TECHNICAL SUPPORT FOR GEIS:
RADIOACTIVE WASTE ISOLATION
IN GEOLOGIC FORMATIONS

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Volume 4

Baseline Rock Properties-Salt

April 1978

Prepared By

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**UNION
CARBIDE**

OFFICE OF WASTE ISOLATION
OAK RIDGE, TENNESSEE

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TM-36/4	Baseline Rock Properties-Salt	D&M
TM-36/5	Baseline Rock Properties-Granite	D&M
TM-36/6	Baseline Rock Properties-Shale	D&M
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ABSTRACT

This volume, Y/OWI/TM-36/4, Baseline Rock Properties - Salt, is one of a 23-volume series, "Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations, Y/OWI/TM-36" which supplements a "Contribution to Draft Generic Environmental Impact Statement on Commercial Waste Management: Radioactive Waste Isolation in Geologic Formations, Y/OWI/TM-44." The series provides a more complete technical basis for the preconceptual designs, resource requirements, and environmental source terms associated with isolating commercial LWR wastes in underground repositories in salt, granite, shale and basalt. Wastes are considered from three fuel cycles: uranium and plutonium recycling, no recycling of spent fuel and uranium-only recycling.

Salt has long been considered a possible repository medium for nuclear waste disposal. This report is a result of a literature survey to determine rock mass properties of a generic salt.

The properties of bedded salt deposits from three different areas are considered, namely, the Salina basin, the Permian basin and the Paradox basin. Dome salts are also considered.

Because of the special characteristics of salt, especially, it's self-healing properties, the rock-mass properties are similar to the intact properties. Nevertheless, some engineering judgment was required in deriving these rock-mass properties.

PREFACE

Project Background

One of the major problems related to the production of electricity by light-water nuclear reactors is the management of radioactive wastes generated by the use of nuclear fuel. However, the subject is considered amenable to a rational solution, and the technology involved is considered to be well within the capabilities of our present-day technological base.

An important step toward the realization of an effective waste management program is the preparation of the generic environmental impact statement for commercial waste management. A pivotal issue in waste management is the means of providing long-term, permanent storage of these wastes in a manner to best assure their isolation from the biosphere. Analyses spanning two decades have generated the widely supported concept for providing final isolation of these nuclear wastes in deep geologic formations. Therefore, the Office of Waste Isolation* was assigned the responsibility for preparation of those sections of this generic statement dealing with deep geologic waste isolation.

The original concept for deep geologic disposal was first advanced in 1957 when a National Research Council Advisory Committee of the National Academy of Sciences suggested the burial of solid radioactive wastes in salt deposits. To date, the majority of the research, development, and demonstration (RD&D) activities have been in salt. The current United States Department of Energy (DOE) National Waste Terminal Storage (NWTs) program calls for the selection of two sites overlying suitable salt formations by 1979, followed by the construction and start-up in 1985 of one NRC-licensed repository designed for the permanent disposal/isolation of commercial nuclear wastes in a salt formation at one of these two sites. In addition to this activity in salt, vigorous RD&D programs have been initiated to determine the appropriateness of various hard rocks as host media for a repository.

*Operated by Union Carbide Corporation-Nuclear Division for the Department of Energy.

The deep-geologic-isolation portion of the generic statement considers repositories located in salt, granite, shale, or basalt. The repositories are designed to handle wastes from the nuclear fuel cycle without reprocessing, in which the spent fuel is considered a waste (no reprocessing) or from either of two fuel cycles that include reprocessing--the cycle with uranium and plutonium recycle and that with only uranium recycle. To prepare this contribution, the Office of Waste Isolation contracted with Dames & Moore, Parsons, Brinckerhoff, Quade & Douglas, Inc. and Science Applications, Inc. In order to prepare this description, generic sites were defined, preconceptual repository designs completed, and resource requirements and effluents from the repositories identified. The preconceptual repository designs for the salt host formation were based on more than two decades of analysis and in-situ experimentation. The data base upon which the repository design for the non-salt host formations were based is much more sparse since repository-oriented analyses of these formations have been proceeding only for the last couple of years. For each of the host rocks additional analyses were performed during the conduct of these studies. Details of this additional technical work are described within the twenty-three volumes of this report.

For an overview of these preconceptual repository design studies, the study objectives and scope, and the major study assumptions, the reader is referred to Volume 1 of this series, the Executive Summary (Y/OWI/TM-36/1).

Volume Summary (Y/OWI/TM-36/4)

Salt is one of the rock types being considered as a possible medium for locating a radioactive waste repository. In order to perform a feasibility study, information must first be collected on the geology, hydrology and rock mass properties of typical salt formations. These data can then be used in studies to determine the gravity and thermal loadings associated with different canister configurations and underground layouts. This report is an evaluation of the rock-mass properties of salt for use in these studies.

The approach taken in this report has been to look at intact rock property data in general in order to obtain a feel for the range of properties encountered. Then, salt formations from different parts of the United States were considered separately and average rock properties for each of these areas derived. The properties from the individual areas were then combined to form a generic set of properties for a typical salt formation.

1.0 INTRODUCTION

The selection of salt (halite) formations to be used as the host geologic medium for underground emplacement of radioactive nuclear waste, has been considered for several years. Although significant research has taken place under laboratory conditions and in the field, there are still many unanswered questions with respect to the magnitude and extent of various physical mechanisms which may or may not take place.

It is very difficult to determine the probable behavior of a material like salt, because it is extremely sensitive to temperature variations. A great deal of research is needed in this area, particularly at depth and under actual anticipated field conditions. It has been suggested that laboratory tests are of little value due to work-hardening of the loaded samples during testing. This strain-hardening does not take place in loading conditions encountered underground; the extent that this statement is true may be in doubt. However, it does highlight the fact that several very basic questions are still in dispute.

2.0 SUMMARY OF INTACT SALT PROPERTIES

Rock salt (halite) is generally considered to be relatively homogeneous and isotropic as compared to other geologic media. Table 2-1 presents the ranges of various physical properties of salt as reported in the literature. It is interesting to note the wide variance associated with Young's Modulus, Poisson's ratio, and permeability. In addition the thermal properties of this material are widely variable as a function of temperature.

Appendix A contains a list of values found in the literature. Generic values refer to general trends while a specific value indicates the actual result of an experiment, i.e. specific quantities are raw data and generic values are processed data (averages). The most important information to be obtained is that salt properties appear to be locally isotropic; however, significant variations may occur from place to place. A complete testing program, therefore, will have to be carried out to determine solutions to the specific problems associated with a particular waste repository.

