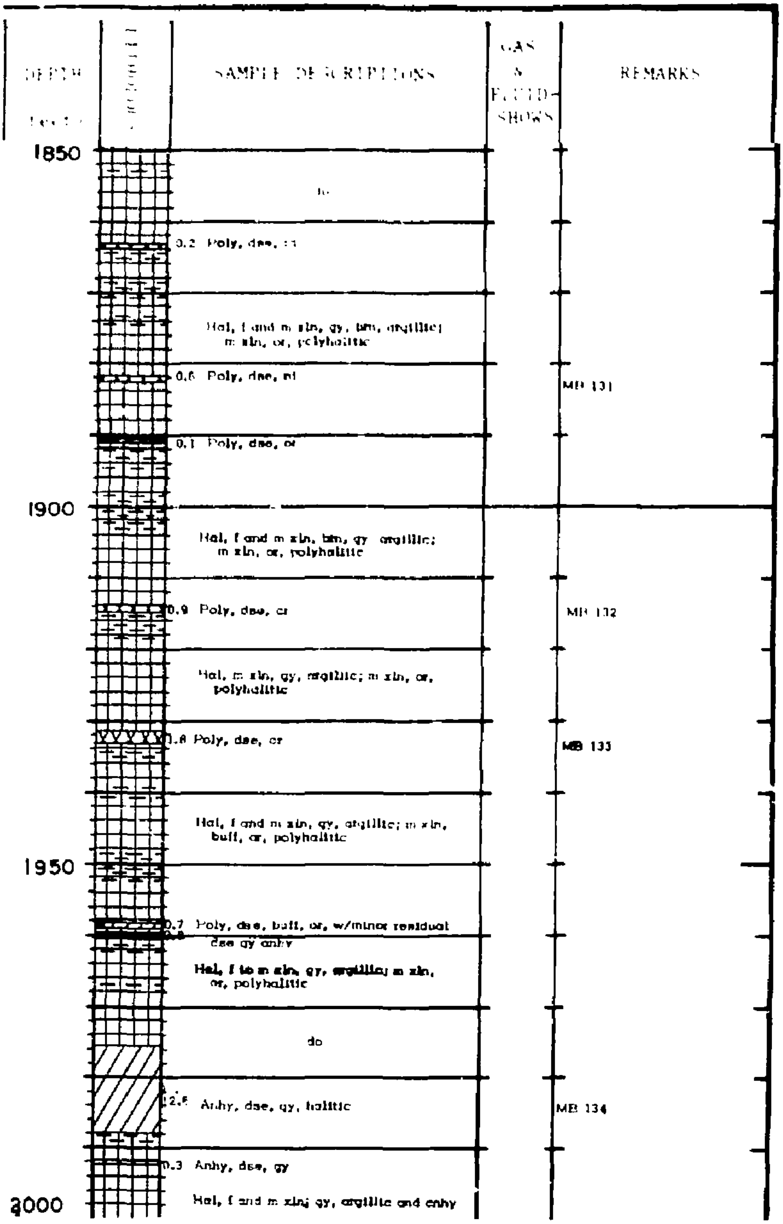


FIG. 46: Deatiled stratigraphy through potential repository horizon (Powers and others, 1978) - Continued

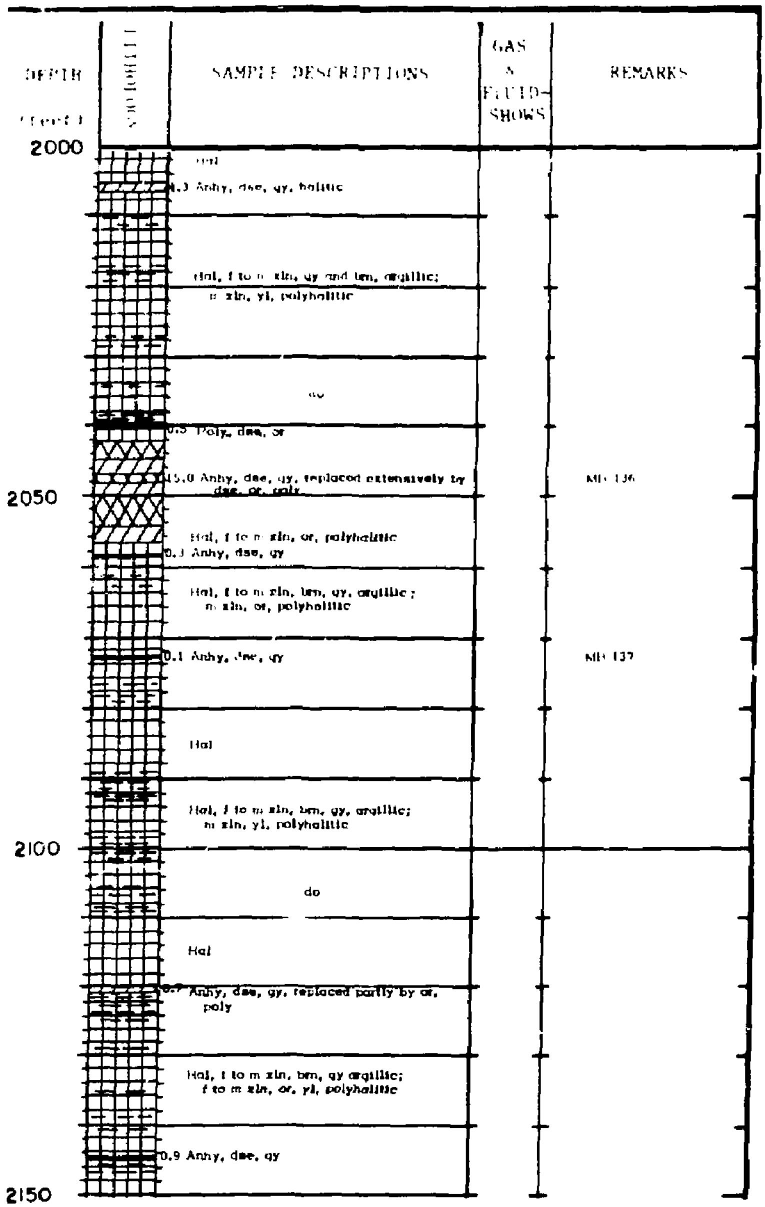


FIG. 46: *Detailed stratigraphy through potential* repository horizon (Powers and others, 1978) - Continued

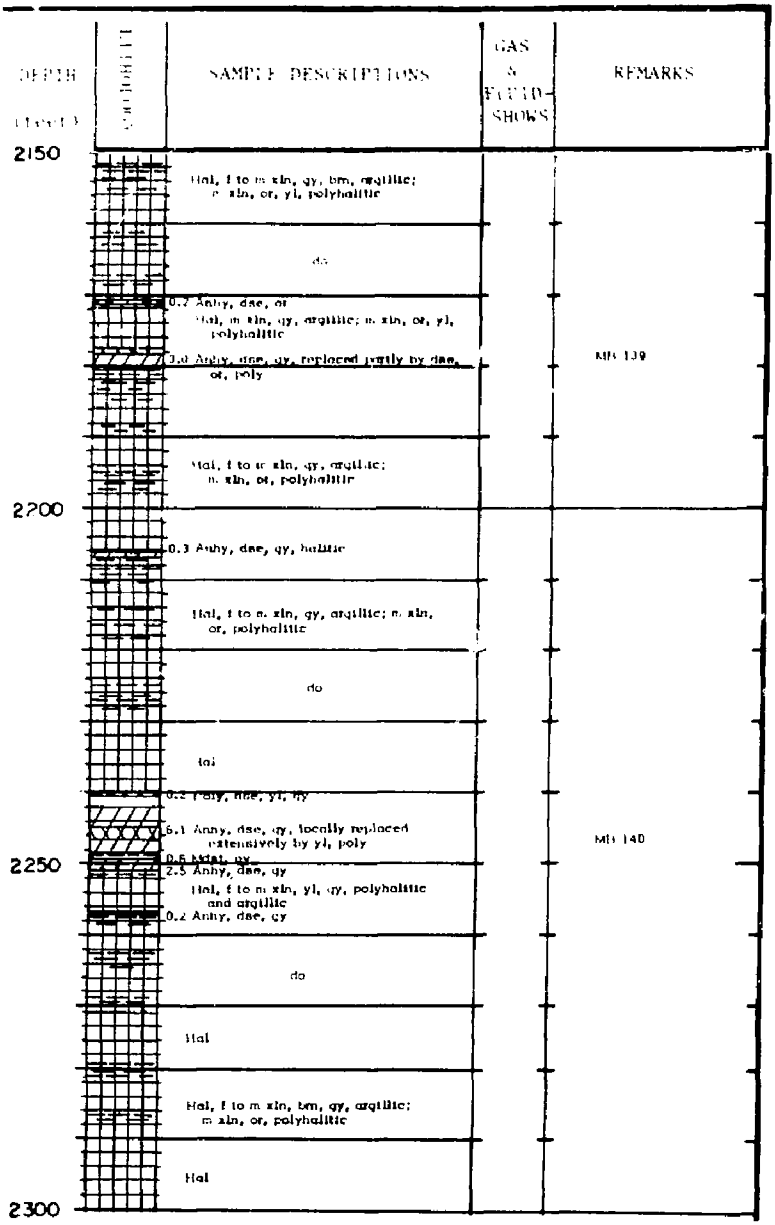


FIG. 46: Detailed stratigraphy through potential repository horizon (Powers and others, 1978) - Continued