TABLE 2-1
RANGE OF VALUES FOR INTACT SALT SPECIMENS
 (HALITE)

BASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	130 to 152 lbs/ft ³
	. Natural moisture content (intact)	0 to 11 %
	. Porosity (total)	1.4 to 10.0 %
Stress-strain	. Young's Modulus	0.09x10 ⁶ lb 7.25x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.22 to 0.50 --
	. Bulk Modulus	-- lbs/in ²
	. Shear Modulus	-- lbs/in ²
Strength	. Cohesion 1500-3500 Friction Angle psi range	900 to 1700 lbs/in ² 20 to 36 degrees
	. Uniaxial Compressive Strength	2300 to 7250 lbs/in ²
	. Tensile Strength	120 to 458 lbs/in ²
	. (Plastic Behavior?)	Visco-plastic flow may occur at stresses as low as 100 psi
Thermal	. Coefficient of Linear Thermal Expansion	2.2x10 ⁻⁵ °F
	. Heat Capacity	0.19 to 47.0 BTU/lb-°F
	. Thermal Conductivity	@0°C - 3.5 @400°C - 1.2 BTU/hr-ft-°F
Hydrological	.	1.7x10 ⁻¹⁵ to 1x10 ⁻² ft/yr

3.0 PROPERTIES OF SALINA BASIN SALT

3.1 INTRODUCTION

The report presents the various rock-mass properties of the Salina Basin salt deposits of Michigan, Ohio, New York, Pennsylvania and Ontario, Canada. The salt of the Salina Group is bedded salt of the Silurian Period. The areal extent of the Salina Group is shown in Figure 3-1¹.

3.2 DESCRIPTION OF ROCK MASS

3.2.1 Lithology

The Salina Group contains the major deposits of rock salt (halite) in the area of study. The Salina consists of a number of stratigraphic units, predominantly salt, carbonates and shales with similar lithologic character over a wide geographic area (Figure 3-2,^{2, 3}). The greatest thickness of salts is in the center of the Michigan basin, where their aggregate thickness is more than 2,000 feet at depths of greater than 6,000 feet (Figure 3-3). As can be seen in Figure 3-1, mining is done on the margins of the basins.

The Salina has been divided into units A through G, from oldest to youngest, with further divisions of the A units. The A-1 salt ranges from 200 to 475 feet in thickness and contains predominantly clean salt with some anhydrite. The A-2 salt is the thickest, most massive salt and is separated from the A-1 by a limestone. It is a clean salt with a thickness of 300 to 475 feet. The B salt is clean salt interbedded with shale and dolomite, and is separated from the A-2 by a dolomite-limestone. The thickness of the B salt is 300 to 475 feet with one-half of the thickness being clean salt. The C unit is red and green shale. The D unit consists of thin (40 to 100 feet) salt beds. The E unit is shale and dolomite. The F unit is a succession of pure and impure salt beds interbedded with shale, dolomite and anhydrite. The F unit can be up to 970 feet thick. The individual salt beds are 5 to 20 feet thick with some 30 to 60 feet thick. The F unit is overlain by the F and G units of dolomite and shale.

The individual salt units are composed of 1 to 6 inch layers of clean salt separated by darker layers. These darker layers may be salt with impurities of anhydrite ⁴.

3.2.2 Mineralogy

Salt is composed of halite crystals with considerable variation in size. The salt is layered with anhydrite laminae. The inclusion-free salt is clear, while the inclusion-rich salt is cloudy. The major salt impurity in the Salina Basin is anhydrite. The laminae have no regular spacing⁵.

3.2.3 Major Structures

The structure of the Michigan basin is relatively simple with the rocks dipping gently toward the center of the basin. The Michigan basin is separated from the Appalachian Basin of Ohio, Pennsylvania and New York by the Findlay arch. The Appalachian basin is poorly defined and more complex structurally.

3.2.4 Minor Structures

Salt deposits can be flat-lying, folded or faulted. Jointing and fracturing common to flat-lying beds are predominantly near-horizontal partings along anhydrite or shale layers. Other structures in horizontal beds are large crystal masses, large rock masses of solidified impurities with lateral continuity, and lateral lithologic changes. Faulting of salt beds is more evident near areas of tectonic activity such as the Appalachian basin ⁶.

The orientation of the shear planes which cause floor heave and slabbing of ribs and pillars in salt mines is a function of the principal strain direction of the in situ stresses. This will vary at individual sites. A description of the typical structure found in the Salina salt is presented in Table 3-1.

3.2.5 Rock Quality

The dynamic elastic moduli can be estimated from the 3-D velocity log at a depth of 900 to 1200 feet, as $2 \text{ to } 4 \times 10^6 \text{ psi}$ ⁸. Equivalent RQD values would be 60 to 80 percent (fair to good).

Laboratory triaxial testing of rock salt from the Salina group has been conducted by Lomenick and Bradshaw (1969),^{9, 10} Obert (1964),¹¹ and Serata (1964)¹². Serata has observed that the major factors which affect the testing results are:

1. Size of test specimen
2. Size of crystalline grains of the specimen
3. Cross-sectional form of the specimen
4. Ratio of specimen width to height
5. Degree of friction on the loading surface
6. Geometry of the loading

Two of the most significant of the above factors are the effects of the width-to-height ratio and the specimen size. Figure 3-4 exhibits the effect of dimension on maximum stress. With respect to size, the random variation of the observed strength was greatest with the smallest specimen size¹¹. Lomenick and Bradshaw (1969)¹⁰ also tested model pillars and size effects. As can be seen in Figure 3-5, the broader model pillars exhibited less vertical deformation. Obert loaded salt models at 10,000 to 12,000 psi and terminated the test after the strain exceeded 25 percent. None of the models failed like a brittle material or exhibited a tertiary (accelerated) creep phase. The extreme creep is typical of all rock salt.

3.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

No testing of individual discontinuities in Salina Group salt have been made. Triaxial testing of bedded rock salt from the Salina Group has been conducted by Serata, 1964¹² (see Figure 3-6). At 2000 psi, cohesion is 800 psi and $\phi = 30^\circ$.

3.4 PHYSICAL PROPERTIES FOR OVERALL ROCK MASS

The physical properties for the Salina Group bedded salt are shown in Table 3-2. The index and strength data were from tests of salt from the Goderick mine by Muir and Cochrane (1966)¹³. The shear strength and elastic moduli were recalculated at a depth of 2000 feet from Serata (1964)¹². No in situ elastic moduli have been determined from the Salina Group.

3.5 ENVIRONMENTAL FACTORS

3.5.1 Time (Creep)

In situ testing of rock salt pillars in the Salina Group has been undertaken by Muir and Cochrane (1966)¹³. Generally, the tests consisted of monitoring pillar shortening over long periods of time. Results of these tests are shown in Figure 3-7.

Obert (1964)¹¹ found that for a family of curves, the creep rate can be expressed as some power of the applied load, that is

$$\dot{\epsilon}_m = D \sigma_o^n$$

where: D and n are constants,

σ_o is the applied load

Lomenick and Bradshaw (1969)^{9, 10} also found that creep is a function of temperature. Details of their creep law are given in Chapter 4.

Muir and Cochrane (1966)¹³ observed in the in situ testing that the convergence at each station could be represented by the linear equation:

$$Y = 0.0015 t + 0.107$$

where: Y = deformation in inches

t = time in days

However, pillars which had been standing for longer periods of time showed deformation rates which decreased with time and were represented by the logarithmic equations:

$$Y = A \log (1 + nt)$$

where: A and n are constants depending on local factors. The logarithmic equation is more in line with modern theory.

3.5.2 Temperature

The physical behavior of Salina group rock salt is drastically affected by temperature. Thermal conductivity and diffusivity decrease sharply with increasing temperature. The amount of deformation increases as observed by Lomenick and Bradshaw (Figures 3-8 and 3-9). Figure 3-8 exhibits the effect of loading at a temperature of 225°C. The deformation curve rises sharply initially, and then proceeds to rise, but at a decreasing rate. Figure 3-9 shows the increased deformation at 100°C of rock salt from the Salina Group near Detroit, Michigan, and Retsof, New York. The Retsof salt was somewhat friable, hence the initial high deformation. However, the curve is essentially similar.

3.5.3 Pressure

Figure 3-10 shows deformation curves for model pillars of rock salt tested at various pressures. It may be noted that the increase of pressure from 4000 psi to 6000 psi at 22.5°C produces small changes in deformation when compared to changes in temperature. Long-term applied pressure can produce very large strains (Lomenick and Bradshaw, 1969)¹⁰.

3.5.4 Water/Moisture

Bedded salt deposits of the Salina Group have moisture trapped internally and along anhydrite partings. Most of the moisture is brine. The total moisture content and porosity of bedded salt is low.

The trapped moisture can be released with considerable energy when the rock salt is heated. Samples of bedded salt from Fairport Harbor, Ohio, Retsof, New York, and Detroit, Michigan, had decrepitation temperatures of 380°C, greater than 400°C and 290°C respectively. The decrepitation temperatures of the samples were the same regardless of the rate of heating¹⁴.

3.5.5 Irradiation

No irradiation studies of bedded salt in the Salina group have been conducted.

3.6 ANTICIPATED ENVIRONMENT

The effect of increased temperature on the rate of creep is expected to be a major environmental factor in any opening in bedded rock salt of the Salina group. The increased creep (or closure) with temperature rise is illustrated in Figures 3-10 and 3-11. The effect of shale partings is illustrated in Figure 3-12.

3.7 EXCAVATION CRITERIA

3.7.1 Water Inflow

Bedded rock salt of the Salina Group contains very little water (Section 3.5.4). Any large water inflow would dissolve the rock salt, thereby endangering the cavity stability. However, water inflows in the bedded salt are not anticipated.

3.7.2 Water Pressure Effects on Stability

Since no water inflows are anticipated, no stability problems from water pressure are possible.

3.7.3 Excavation Techniques

The bedded salt of the Salina Group consists of individual beds of salt separated by layers of shale, dolomite and anhydrite. The effect of some of these layers on deformation is shown in Figure 3-12. The shales are planes of weakness which can cause roof falls and floor heave. Gas and brine pockets can also form along these contacts. Historically, few problems have been encountered in mines in the Salina Group. The Goderick Mine has had roof problems which required a roof bolting program¹³. The Fairport Mine in Ohio has had significant problems with ground control and it is necessary to leave 2 to 3 feet of salt in the roof and one foot in the floor. Knowledge of the principal stress orientation and proper

alignment of the mining plan, accounting for this orientation eliminated most of the unstable ground conditions. Faulting is rare in Michigan mines, but has been encountered in two mines in the Appalachian Basin.

Major problems for mining salt in the Michigan and Appalachian Basins occur in sinking the shafts, because of the high ground water flow rates in the overlying formations and alluvial cover.

The mines range from 1060 to 2025 feet deep with opening heights of 9 to 45 feet in height.

3.7.4 Temporary and Permanent Support

The lithologic discontinuities such as shale or anhydrite can cause roof falls or floor heave. These may be controlled by rock bolting. Based on a review of pertinent literature, other support measures are not required.

3.7.5 Extraction Ratios

The Goderick Mine, Ontario, Canada is laid out on a room and pillar pattern at 1800 feet depth. Rooms are opened 60 feet wide by 42 feet high. Pillars are 210 feet square for an extraction ratio of approximately 40 percent. Estimated pillar loading is 3500 psi. No excessive spall or failures are occurring in the mine¹³.

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FIGURE 3-1 Extent and Depth of the Salina Basin Salt
 (Pierce and Rich, 1962)

STRATIGRAPHIC COLUMN OF SILURIAN AND DEVONIAN SEQUENCE IN NORTHEASTERN MICHIGAN SHOWING PRINCIPAL EVAPORITE-CARBONATE UNITS OF SALINA GROUP.

FIGURE 3-2 (OWI, 1976)

FIGURE 3-3 Thickness and Depth of Salina Basin Salt
(Pierce and Rich, 1962)

FIGURE 3-4 Effect of Sample Dimension on Maximum Stress
(after Serata, 1964)

FIGURE 3-5 Deformation of Pillar Models at 400 psi and 25.5°C. Width to height ratios of 2, 3 and 4. (Lomenick and Bradshaw, 1969)

FIGURE 3-6 Determination of Young's Modulus and Shearing Strength (Serata, 1964)

FIGURE 3-7 Deformation of Pillar Over time
(Muir and Cochrane, 1966)

FIGURE 3-8 Deformation of Pillar Models at 4000 psi and 22.5°C (Lomenick and Bradshaw, 1969)

FIGURE 3-9 Deformation of Pillar Models at 4000 psi and 100°C (Lomenick and Bradshaw, 1969)

FIGURE 3-10 Deformation of Pillar Models at Various Temperatures and Pressures (Lomenick and Bradshaw, 1969)

FIGURE 3-11 Deformation of Pillar Model at 4000 psi and (1) temperature at 22.5°C and (2) Temperature to 100°C (Lomenick and Bradshaw, 1969)

FIGURE 3-12 Deformation of Pillar Models at 4000 psi and 22.5°C with and without simulated shale partings. (1) Friction reducer at floor and ceilings. (2) Without friction reducer. (3) Friction reducer at center of pillar (Lomenick and Bradshaw, 1969)

TABLE 3-1 DESCRIPTION OF SALINA STRUCTURE

Mineralogy: 2 mm to 50 mm diameter halite crystals
2 to 10% impurities--anhydrite.

Lithology: Sequential evaporate, 1 to 6-inch layers separated by anhydrite. Total thickness of beds thin to 300 feet.

Major Structures: Near horizontal laminae, minor faulting or folding.

Weathering/Alteration: In situ salt exhibits no alteration

Hydrology/Water Content: Water or brine inclusions, 0.5% of total mass.
Effective Porosity = 0%, Permeability = 10^{-15} cm/s = intact k

Jointing: Discontinuities are dependent on mine location.