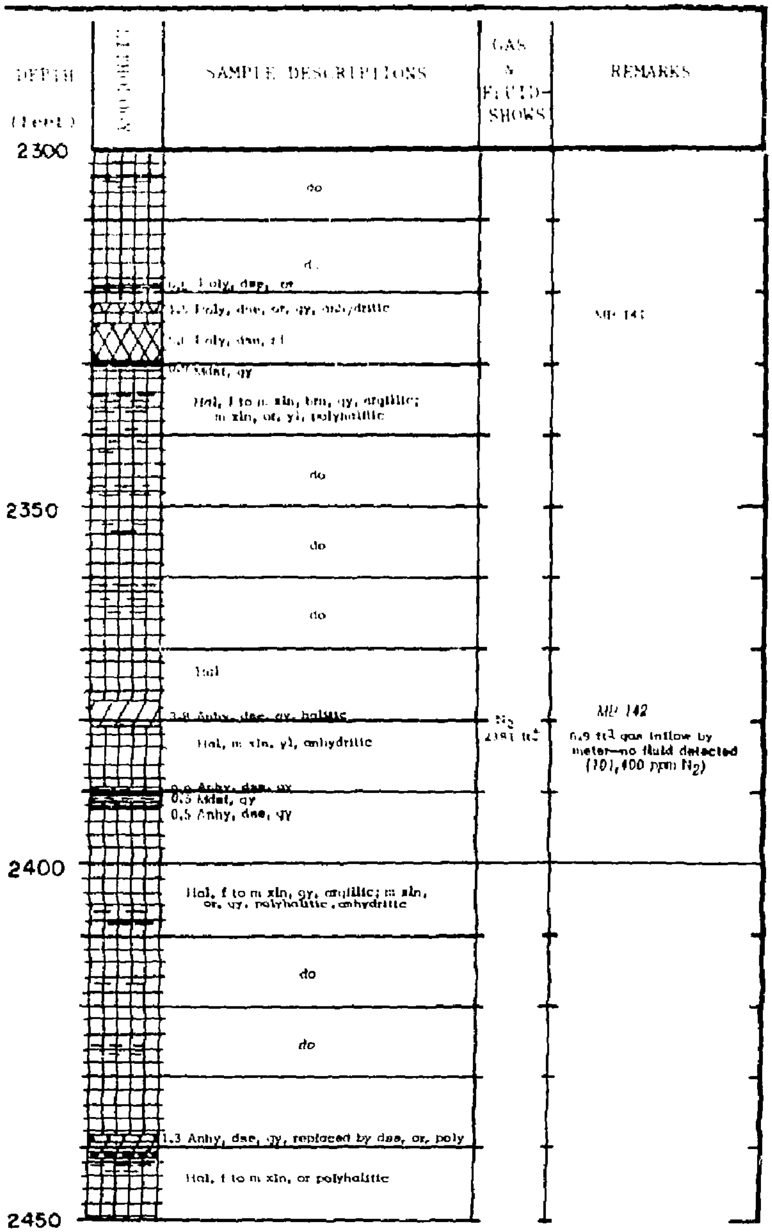


FIG. 46: Detailed stratigraphy through potential repository horizon (Powers and others, 1978) - Continued

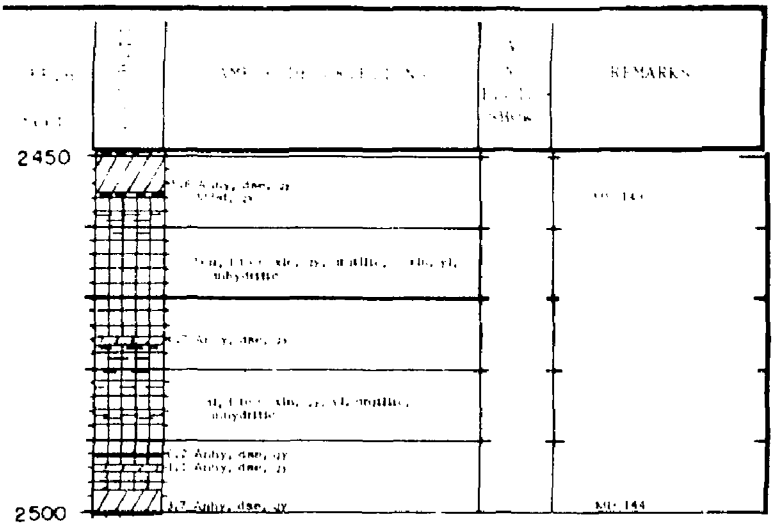


FIG. 46: Detailed stratigraphy through potential repository horizon (Powers and others, 1978) - Continued

one km near basin margins up to 10 km in all directions from the repository site within the cores of salt-bearing sedimentary basins. If facies [illegible] prove significant to far-field models, the bedded salt deposits can be assumed to interfinger with a rock sequence consisting of equal parts of dolomite, anhydrite and mudstone. It must be emphasized that geologic conditions at an actual candidate site and its environs can be expected to vary significantly from the generic average.

General Structural Considerations for Performance Modeling

As noted in Chapter 2, bedded salt deposits are relatively simple structural systems. Local features should be expected but the overall structural setting will be characterized by *uniformity* as contrasted with complexity. Based upon literature descriptions, representative values for structural properties of interest for performance modeling are presented in Table 23.

Igeneous dikes and sills are a *minor* feature in bedded salt basins and probably can be avoided during repository siting. So called "*mud plugs*" are also minor features and are reported to be confined to potash sequences (GAI, 1979a) which would be avoided in selecting candidate repository horizons. Therefore, these rare geologic features do not appear to require characterization for generic performance modeling.

Seismic Hazards in Performance Modeling

The potential seismic hazard for a nuclear waste repository in bedded salt would have two components. The first component would be earthquakes

TABLE [illegible]

[illegible]

Structural Property	Salt	Associated Strata	Comments
[illegible]	[illegible]		
[illegible] Features	[illegible] within repository horizon. Absent to present [illegible] above repository horizon.		
Salt Flowage Structures	[illegible] thickness changes	No thickness changes	
Fracture Spacings	30m-large	0.3-2m	large - essentially unjointed within repository volume
Bedding Plane Spacings	0.3-3m	0.01-3m	
Faults	1-6m vertical displacements 0.5-3 km. spacings		Inactive, fault planes healed with salt, dip 70°-90°
Induced Fracture Zones	See Table 2		

generated by active faults or tectonically active structures. The second component would be a diffuse background seismicity of unknown geologic origin.

Since, as discussed in Chapter 3, bedded salt deposits are largely located outside of seismically active areas, it is likely that candidate sites in bedded salt could be found in areas remote from active faults or tectonically active structures. Bedded salt sites could be shaken by earthquakes generated by distant active faults and or structures but the effects would be highly site specific and would depend upon such features as earthquake magnitude, distance to the earthquake source, site response characteristics and operative attenuation laws.

Because of the high uncertainty and site specific nature of the critical components of seismic hazard, it is deemed inappropriate to provide a generic design basis or safe shutdown earthquake for a nuclear waste repository in bedded salt.

Similarily, the second component of the seismic hazard, difuse background seismicity, is of highly uncertain character and little understood. In general, earthquakes generated by the seismic background are of low magnitude. However, the actual degree of hazard posed by such events should be included in the detailed seismic hazard analysis provided for a candidate site.

Gas Hazards in Performance Modeling

Various gases are present in bedded salt deposits and could be encountered during repository mining. Such encounters could lead to mining-type accidents and a nuclear waste repository in bedded salt should be treated as a gassy mine until sufficient experience is gained to support a definite classification.

At present, there is [illegible] quantitative data available regarding [illegible] is therefore likely to be highly site specific.

[illegible] Thermal and Mechanical Parameters

The physical properties needed to perform thermal analyses of a geologic repository are the thermal conductivity, the density and the specific heat of each definable geologic material. For stratigraphic layers composed of several materials the density and specific heat may be calculated on a relative mass weighted basis, however, this is not acceptable for determining the effective thermal conductivity of a mixed material.