	Set A	Set B	Set C	Set D
Type of Joint	Bedding	Joints		
Filling	Anhydrite	Anhydrite		
Orientation (dip dir/dip)	0°	80-90°		
Opening Width	nil	nil		
Spacing	1/ft	Rare		
Waviness	0	0		
Extent of Joints (lengths)	10-50'	1'-30'		

Typical RQD: 60 - 80%

Typical Fracture Frequency: 1-2/ft
3-20

TABLE 3-2
PROPERTIES OF SALINA SALT

BASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	137 lbs/ft ³
	. Natural moisture content (intact)	0.13 %
	. Porosity (total)	less than 0.5%
Stress-strain	. Young's Modulus	(0.35-1.0x10 ⁶) 0.7x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.40 --
	. Bulk Modulus	1.12x10 ⁶ lbs/in ²
	. Shear Modulus	2.5x10 ⁵ lbs/in ²
Strength	. Cohesion 1500-3500 Friction Angle psi range	850 lbs/in ² 30 degrees
	. Uniaxial Compressive Strength	5000 lbs/in ²
	. Tensile Strength	440 lbs/in ²
	. (Plastic Behavior?)	
Thermal	. Coefficient of Linear Thermal Expansion	2.2x10 ⁻⁵ °F ⁻¹
	. Heat Capacity	0.22 BTU/lb-F°
	. Thermal Conductivity	1.5 BTU/hr-ft-F°
Hydrological	. Horizontal permeability	10 ⁻¹⁸ ft/min
	. Vertical permeability	10 ⁻¹⁸ ft/min

4.0 PROPERTIES OF PERMIAN BASIN SALT

4.1 INTRODUCTION

This section presents the various rock properties of the Permian Basin salt deposits of Kansas and New Mexico. The salt is a bedded salt of the Permian Period. The areal extent of the Permian salt is shown in Figure 4.1¹. The Permian Basin salt is divided into two areas, the Delaware and other sub-basins of New Mexico and Texas, and the sub-basin in southwestern Kansas and the Oklahoma Panhandle.

4.2 DESCRIPTION OF ROCK MASS

4.2.1 Lithology

The lithology and stratigraphy of the Permian salt deposits may be considered by dividing the area into the sub-basins of Kansas and New Mexico.

Salt in Kansas occurs in as many as seven middle Permian units. The most widespread zone, however, is that of the Hutchinson salt member of the Wellington Formation. Two other members can be subdivided from the Wellington Formation. These are the anhydrite beds at the base, consisting of alternating gray shale and anhydrite, and an unnamed member at the top, consisting of gray shale with some red shale (see Figure 4-2²). The Hutchinson salt member consists of a "rather irregular alternation of clear, white, coarsely crystalline halite, in beds several inches thick, with thin laminae of gray silty shale, gypsum, and anhydrite"³. The total thickness of the Hutchinson member is as much as 400 feet (Figure 4-3²). The depth to the salt beds ranges from about 400 feet in east-central Kansas to more than 1500 feet east of the Oklahoma Panhandle. The depth of the thickest salt ranges from 700 to 1,100 feet.

A corehole drilled by the AEC to a total depth of 1300.8 feet in Kansas (Section 26, Township 19S, Range 8W, Rice County), provides detailed information on the Wellington Formation and the Hutchinson Salt Member. The top of the Hutchinson member is at 815.1 feet and it is

269 feet thick. The salt is interbedded with siltstone and shale and interlaminated with clay and anhydrite. Salt beds range from 1 foot to 33 feet thick ⁴. Generally, 60 percent of the mined salt section consists of rock salt. Shale beds several inches thick and separated by 15 to 18 feet of salt are common.

Two sub-basins in the Permian Basin area of west Texas and southeast New Mexico, namely the Midland and Delaware Basins, contain extensive salt deposits, (Figure 4-4). Only the Delaware Basin is considered in this report.

The thickest and most extensive beds of salt in the Permian Basin are in the Ochoa system of the Late Permian Period. The Ochoa contains three salt-bearing formations; the Castile, Salado, and Rustler formations in ascending order (Table 4-1) ⁵. The Castile formation contains the oldest thick Permian salt deposits of the area. The formation ranges in thickness from 1,500 to 2,000 feet, except for some thinning to the north and east.

The Castile consists of a basal limestone, grading upward into interlaminated anhydrite and limestone, then into anhydrite 50 to 500 feet thick interbedded with relatively pure salt and with beds ranging in thickness from 0 to 700 feet.

The Salado Formation consists of salt, anhydrite, and potassium salts. The formation is characterized by thick salt units alternating with thinner units of anhydrite and polyhalite with a few beds of sandstone and siltstone at large intervals. The formation is divided into three informal units: lower and upper salt members (1,100 and 550 feet thick, respectively) and the McNutt potash zone (400 to 500 feet thick), which is generally rich in sylvite and other potassium minerals. The Salado Formation ranges in thickness from 1,700 to 1,900 feet. This formation is the principal mined zone in the area. It is 150 to 2000 feet below the surface.

The Rustler formation consists mostly of anhydrite with some discontinuous salt and dolomite beds. It is 200 to 400 feet thick ^{5, 6}.

4.2.2 Mineralogy

The salt of both the Hutchinson Salt Member and the Salado Formation is composed of halite crystals having a considerable size variance.

The major impurities of the Hutchinson salt are clay and anhydrite. The laminae are primarily spaced between 0.25 and 3.0 inches apart. The significant features in the salt are layering of clear and cloudy salt, seasonal layering of shale and anhydrite, and interbedded thick shales and anhydrite².

Less is known about the salt of the Salado formation. The major impurities of the Salado are polyhalite, anhydrite and sylvite. Laminae thicknesses of these impurities and the rock salt are similar to those in the Hutchinson member.

4.2.3 Major Structures

The major structure of the bedrock in the east-central Kansas area is the Prairie Plains homocline with its very gentle dip to the west. Several faults are present in the general vicinity of the Lyons Salt Mine.

In the Delaware Basin the major structural feature is the gentle dip of strata toward the central areas of the basin itself. The basin is flanked by a gentle arch to the east. Two main fault zones are present on either side of the arch. Faults almost encircle the Delaware basin, particularly on the west side. Alkali syenite dikes cut the Castile Formation in the western part of the basin. Some diapiric salt intrusion has been found in the Castile Formation. Associated with the structure is some buckling and downwarping of rocks in the Salado Formation as well as the uplifting of some younger rocks⁷.

4.2.4 Local Structures

Salt deposits can be flatlying, folded or faulted. Jointing or fracturing common to flat-lying beds are predominantly near-horizontal partings along impurity layers (shale or anhydrite). These partings range from very thin laminations to 0.5 feet thick⁴. Large crystal masses or large impurity masses can also be present.

The bedded salt of the Hutchinson Salt Member is generally free of folding or faulting. Cross-sections across the Lyons Mine reveal relatively flat-lying beds with no major structure⁸.

The Salado Formation in the Delaware Basin has been cut by lamprophyre dikes in two potash mines and numerous folds and faults (Figure 4-5⁶).

A description of the structure found in the New Mexico potash and the Kansas rock salt are given in Table 4-2.

4.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

No testing of individual discontinuities of salt or potash from the Permian Basin was found in the literature.

Triaxial testing of Permian-age potash and rock salt in Germany was conducted by Hofer and Thoma (1968)⁹. However, the data were not presented in a form that allowed the shear strength to be calculated. Winkel, Gerstle and Ko (1972)¹⁰ conducted uniaxial creep tests on Carlsbad potash. From these tests, octahedral shear strength was calculated (Figure 4-6). For a mining depth of 2000 feet, τ_{oct} is on the order of 1200 psi.

No discontinuity testing, either triaxial or uniaxial creep tests were found in the literature for the Hutchinson salt member.

4.4 PHYSICAL PROPERTIES FOR OVERALL ROCK MASS

The physical properties for the Hutchinson Salt Member and Salado Formation are shown in Tables 4-3 and 4-4.

The majority of the index properties, strength, and stress-strain data for the Hutchinson Salt Member was obtained by Bradshaw, et al., (1968)¹¹ during studies for Project Salt Vault. The salt exhibited isotropic behavior (equal strength, parallel or perpendicular to bedding). Cohesion and friction angle were estimated from Serata (1964)¹². Thermal properties were taken from Claiborne (1974)¹³ in a report for Union Carbide, Nuclear Division.

The index properties for Salado Formation rock salt and potash were obtained from Wawersik, et al., (1977)¹⁴. Many uniaxial, quasi-static

tests were conducted by Hansen and Gnirk (1975)¹⁵ from AEC coreholes in southeastern New Mexico. The testing indicated that the deeper rock salts had 20 to 35 percent stronger tensile and compressive strengths and similar elastic constants. Anhydrite exhibits much higher elastic moduli and strengths. Polyhalite-rich rock salt also exhibited slightly higher strengths¹⁵. See Figures 4-7, 4-8, 4-9 and 4-10 for examples. Thermal properties were given by Callahan and Ratigan (1975)^{16, 17}. Cohesion and friction angle were estimated from Winkel, et al., (1972)¹⁰. Hansen (1977)^{18, 19, 20} conducted numerous triaxial quasi-static compression and creep tests on bedded salt from New Mexico. Four triaxial compression tests gave tangent moduli of 0.21 to 0.44×10^6 psi.

4.5 ENVIRONMENTAL FACTORS

4.5.1 Time (Creep)

Extensive in situ and laboratory testing of rock salt pillars from the Hutchinson Salt Member has been conducted during Project Salt Vault and by others.

Obert (1964)²¹ conducted creep studies of rock salt and potash model pillars under different axial stresses with strains up to 25 percent (Figure 4-11 and 4-12). He found that the creep rate can be expressed as some power of the applied load for either salt or potash.

Hofer and Thoma (1968)⁹ conducted triaxial creep tests on Permian-age bedded salt under different radial stresses. They observed that rock salt can experience significant inelastic deformation under high confining pressure (Figure 4-13).

Lomenick and Bradshaw (1969)^{22, 23} conducted extensive tests of model pillars from bedded and dome salt. Included in the studies were samples from 2 areas in the Hutchinson Salt. Creep tests were conducted at varying temperatures and axial loads, and with thin shale beds and different pillar shapes. It was observed that there is an initially high rate of deformation that diminishes and becomes constant for all various types. Figures 4-14, 4-15 and 4-16 show the effect of shale partings and pillar shapes.

The laboratory creep tests were correlated with convergence measurements in salt mines of the Hutchinson Salt Member in Project Salt Vault by Bradshaw, Boegly, and Empson (1964) ²⁴. The data is shown in Figure 4-17. They concluded that laboratory pillar model tests of 1000 hours or less duration, run at several different values of average pillar stress, appear to be sufficient to allow estimation of a creep rate for vertical closure rates. However, Baar (1975) ²⁵ warns that theoretical calculations based on laboratory experiments must not be applied to in situ conditions, because of a lack of strain-hardening in pillars and stress adjustment.

Reynolds and Gloyna (1961) ²⁶ also conducted in situ creep measurements in the Hutchinson Salt Member and concluded that the creep rate of the mine was less than in comparable mines in dome salt and that the creep rate decreases. This is a function of the relatively shallow depth of the mine ²⁶.

Hansen and Gnirk (1975) ¹⁵ conducted laboratory tests on rock salt from New Mexico. The conclusion was reached that for a constant stress level, strain is a function of time to a constant power, and is a non-linear function of stress (Figures 4-18 and 4-19). The curves are similar to Kansas rock salt. No in situ creep testing was conducted. Hansen (1977) ¹⁸ conducted further triaxial creep tests with large strains under higher confining pressure. However, he reached no significant conclusions in the report.

4.5.2 Temperature

The physical behavior of the Hutchinson rock salt is drastically affected by temperature. Thermal conductivity, thermal diffusivity and strength decrease sharply with increasing temperature while the deformation rate increases sharply. These tests were conducted in the laboratory and in situ in connection with Project Salt Vault by Lomenick and Bradshaw (1969) ^{22, 23}, Bradshaw et al., (1968) ¹¹ and McClain and Bradshaw (1970) ²⁷.

Laboratory testing by Lomenick and Bradshaw (1969) indicate that higher temperatures with constant stress increase the amount of strain by

seven times (Figures 4-20 and 4-21). Increasing temperature after loading also accelerates strain (Figure 4-22).

McClain and Bradshaw (1970)²⁷ installed heaters in a room in a rock salt mine in Kansas. The increased vertical convergence is shown in Figure 4-23 and 4-24.

Bradshaw et al. (1968)¹¹ demonstrated that the compressive strength of bedded salt is reduced by approximately 10 percent when tested at 200°C.

For multi-stage creep tests Hansen (1977)²⁰ obtained higher strain for tests at 100°C when compared to 28°C (Figure 4-25 and 4-26).

4.5.3 Pressure

Increased pressure on model pillars has caused increased strain. When compared to an increase in temperature, however, the changes are small (Figure 4-27)²³. Long-term applied pressure can produce very large strains in the laboratory²¹. Baar (1975)²⁵ predicts that this is also possible in situ if measures are not taken to relieve the pressure.

4.5.4 Water/Moisture

Bedded salt deposits of the Hutchinson Salt and Salado Formation have moisture trapped internally in vesicles and along partings. Most of the moisture is brine. Wawersik, et al. (1977)¹⁴ found 0 to 3.5% moisture content in New Mexico Rock Salt. Bradshaw et al. (1968)¹¹ found 0.048 to 1.08 percent moisture in rock salt from Kansas.

The trapped brine can be released with considerable energy fracturing the rock, when the rock is heated. For salt samples from two mines in Kansas, disintegration occurred at temperatures of 260 to 320°C¹¹.

4.5.5 Irradiation

The effect of irradiation on bedded salt was studied by Bradshaw, et al. (1968)¹¹. It was concluded that radiation exposure doses of 5×10^8 R produce some change in structural properties, but the effect on mine stability would be negligible. This is shown in Table 4-5 and in Figure 4-28.

4.6 ANTICIPATED ENVIRONMENT

The effect of increased temperature on the rate of creep is expected to be a major environmental factor. To allow for retrievable wastes, closure rates will have to be accurately estimated and appropriate accommodations will have to be made in the repository designs.

4.7 EXCAVATION CRITERIA

4.7.1 Water Inflow

Bedded rock salt of Kansas or New Mexico contains very little water (Section 4.5.4).

4.7.2 Water Pressure Effects on Stability

Since no major water inflows are anticipated, no stability problems from such water are possible. Rock salt with brine inclusions, however, may be accompanied by explosive reactions (i.e. decrepitation) when the temperature is raised.

4.7.3 Excavation Techniques

The bedded rock salt of the Hutchinson Salt Member and the potash of the Salado Formation are mined primarily by the room and pillar method except in one mine in New Mexico which is mined by modified longwall techniques. The heights of the mines vary from 5.5 to 10 feet and they are mined by conventional drilling and blasting techniques with increasing use of continuous miners. Room widths vary from 20-100 feet and depend on mine depth, physical characteristics of the salt and surrounding strata and operating techniques. Extraction ratios average 60 percent. Tunneling machines could be utilized in the rock salt because the salt is low in abrasion and has sufficient stand-up time²⁸.