The thermal conductivity is in general temperature dependent. This dependence need not be taken into account unless the material will undergo a significant temperature change, such as that occurring in the salt near the heat source.

Thermal properties are dependent upon the moisture content of all geologic materials. As before, with mixed materials, density and specific heat may be mass averaged, but the conductivity may not. In materials with pores containing water, the mechanism of heat conduction is in reality a combination of conduction between grains combined with conduction through water and convection of the water in interconnected pores.

Table 24 lists the thermal properties of salt and associated rock types. The values quoted are general in nature and should serve only for preliminary calculations of repository performance.

TABLE [illegible]

Thermal [illegible] and Associated [illegible] Types

[illegible]	[illegible]ensity (Mg/m[illegible])	[illegible] Heat ([illegible])	Thermal [illegible] ([illegible])
[illegible]	[illegible]	[illegible]	[illegible]
			100 4.2[illegible]
			[illegible]
			[illegible] 3.11
			[illegible] 2.4[illegible]
			400 2.0[illegible]
[illegible]	1.[illegible]	.84-1.05 Assumed	1.5-3.5
[illegible]	[illegible]	.84-1.05 Assumed	?
Dolomite	[illegible]	.84-1.05 Assumed	3-5
Limestone	1.6-3.4	.84-1.05 Assumed	2-3
Anhydrite	2.2-3.4	.84-1.05 Assumed	5-6

[illegible] the [illegible] [illegible] and the [illegible] [illegible] materials the relationships between stress, strain, time and temperature.

[illegible] be reasonably expected that, for all other materials associated with bedded salt, except [illegible] and [illegible], their response will be essentially elastic. When site specific materials are chosen, the assumption of essentially elastic behavior will have to be verified.

[illegible] discussed at length the behavior of salt and reached the conclusion that no single relationship has been agreed upon regarding its behavior under the conditions to be expected in a geologic repository. For relatively short times, perhaps during the operational life of the repository, it may be reasonable to assume that primary creep will be the controlling factor in determining the closure rates of the storage rooms and associated drifts. Fo[illegible]ger times, it can also be assumed that secondary, or steady-state cree[illegible] control the behavior of the salt.

Witho[illegible] specific testing over a long period of time we suggest the following relationships for the preliminary modeling of the behavior of salt:

Primary Creep (Lomenick and Bradshaw, 1969)

$$\dot{\varepsilon}_p = 1.278 \times 10^{-44}\ T^{9.5}\ \sigma^{3}\ t^{-0.7}$$

σ in MPa
T in °K
t in hours

Secondary (Steady-state) Creep (Heard, 1972)

$$\dot{\varepsilon}_s = 3.4 \times 10^{-8} \exp\ (-11833/T)\ \sigma^{5.5}$$

σ in MPS
T in °K
t in hours

Table 25 lists the other properties of associated rock types. As with the thermal properties, the values are general in nature and should be used only for preliminary performance predictions.

Table 25

Mechanical Properties of Salt and Associated Rock Types

Rock Type	Linear Thermal Expansion Coefficient	Young's Modulus [illegible]	Poisson Ratio
Salt	11.1 - 13.9 [illegible]$^{-1}$	29.0 - [illegible]	.1[illegible] - .2[illegible]
Sandstone	2.2 - 4.3	1[illegible]	.1 - .25
Siltstone	-	15 - 40	.15 - .30
Dolomite	-	50 - [illegible]	.15 - .30
Limestone	1.1 - 2.8	30 - 60	.15 - .30
Anhydrite	-	20 - 75	.25 - .30
Shale & Mudstone	-	10 - 60	.15 - .25

1.4. Hydrogeological Parameters

For purposes of modeling groundwater flow and solute transport, accurate parameter values for each of the several sedimentary formations associated with bedded salt deposits must be known. Typically these sedimentary sequences contain shales, mudstones and siltstones, limestones and dolomites, sandstones, and salt. Parameters needed for modeling of flow and non-reactive solute transport (reactive chemical parameters are discussed in the next section) are fluid density and viscosity, permeability, dispersivity, and effective porosity.

Fluid density and viscosity are temperature dependent and tables of their variation as a function of temperature can be found in basic texts on fluid mechanics or in the Handbook of Chemistry and Physics. Fracture permeability may also be very temperature dependent but at present very few data are available on this subject.

In addition to being temperature dependent, the fluid density also depends upon total dissolved solids (TDS), especially if the TDS is high. Brines are commonly encountered near salt deposits and these brines can have specific gravity values as high as 1.2. Brines were discussed in more detail in Chapter 7.

Bedded salt deposits are usually isolated from circulating groundwater by very low permeability sedimentary deposits both above and below. The salt itself has a low porosity and interconnected pores are virtually non-existent, hence the salt may behave as an impermeable mass. However laboratory tests on salt core have shown hydraulic conductivity values as high as $10^{-[illegible]}$ cm/sec at a confining pressure of 1000 psi. But other tests have shown the hydraulic conductivity to be zero.

Typical ranges of values of parameters are shown in Table 26. These values apply to the rock matrix; for fractured rock different values would apply. Recent tests (Trimmer, et. al., 1980) have shown that, in jointed rock, the permeability of fractures is 5 to [illegible] orders of magnitude larger than the rock matrix, which had permeabilities of 10^{-16} to 10^{-12} m/s. Schubert (1980) has reported that for coal bearing strata, fracture permeability is 3 to 4 orders of magnitude larger than that of the matrix which had permeabilities of 10^{-12} to 10^{-9} m/s. Similar results might be expected for some of the rock types in Table 26. The difference between matrix and fracture permeability rocks would probably not be as great for the more permeable rock types.

In the salt deposits, fractures would tend to heal with time due to the creep of salt.

Values of dispersivity are, in general, not well known due to a lack of appropriate data. In particular the values of dispersivity for salt, shale, and mudstone/siltstone were simply assumed. These values apply to relatively homogeneous formations. As heterogeneity increases, so do the values for dispersivity.

The overall data base for determining these parameter values is extremely limited. Most of the parameter values in the Table 26 are a best estimate guess.

TABLE [illegible]

[illegible]

Rock Type	Hydraulic Conductivity[1] (m s⁻¹)	Longitudinal Dispersivity[2] (m)	Transverse Dispersivity[3,4] (m)	Effective Porosity (%)
Salt	[illegible]	[illegible]	[illegible]	0.5 - 1.5
Shale	4×10^{-14} - [illegible]	1 - 1[illegible]	[illegible]	0.5 - 25
Mudstone/Siltstone	1×10^{-11} - $2\times10^{-[illegible]}$	3 - 40	1 - [illegible]	0.5 - 15
Limestone/Dolomite	3×10^{-10} - 1×10^{-6}	2 - 25	0.5 - 8	1 - 10
Sandstone	6×10^{-11} - 1×10^{-6}	5 - 60	1 - 20	5 - 20

1 For water at 20°C.

2 Most values simply assumed due to lack of data.

3 Most values simply assured to be 3 to 5 times smaller than longitudinal dispersivity.

4 Dispersivity is the property of a porous matrix to cause spreading of a tracer travelling through it. The coefficient of dispersion, used in transport calculations, is equal to the product of the dispersivity and the average longitucinal velocity.

[illegible].4.4 Geochemical Parameters

Geochemical studies of interest include determination of the mineralogy and petrology of formation rocks and the chemical composition of the groundwaters native to the rocks. These studies provide information concerning the chemical processes which have taken place and which will take place. We are particularly interested in processes which will retard the migration of radionuclides. Hence our main interest lies in the chemical composition of the native groundwaters and the sorption capacity of the rock formations, as indicated by the values of distribution coefficient, K_d.

A discussion of brine chemistry has been given in Chapter [illegible]; representative brine compositions are given in Table 6a.

After groundwaters or brines leach the waste form, the nuclide bearing liquid will contact clay-containing halite in the repository horizon, polyhalite beds, anhydrite beds, and finally the sandstone and dolomite formations which are the bounds of the evaporites. K_d values for various nuclides flowing through these rocks are presented in Tables 8-13, as reported by Powers, et. al. (1978, SAND 78-1596) and other investigators.

Molecular diffusion is another geochemical transport process which must be considered. It is characterized by a coefficient of diffusion. Values of diffusion coefficient for radionuclides are not well known at this time. Molecular diffusion coefficients for NaCl in water are shown as a function of temperature in Table 27. At 25°C these values of NaCl are within an order of magnitude of values for radionuclides that are known. Almost no data exists for radionuclide diffusion at higher temperatures. Diffusive diffusion

Temperature, °C	Diffusion coefficient, 10^{-5} cm^2/s
5	0.80
10	1.03
15	1.18
20	1.36
25	1.62
30	1.85

[1] Water Resources Engineers, 1979

transport through a porous medium is further complicated due to the tortuosity of transport flow paths. The tortuosity has the effect of reducing the magnitude of the diffusion coefficients. The effective diffusion coefficients for porous rock are at least a factor of smaller than those in the table.

12.5 Judgments Regarding Hydrologic Failure Scenarios

Various hydrologic failure scenarios have been described in previous subsections. Some discussions of the likelihood of their occurrence have been included, but no overall assessment of the potential importance of the various scenarios has been presented.

Consideration of past and ongoing efforts to locate a nuclear waste repository in bedded salt demonstrates that no one scenario is likely to be of overriding, universal importance. Thus, at the WIPP site, breccia blanket formation is an obvious concern. Dissolution along old wells and past solution mining projects proved critical at the Lyons, Kansas site. Other specific sites will doubtless have their own assemblage of geohydrologic problems.

However, subject to severe limitations imposed by the present state of knowledge and the recognition that other well-informed geologic and engineering judgments will be brought to bear on the subject, the following judgments are provided regarding the potential importance of the various failure scenarios for long-term nuclear waste isolation.

The presence of failed wells and evidence of salt dissolution features near two proposed nuclear waste repositories is strong evidence for the importance of these scenarios in future assessments of the nuclear waste isolation capabilities of bedded salt.

Breccia blanket and breccia pipe formation are processes that occur in geologic time and it may be possible to demonstrate that these processes will be slow enough so as not to compromise the waste isolation potential of a given site. However, present estimates of leach rates are very uncertain and based upon geologic assumptions that may not stand detailed study and analysis. Therefore, these geologic processes must be regarded as potentially important to successful nuclear waste isolation in bedded salt.

Dissolution around old wells has been experienced in a very short geologic time frame (< 100 years in most cases). This experience indicates the importance of dissolution modes in assessing the nuclear waste isolation potential of bedded salt. Considerable attention is being given to well and shaft sealing techniques and detection of old wells and doubtless, more effective materials and detection methods will exist in the future than are presently available. However, attention should be drawn to some aspects of the sealing problem that are likely to severely challenge materials science in the foreseeable future, although it should be noted that a long time period will be available to address the problem.

As discussed in Chapter 2, geotechnical theory predicts an exponential outward decrease in fracturing about an underground opening. Thus, toward the outer fringes of fracture zones around shafts, boreholes, and wells, fractures are expected to be of small aperture width and erratic interconnections. They will of course convey very small amounts of water and may prove inconsequential during the operating life of a repository.

However, such small fracture zones will be impossible to completely seal during repository decommissioning since sealing materials will not completely penetrate them. These remaining flaws will likely be very minor at first, but they will exist and they will be subject to enlargement as a result of future dissolution and/or tectonic processes. Therefore, future scientists called upon to determine the cause of failure of a nuclear waste repository in bedded salt may find a halo of porous and permeable rocks outside of well-sealed shafts, boreholes, and rock masses located immediately adjacent to these former penetrations.

Rock sealing problems are therefore seen, based on present judgment, as a potentially important failure scenario for a nuclear waste repository in bedded salt.

Other potential failure scenarios are presently regarded as of less importance than the foregoing. The presence and density of fractures in bedded salt and associated strata will be site specific and be determined by thorough site characterization studies which include exploratory tunneling and proof testing. Observations during these phases of site study will permit an assessment of the potential and extent of new fracture formation and the data will be available prior to repository licensing.

Similarly, the potential for repository compromise as a result of lithologic variations and facies distributions will be available from geologic studies prior to repository licensing.

Based on present knowledge, intact bedd... salt and associated strata may be expected to have very low interstitial porosities and permeabilities, and therefore, interstitial flow should not be expected to prove to be a significant escape path for radionuclides from a nuclear waste repository in bedded salt. Similarly, while the movement of fluid inclusions in salt may be worthy of additional study, it appears that this mechanism for nuclide migration will, at most, operate in the immediate vicinity of waste canisters, and is therefore of inconsequential importance to waste migration. Large brine pockets could pose problems during repository construction, but do not appear important for waste isolation.

Inadvertent penetration of a repository by future mankind is a likely event, but its consequences appear overstated. Some exposure risk must be assumed, and financial costs required to clean up the mess and seal the penetration will fall on a future private or governmental entity, to its displeasure, but the potential for catastrophy appears remote. Present draft regulations appear to assure administrative control of a repository site long enough to significantly reduce the risk of contact with high levels of short-lived, highly hazardous radioisotopes.