4.7.4 Temporary and Permanent Support

Mining conditions in the salt mines of the Permian basin are described as possibly the most severe of any salt mines in the United States. Pillar and roof spalling and floor heave have been reported. The

problems are directly associated with depth of mine and shale partings in the roof and floor ²⁸. The roof spall has been effectively controlled with short rock bolts ²⁹. Floor heave and pillar spall have been reduced by leaving one foot of rock salt in the floor and mining 6-foot rather than 9-foot layers.

4.7.5 Extraction Ratios

The mines of Kansas and New Mexico are primarily room-and-pillar patterns with depths ranging from 645 to 1150 feet and mining heights of 5.5 to 10 feet. Estimated extraction rates are 40 to 60 percent. Pillar loadings range from 1500 to 4000 psi.

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FIGURE 4-1 Permian Basin Salt Fields of Kansas, Oklahoma, Texas and New Mexico (D'Appolonia, 1976)

FIGURE 4-2 Distribution of Salt Beds in the Permian of Kansas (Dellwig, 1961)

FIGURE 4-3 Extent of Hutchinson Salt in Oklahoma and Kansas and Thickness of the Salt in Kansas in Feet (Dellwig, 1961)

FIGURE 4-4 Relationship of Structural and Physiographic Features of Permian age to area underlain by salt beds of the Ochoa Series (Pierce and Rich, 1962)

FIGURE 4-6 Relationship Between Octahedral Shear Yield and Mean Normal Stress (Winkel, Gerstle, and KO, 1972)

FIGURE 4-7 Circumferential Strain Versus Axial Stress for Polyhalite-Rich Rock Salt
(Hansen and Gnirk, 1975)

FIGURE 4-8 Axial Strain vs. Axial Stress in Rock Salt
(Hansen and Gnirk, 1975)

FIGURE 4-9. Axial Strain vs. Axial Stress in Polyhalite-Rick Rock Salt (Hansen and Gnirk, 1975)

FIGURE 4-10 Axial Strain vs. Axial Stress in Halite-Rich Anhydrite (Hansen and Gnirk, 1975)

FIGURE 4-11 Kansas Salt, Strain vs. Time
(Obert, 1964)

FIGURE 4-12 New Mexico Potash, Strain vs. Time
(Obert, 1964)

FIGURE 4-13 Rock Salt Deformation Curves
(Hofer and Thoma, 1968)

FIGURE 4-15 Deformation of Pillar Models at
4000 psi and 22.5 °C. (1) Natural shale
of (2) Simulated Shale Parting
(3) Natural Shale Parting (4) Without
Shale Parting (Lomenick and Bradshaw, 1969)

FIGURE 4-14 Deformation of Pillar Models at
4000 psi and 22.5 °C with and without simulated
shale partings. (1) Friction reducer at
floor and ceilings. (2) Without friction
reducer. (3) Friction reducer at center of
pillar (Lomenick and Bradshaw, 1969)

FIGURE 4-16 Deformation of Pillar Models at
4000 psi and 22.5 °C and with width to height
ratios of 2, 3 and 4 (Lomenick and Bradshaw,
1969).

FIGURE 4-17 Measured Mine Convergence Rates Superimposed on Plots of Equation Derived from Model Tests (Bradshaw, Boegly and Empson, 1964).

FIGURE 4-18 Log-log Plot of Strain
vs. Time
(Hansen and Gnirk, 1975)

FIGURE 4-19 Log-log Plot of Strain
vs. Time
(Hansen and Gnirk, 1975)

FIGURE 4-20 Deformation of Pillar Models from Various Localities at 4000 psi and 25.5°C (Lomenick and Bradshaw, 1969)

FIGURE 4-21 Deformation of Pillar Model from Various Localities at 4000 psi and 100°C (Lomenick and Bradshaw, 1969)

FIGURE 4-22 Deformation of Pillar Model at 4000 psi and 22.5°C and 100°C (Lomenick and Bradshaw, 1969)

Summary of Deformations in and Around Center Pillar (Vertical Section) Between 1170-1500 Standard Days.

FIGURE 4-23 Summary of Deformations Around Center Pillar (Vertical Section) During Heating (McClain and Bradshaw, 1970)

FIGURE 4-24 Vertical Deformation of Heated Pillar as a Function of Time (McClain and Bradshaw, 1970)

FIGURE 4-25 Cumulative Axial Strain as a Function of Differential Stress for Multi-Stage Creep Test (Hansen, 1970)

FIGURE 4-26 Cumulative Axial Strain as a Function of Differential Stress for Multi-Stage Creep Test (Hansen, 1977c)

FIGURE 4-27 Deformation of Pillar Models at Various Temperatures and Pressures (Lomenick and Bradshaw, 1969)

FIGURE 4-28 Compression Test of Hutchinson, Kansas, Bedded Salt at Room Temperatures (Bradshaw, 1968)

Age		Rock Unit	Thickness (feet)	Description
Quaternary	Holocene	Mescalero Sand	0-15	Dune sand, uniformly fine-grained, light-brown to reddish-brown
		Caliche	0-5	Limestone, chalky, includes fragments of underlying rock
		Gatuna Formation	0-375	Sandstone and siltstone, poorly indurated, dominantly reddish-orange
Tertiary	Pliocene	Ogallala Formation	20-60	Sandstone, fine- to medium-grained, tan, pink, and gray. locally conglomeratic, and typically has resistant cap of well-indurated caliche
		Chinle Formation	300-800	Mudstone shaly, reddish-brown and greenish-gray, interbedded lenses of conglomerate, and gray and reddish-brown sandstone
Triassic	Late Triassic	Santa Rosa Sandstone	212-245	Sandstone, medium- to coarse-grained, commonly cross-stratified, gray and yellowish-brown, contains conglomerate and reddish-brown mudstone
		Dewey Lake Redbeds	505-560	Siltstone and sandstone, very fine to fine-grained, reddish-orange to reddish-brown, contains interbedded reddish-brown claystone, small-scale lamination and cross-stratification common
Permian	Ochoan	Rustler Formation	280-490	Anhydrite and rock salt with subordinate dolomite, sandstone, claystone, and polyhalite
		Salado Formation	1200-2310	Rock salt with subordinate anhydrite, polyhalite, potassium ores, sandstone, and magnesite
		Castile Formation	30-1830	Anhydrite and rock salt with subordinate limestone

BLE 4-1 Summary of Rock Units of Latest Permian (Ochoan) and younger age, Los Medanos area, Eddy and Lea Counties, New Mexico
(Jones et al. 1973)

TABLE 4-2 Description of Permian Basin Structure

Mineralogy: 2 mm to 50 mm diameter halite crystals
 2 - 10% impurities - anhydrite, clay, polyhalite, sylvite
OR sylvite-rich with halite (Potash)

Lithology: Sequential evaporite, laminae 0.25 to 3.0 inches apart, clay and anhydrite interlams, In New Mexico, also polyhalite.