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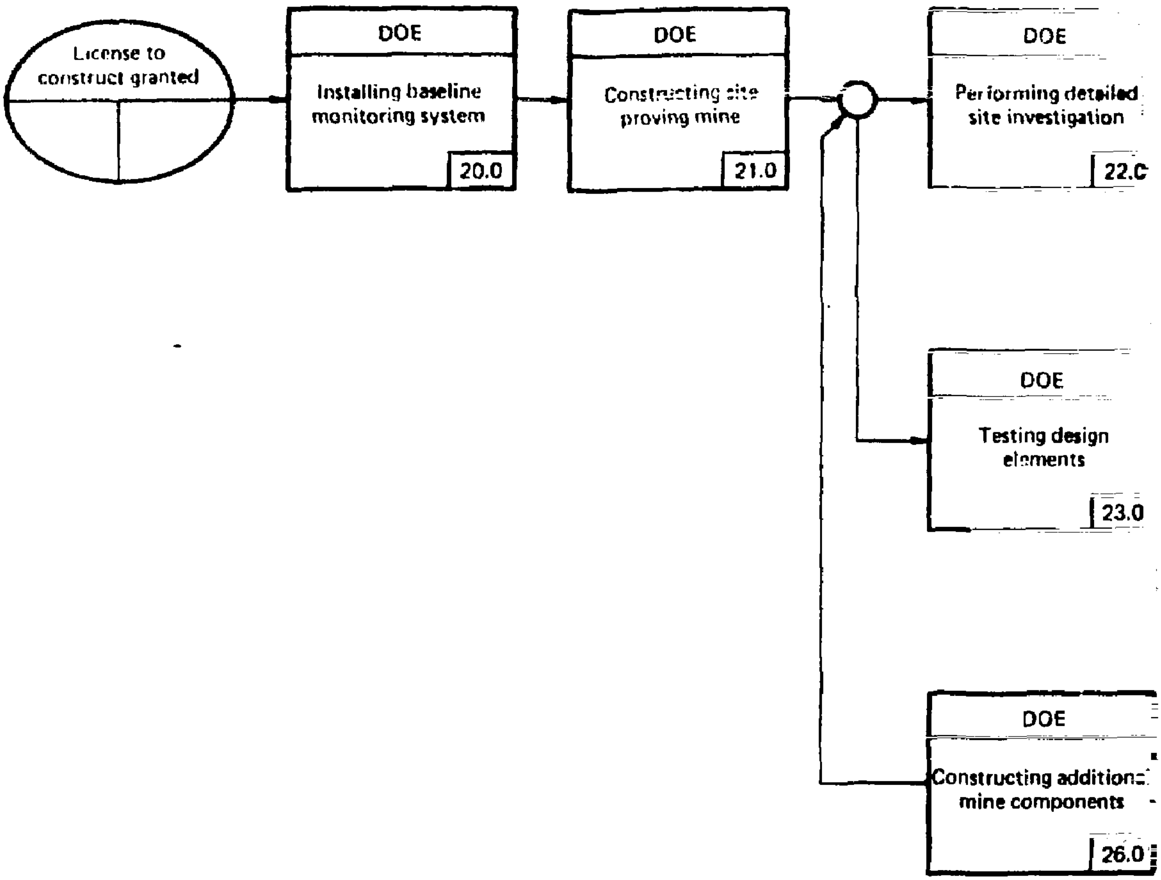
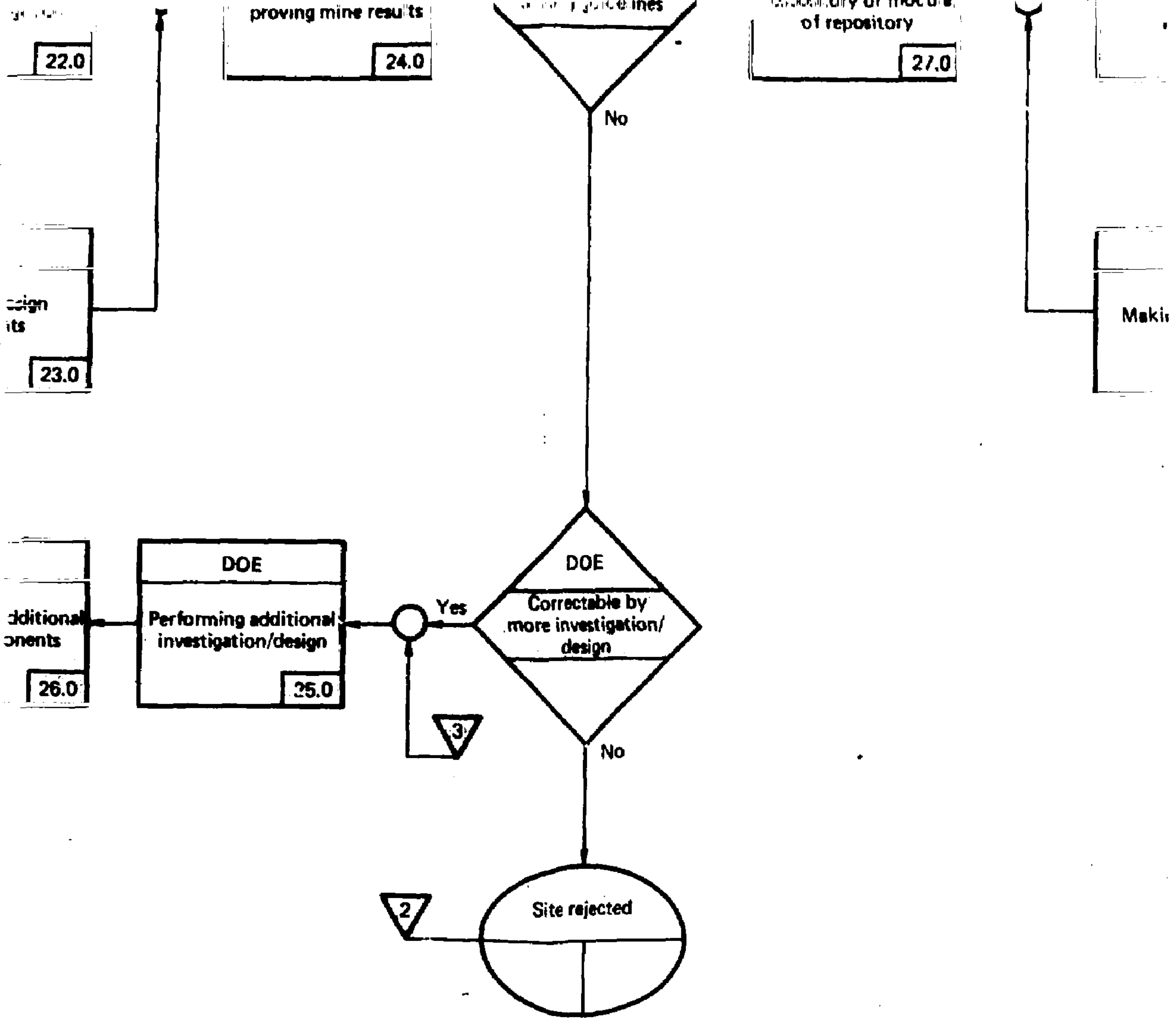
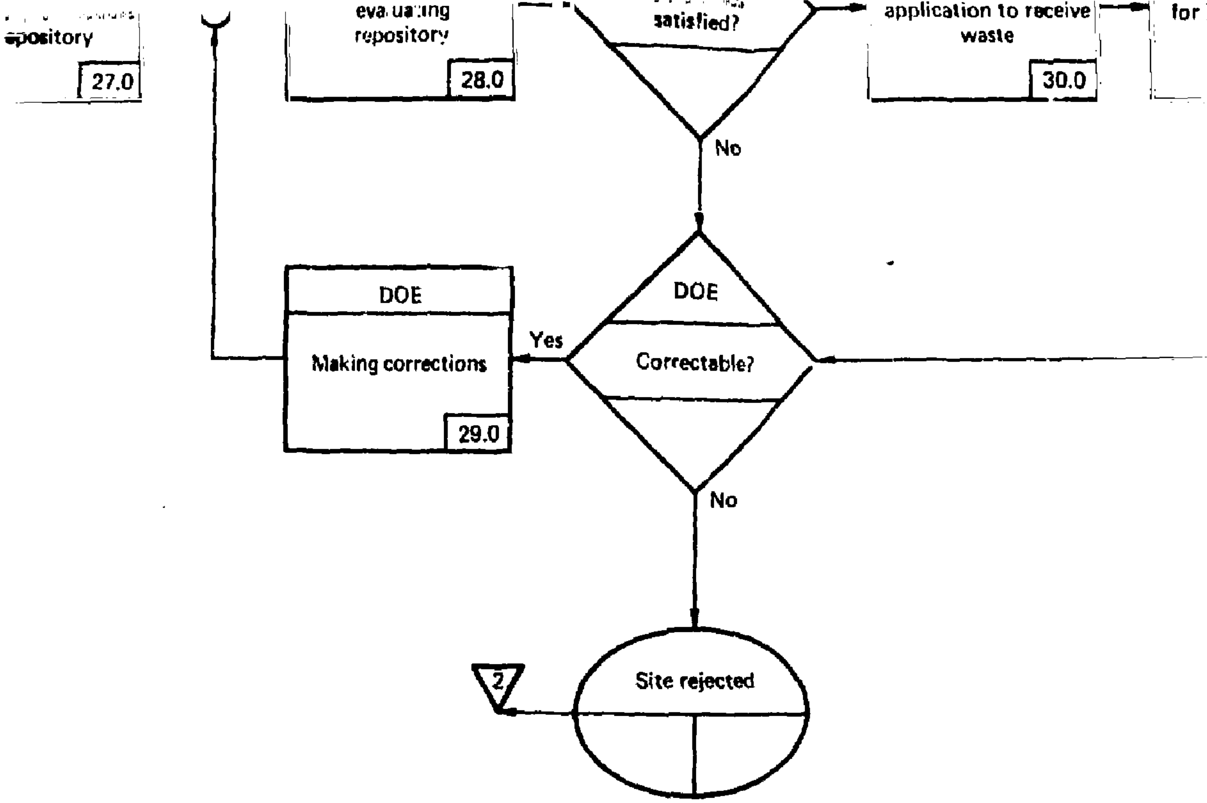
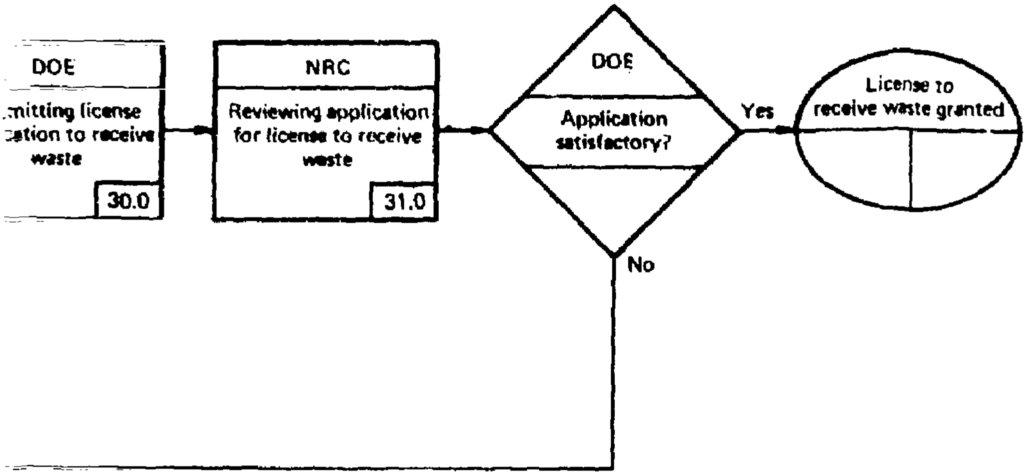
APPENDIX A


License to construct granted
DOE
Installing baseline monitoring system
20.0
DOE
Constructing site proving mine
21.0
DOE
Performing detailed site investigation
22.0
DOE
Testing design elements
23.0
DOE
Constructing additional mine components
26.0


22.0
proving mine results
24.0
of repository
27.0
No
23.0
Makii
DOE
Performing additional investigation/design
25.0
26.0
Yes
DOE
Correctable by more investigation/ design
No
3
2
Site rejected

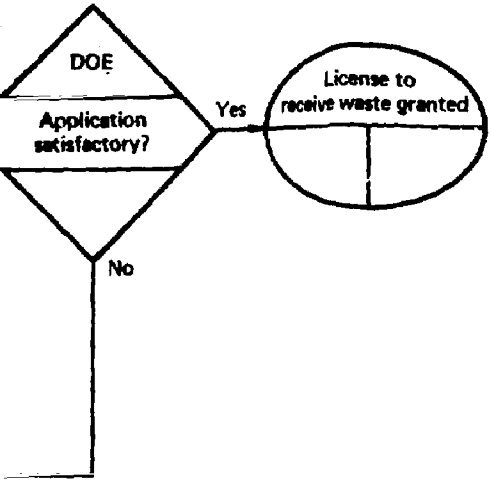


epository
27.0
evaluating repository
28.0
satisfied?
No
application to receive waste
30.0
for
DOE
Making corrections
29.0
Yes
DOE
Correctable?
No
Site rejected
2



DOE
mitting license
cation to receive
waste
30.0
NRC
Reviewing application
for license to receive
waste
31.0
DOE
Application
satisfactory?
Yes
No
License to
receive waste granted

AA



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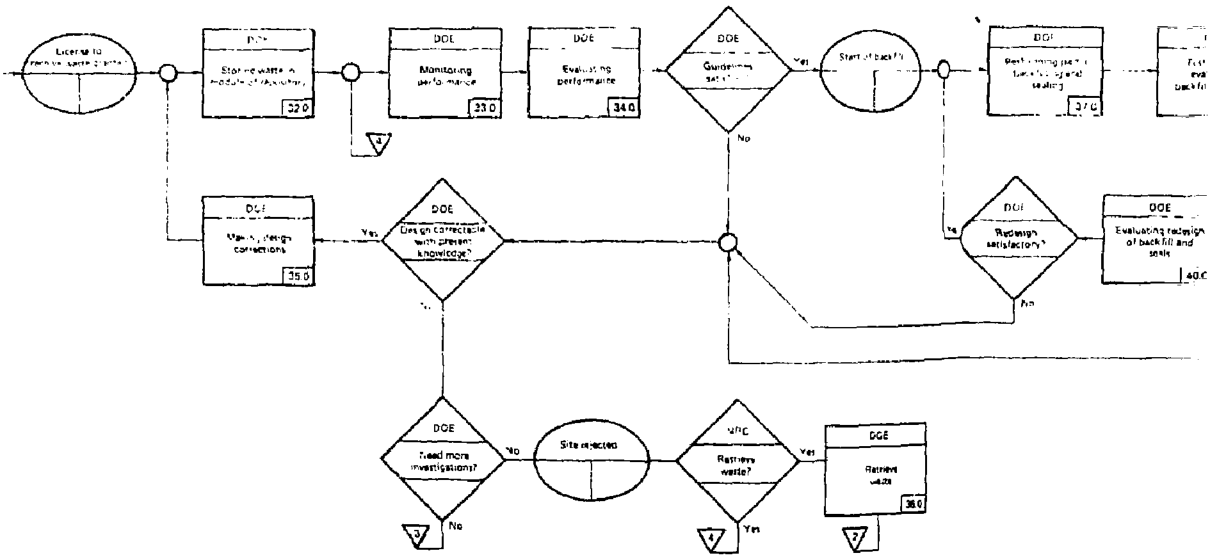
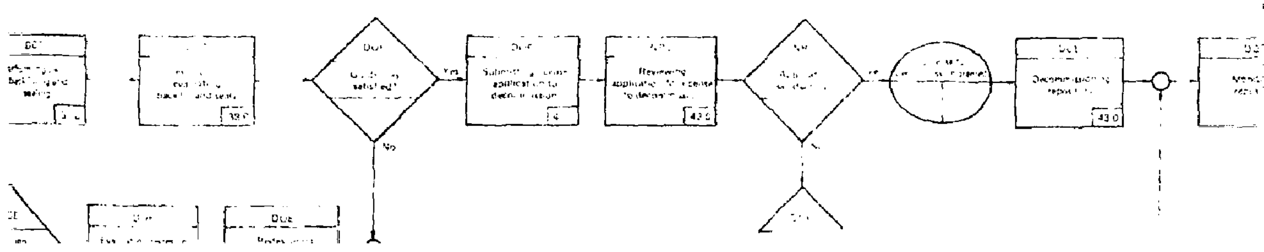
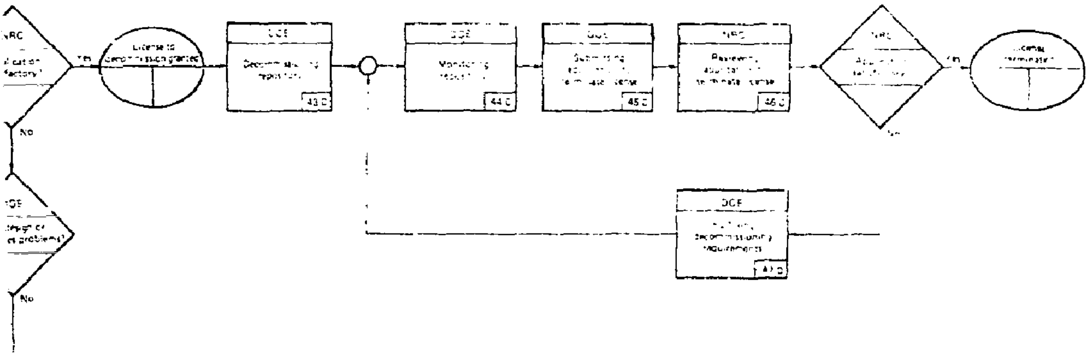


DOE
Monitoring performance
33.0
DOE
Evaluating performance
34.0
32.0
DOE
Yes
No
37.0
DOE
35.0
DOE
Design correctable with present knowledge?
Yes
DOE
Redesign satisfactory?
No
DOE
Evaluating redesign of backfill and seals
DOE
Need more investigations?
No
No
Site rejected
Retrieve waste?
Yes
Yes
DOE
Retrieve
38.0