Major Structures: Near-horizontal minor structure in Kansas, some faulting and lamphophyre dikes in New Mexico.

Weathering/Alteration: In situ salt exhibits no alteration

Hydrology/Water Content: Water or brine inclusions, 0.5% of total mass
 Porosity = 0%, Permeability = 10^{-15} cm/s (intact)

	SALT		POTASH	
	Set A	Set B	Set C	Set D
Type of Joint	Bedding	Joints	Bedding	Joints
Filling	Clay Anhydrite	red halite	halite, clay anhydrite	polyhalite
Orientation (dip dir/dip)	0°	90°	0°	90°
Opening Width	nil	nil	nil	nil
Spacing	1 to 3/ft	Occasional	1 to 3/ft	Rare
Waviness	0	0	0	0
Extent of Joints (lengths)	Extensive	1-6 inches	Extensive	1-6 inches

Typical RQD: 50-90 Salt
 50-90 Potash

Typical Fracture Frequency:
 1 to 3/ft

TABLE 4-3

TYPICAL ROCK MASS PROPERTIES NEW MEXICO POTASH-RICH ROCK SALTBASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	132 lbs/ft ³
	. Natural moisture content (intact)	1.75 %
	. Porosity (total)	less than 3.0%
Stress-strain	. Young's Modulus	0.2-2x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.33 --
	. Bulk Modulus	3.3x10 ⁶ lbs/in ²
	. Shear Modulus	2.5x10 ⁵ lbs/in ²
Strength	. Cohesion 1500-3500	1200 lbs/in ²
	Friction Angle psi range	20 degrees
	. Uniaxial Compressive Strength	4000 lbs/in ²
	. Tensile Strength	240 lbs/in ²
	. (Plastic Behavior?)	
Thermal	. Coefficient of Linear Thermal Expansion	22.2x10 ⁻⁶ °F
	. Heat Capacity	0.22 BTU/lb-F°
	. Thermal Conductivity	2.43 BTU/hr-ft-F°
Hydrological	. Horizontal permeability	10 ⁻¹⁸ ft/min
	. Vertical permeability	10 ⁻¹⁸ ft/min

TABLE 4-4

TYPICAL ROCK MASS PROPERTIES KANSAS SALTBASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	135 lbs/ft ³
	. Natural moisture content (intact)	0.15 %
	. Porosity (total)	less than 0.5%
Stress-strain	. Young's Modulus	0.35×10^6 lbs/in ²
	. Poisson's Ratio	0.4 --
	. Bulk Modulus	5.83×10^5 lbs/in ²
	. Shear Modulus	1.25×10^5 lbs/in ²
Strength	. Cohesion 1500-3500	900 lbs/in ²
	Friction Angle psi range	30 degrees
	. Uniaxial Compressive Strength	4100 lbs/in ²
	. Tensile Strength	400 lbs/in ²
	. (Plastic Behavior?)	
Thermal	. Coefficient of Linear Thermal Expansion	22.2×10^{-6} °F
	. Heat Capacity	0.22 BTU/lb-F°
	. Thermal Conductivity	2.43 BTU/hr-ft-F°
Hydrological	. Horizontal permeability	10^{-18} ft/min
	. Vertical permeability	10^{-18} ft/min

All results have been rounded off to the nearest 100 psi and the standard deviation, to the nearest 50 psi.

Type of salt:	Exposure dose (R)	Compressive strength (psi)	Yield strength (psi)	Apparent elastic limit (psi)	Modulus of elasticity (psi) $\times 10^6$
<i>At 20° C</i>					
Bedded parallel	0	4200 $\pm$ 500	2500 $\pm$ 300	1500 $\pm$ 300	0.35 $\pm$.06
	10 ⁶	4500 $\pm$ 500	2500 $\pm$ 150	1500 $\pm$ 200	0.32 $\pm$.06
	10 ⁷	4600 $\pm$ 400	2700 $\pm$ 250	2100 $\pm$ 200	0.35 $\pm$.02
	10 ⁸	4600 $\pm$ 150	3400 $\pm$ 250	2500 $\pm$ 200	0.36 $\pm$.09
	5 $\times$ 10 ⁸	3500 $\pm$ 50	2700 $\pm$ 200	2000 $\pm$ 300	0.39 $\pm$.07
Bedded perpendicular	0	4000 $\pm$ 400	2300 $\pm$ 300	1700 $\pm$ 200	0.36 $\pm$.17
	10 ⁶	3800 $\pm$ 500	1800 $\pm$ 250	1400 $\pm$ 250	0.35 $\pm$.10
	10 ⁷	4100 $\pm$ 400	2300 $\pm$ 500	1800 $\pm$ 500	0.38 $\pm$.04
	10 ⁸	4000 $\pm$ 400	2400 $\pm$ 500	1900 $\pm$ 300	0.38 $\pm$.05
	5 $\times$ 10 ⁸	3500 $\pm$ 400	2400 $\pm$ 300	1900 $\pm$ 250	0.37 $\pm$.11
Dome	0	5600 $\pm$ 100	2900 $\pm$ 150	2000 $\pm$ 100	0.50 $\pm$.05
	10 ⁶	5300 $\pm$ 100	2900 $\pm$ 150	2000 $\pm$ 300	0.51 $\pm$.12
	10 ⁷	5100 $\pm$ 200	3000 $\pm$ 100	2100 $\pm$ 300	0.62 $\pm$.05
	10 ⁸	4100 $\pm$ 200	2700 $\pm$ 100	1800 $\pm$ 200	0.48 $\pm$.04
	5 $\times$ 10 ⁸	3600 $\pm$ 500	2500 $\pm$ 200	1300 $\pm$ 50	0.59 $\pm$.12
<i>At 200° C</i>					
Bedded parallel	0	3900 $\pm$ 200	1600 $\pm$ 200	1400 $\pm$ 100	0.09 $\pm$.01
	5 $\times$ 10 ⁸	3400 $\pm$ 400	1600 $\pm$ 250	1500 $\pm$ 250	0.12 $\pm$.02
Bedded perpendicular*	0	3600 $\pm$ 100	1600 $\pm$ 100	1500 $\pm$ 150	0.11 $\pm$.01
	5 $\times$ 10 ⁸	3300 $\pm$ 400	2100 $\pm$ 150	1300 $\pm$ 100	0.12 $\pm$.01
Dome	0	3600 $\pm$ 500	1900 $\pm$ 150	1500 $\pm$ 200	0.14 $\pm$.01
	5 $\times$ 10 ⁸	3100 $\pm$ 300	2300 $\pm$ 150	1800 $\pm$ 200	0.16 $\pm$.01

Bedded parallel: bedded salt, force applied parallel to the planes of stratification
 Bedded perpendicular: bedded salt, force applied perpendicular to the planes of stratification

* Only two samples tested

TABLE 4-5 Physical Properties of Rock Salt from Hutchinson, Kansas and Grand Saline, Texas (Bradshaw, et al, 1968)

5.0 PROPERTIES OF PARADOX BASIN SALT

5.1 INTRODUCTION

This section presents the various rock-mass properties of the Paradox Basin salt deposits of Utah and Colorado. The primary salt is that of the Paradox Member of the Pennsylvanian Hermosa Formation. The areal extent of the Paradox Basin is shown in Figure 5-1 ¹.