DOE
satisfied?
Yes
No
Reviewing
43.0
43.0



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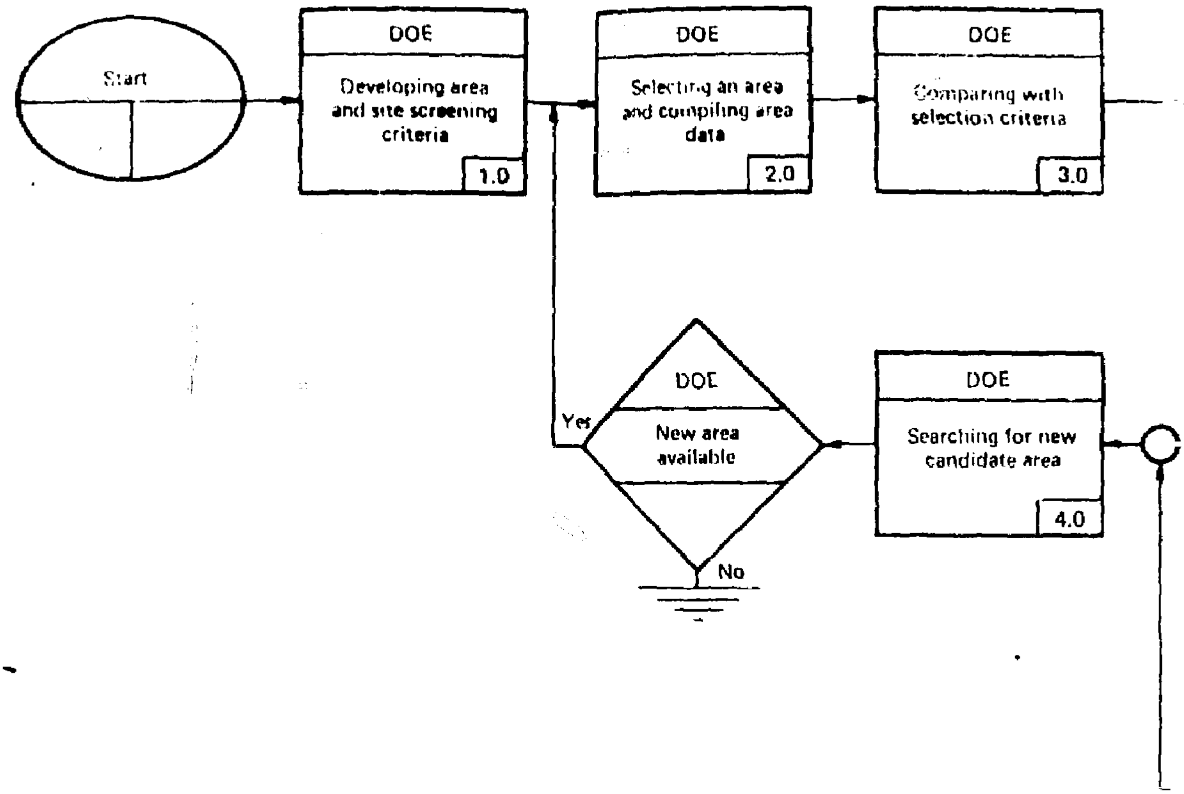
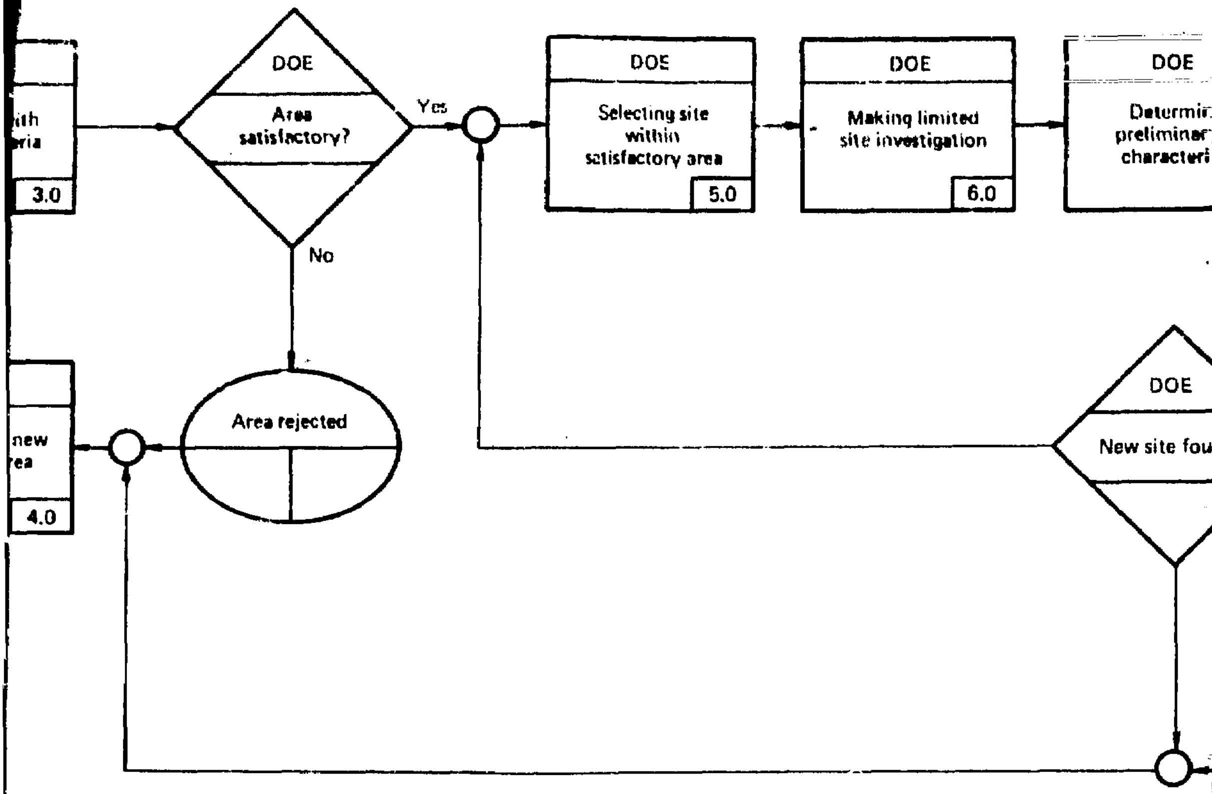
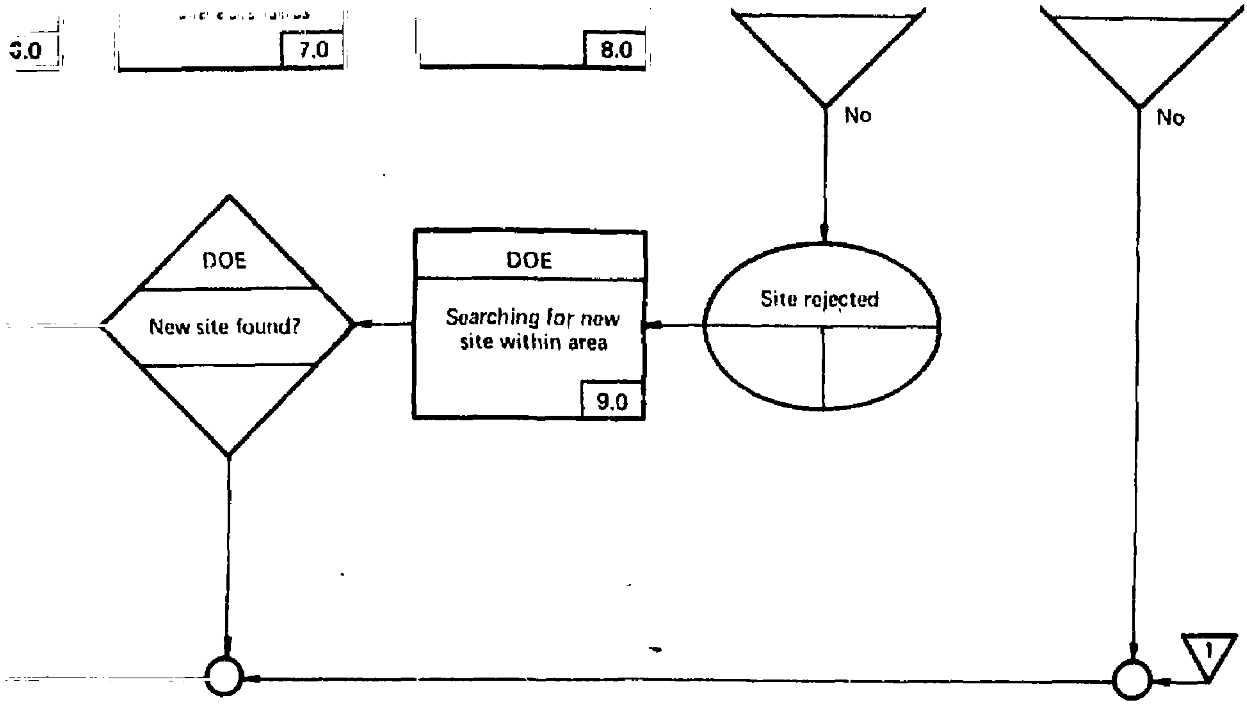
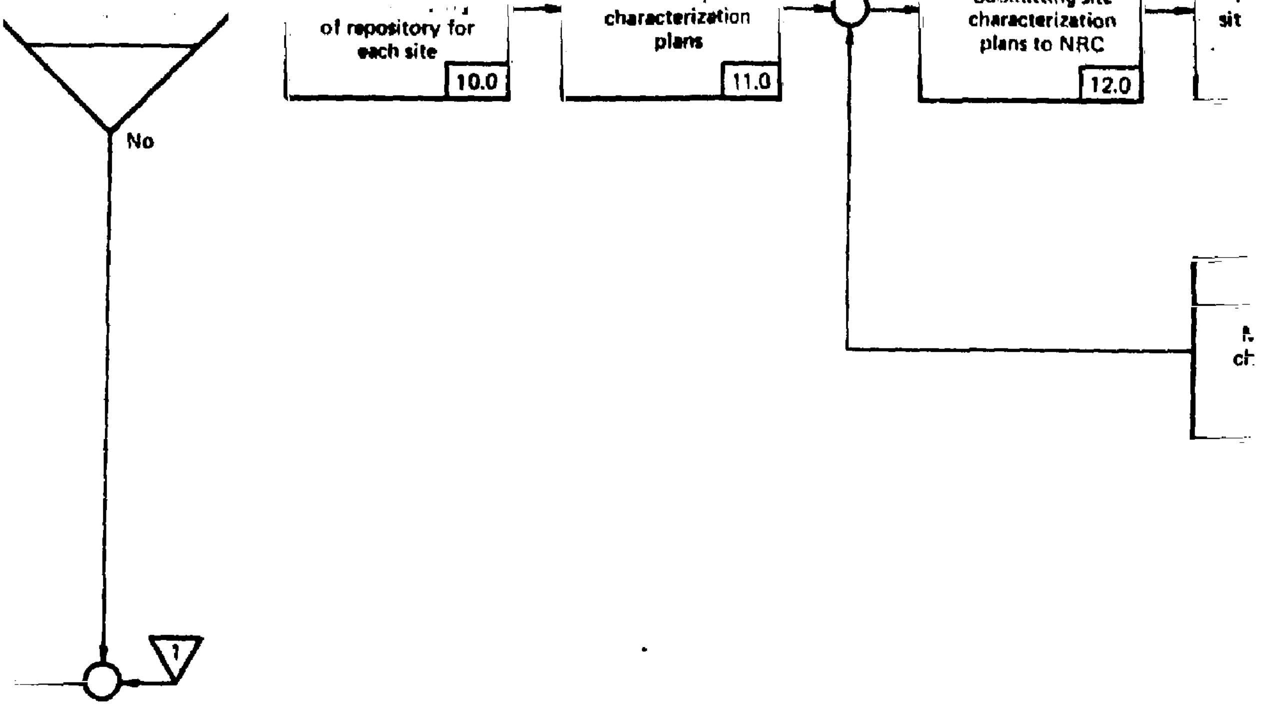

Start
DOE
Developing area and site screening criteria
1.0
DOE
Selecting an area and compiling area data
2.0
DOE
Comparing with selection criteria
3.0
DOE
New area available
Yes
No
DOE
Searching for new candidate area
4.0

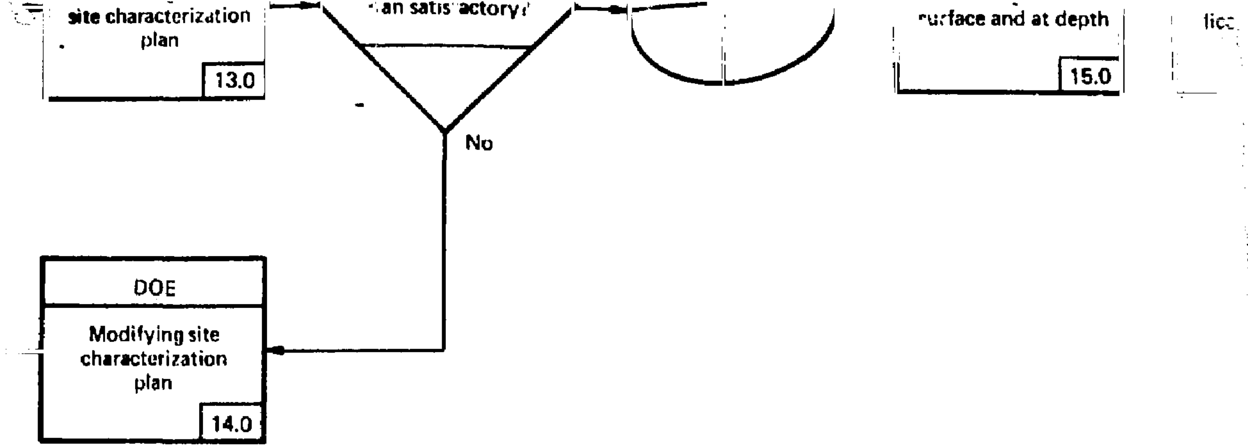


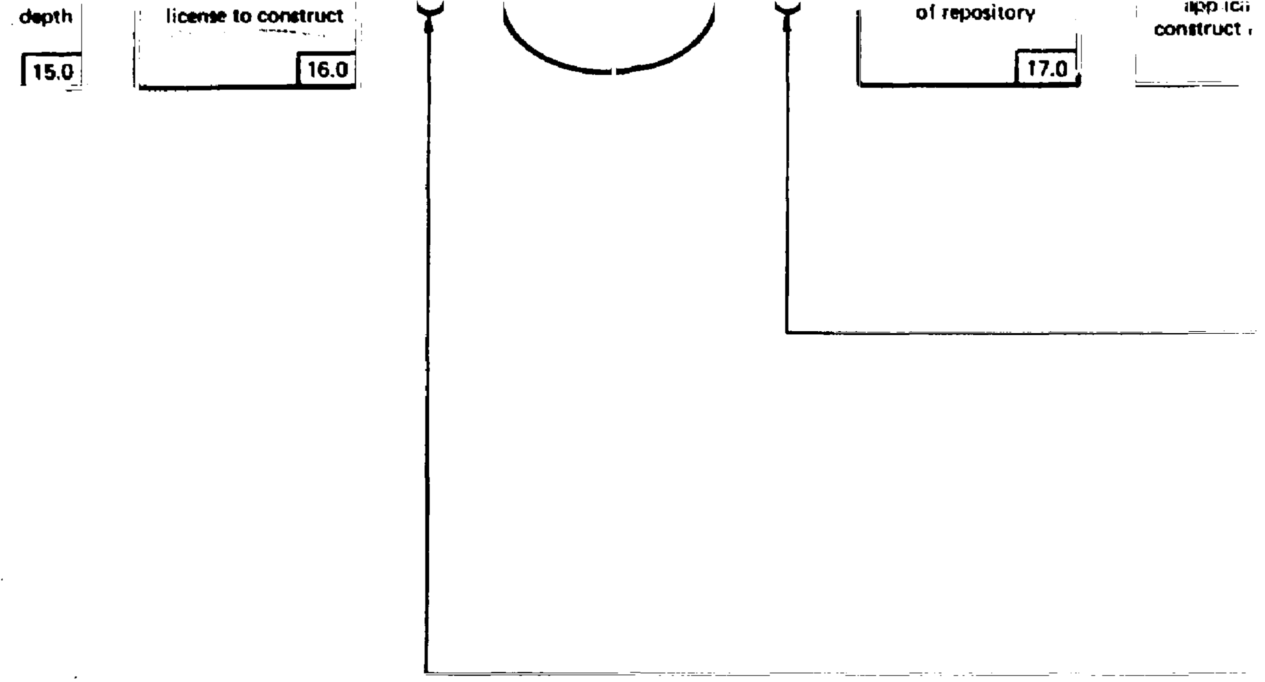
ith
eria
3.0
DOE
Area satisfactory?
Yes
No
DOE
Selecting site within satisfactory area
5.0
DOE
Making limited site investigation
6.0
DOE
Determin
preliminar
characteri
new
rea
4.0
Area rejected
DOE
New site fou

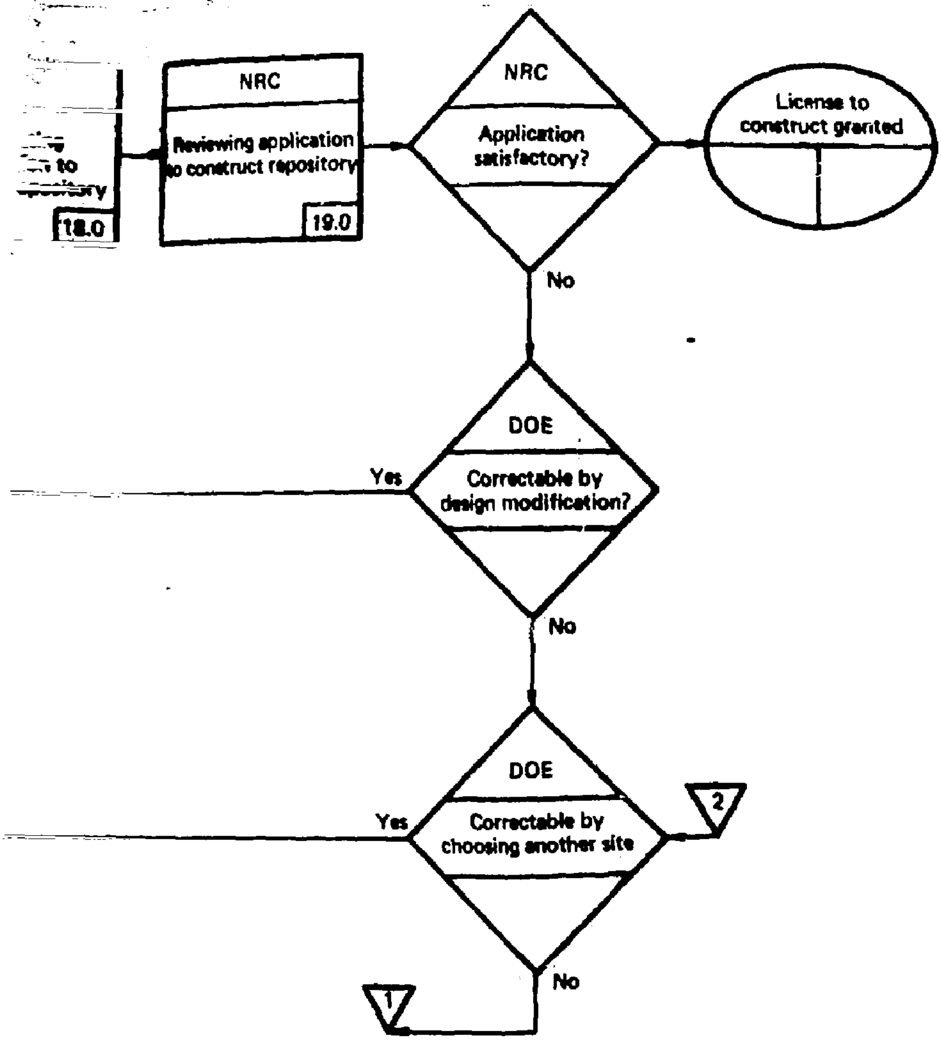


6.0
7.0
8.0
No
No
DOE
New site found?
DOE
Searching for new site within area
9.0
Site rejected
1


of repository for
each site
10.0
characterization
plans
11.0
characterization
plans to NRC
12.0
No
1


site characterization plan
13.0
No
DOE
Modifying site characterization plan
14.0
15.0


depth
15.0
license to construct
16.0
of repository
17.0
construct


18.0
NRC
Reviewing application to construct repository
19.0
NRC
Application satisfactory?
License to construct granted
No
DOE
Correctable by design modification?
Yes
No
DOE
Correctable by choosing another site
Yes
2
No
1