5.2 DESCRIPTION OF ROCK MASS

5.2.1 Lithology

This section will primarily concentrate on the Cane Creek Anticline and vicinity because of the availability of data from this area.

In general, the Paradox basin is a wedge-shaped sequence of sedimentary rocks covering Cambrian through Tertiary rocks, with the exception of the Ordovician and Silurian periods (Figure 5-2) ¹.

The Paradox Member is the middle member of the Middle Pennsylvanian Hermosa Formation. The Hermosa can be subdivided into an upper member above the halite and a lower member below, both consisting of carbonates. The Paradox member exhibits a cyclic pattern of chemical and clastic sedimentation and can be subdivided into 29 evaporite cycles. The thickness of the evaporite facies is highly variable due to the widespread effects of salt flowage in the numerous salt anticlines. The original thickness is estimated to be 5,000 to 6,000 feet. In the salt anticlines, the thickness can be nearly 14,000 feet.

A typical cycle of the Paradox Member is shown in Figure 5-3 ¹. The anhydrite is laminated with dolomitic mud and is very dense and impermeable except where fractured. It is the least abundant lithology of the cyclic pattern. The dolomite is fine-grained, dense and composed of 50 percent quartz silt. The black shale is 20 to 30 percent dolomite or calcite. The remainder is clay-size detritus and organic matter. Fracturing is widespread in the shale.

5.2.2 Mineralogy

The mineralogy of the ore in the Cane Creek potash mine consists of regular alternations of sylvinite (sylvite and halite) layers 1 to 6 inches thick, and anhydrite laminae less than 1/8 inch thick ². The rock is composed of an intergrowth of halite-sylvite crystals that range from 2mm to 50mm in diameter. Average crystal size is about 5 mm. The rock is generally a smokey gray, tan or red color. The salt rock contains no more than 2 or 3 percent of minerals insoluble in water. Nearly all of this fraction is anhydrite with trace amounts of dolomite, quartz, clay and talc. Carnallite (a potash mineral) is often present with sylvite.

5.2.3 Structure

The general structure of the Paradox basin is that of an asymmetrical basin made complex by numerous anticlinal structures. These salt anticlines are the dominating structural features of the basin. The salt anticlines have been divided geographically and structurally into five systems. The general areas of these features can be seen in Figure 5-1.

A typical anticline can be broken into three structural components: the floor of non-evaporitic rocks beneath the anticline, the central core of halite and its associated caprock, and the overlying or flanking beds of non-evaporite rocks. A typical structure is shown in Figure 5-4. The central cores of salt anticlines range in thickness from 2,500 to 14,000 feet.

There are basically two types of anticlines -- diapiric (Figure 5-4) and nondiapiric. Cane Creek is an example of non-diapiric anticline (Figure 5-5). The nondiapiric anticlines are characterized by disharmonic folding and minor faulting. Evans and Linn (1969) ² have conducted detailed studies of the folding in the Cane Creek mine. The structure is complex with up to fifth-order folds.

A description of the structures found in the Utah sylvinite are given in Table 5-1.

5.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

No testing of individual discontinuities of rock salt or sylvinite from the Paradox Basin was found in the literature.

Winkel, et al. (1972) ³ estimated a shear strength from in situ measurements of closure in the Cane Creek Mine. On the basis of these data the apparent cohesion is estimated to be 900 to 1200 psi, with the angle of internal friction equal to 20 to 30 degrees.

5.4 PHYSICAL PROPERTIES FOR OVERALL ROCK MASS

The physical properties for the Paradox Member sylvinite are shown in Table 5-2.

Many of the properties were estimated to be similar to Carlsbad Potash or other rock salts. These included unit weight, thermal properties and hydrological properties. Natural moisture content was determined by Hite and Lohman (1973) ¹. Strength properties were from studies by Winkel et al. (1972) ² and pillar strength estimates from the Cane Creek Mine by Wiselmann (1972) ⁴. Stress-strain parameters were also estimated from Winkel et al. (1972) ².

5.5 ENVIRONMENTAL FACTORS

5.5.1 Time (Creep)

Limited creep testing has been performed on potash in the laboratory and at Cane Creek Mine.

King and Acar (1969) ⁵ studied the creep properties of Saskatchewan potash as a function of temperature and stress. The resulting pillar deformations were found to correlate with the power law.

$$\epsilon = at^b$$

where: a and b are constants

$$0 < b < 1$$

Their results were found to agree with previous studies by Obert (1964) ⁶, Lomenick and Bradshaw (1969) ^{7, 8}, and Bradshaw et al. (1964) ⁹. Details of these studies are given in Chapter 4. All use some form of the power law.

Lomenick and Bradshaw (1969)^{7, 8} studied the ASSE II salt from Germany which is from salt anticlines similar to those of the Paradox Basin.

Closure measurements by Weiselmann (1972)⁴ at the Cane Creek Mine were made as part of studies to reduce the amount of closure. The closure at Cane Creek was very high due to the high horizontal and vertical pressures below 3000 feet. The rates were reduced, but not enough to prevent abandonment of the mine. Closure rate versus percentage extraction is shown in Figure 5-6.

Winkel, Gerstle, and Ko (1972)³ also found the predicted closure from finite element analysis was much higher than measured closure in the Cane Creek Mine (Figure 5-7).

Baar (1965)¹⁰ made measurements of rock pressures in deep potash mines and concluded that:

1. The rock is subject to high triaxial stress and will react immediately if one stress component is removed.
2. Plastic deformation is a function of time and in situ properties.
3. Brittle fracture is possible in stronger potash.

Baar measured very large deformations in deep mines -- these continued for more than one year without decreasing.

5.5.2 Temperature

Increased temperature drastically affects the physical properties of sylvinite or potash.

This was shown by Lomenick and Bradshaw (1969)^{7, 8} with the ASSE II salt in Figures 5-8 and 5-9. The deformation at 100°C was 3 times that at 22.5°C.

King and Acar (1969)⁵ also studied temperature effects. The natural strain increased two times (at a pressure of 5000 psi) when the temperature was increased from 80°F to 110°F. This is shown in Figures 5-10 and 5-11.

5.5.3 Pressure

Long term applied pressure on sylvinite or potash can cause large deformations. This is particularly confirmed by Baar (1965)¹⁰ in the

deeper potash mines. The increased pressure at the greater depths is an important environmental factor.

5.5.4 Water/Moisture

The sylvinite at the Cane Creek Mine contained only 0.093 to 0.14 percent moisture. Water can also be found along the shale partings. However, the amounts are not large.

5.5.5 Irradiation

The effect of irradiation on sylvinite or potash has not been studied.

5.6 ANTICIPATED ENVIRONMENT

The high vertical and horizontal pressures at the greater depths of the sylvinite or potash mines is expected to be a major problem. Cane Creek Mine was closed due to rock mechanics problems, the marginal extraction ratios and other problems.

5.7 EXCAVATION CRITERIA

5.7.1 Water Inflow

The sylvinite of Cane Creek Mine contained very little water.

5.7.2 Water Pressure Effects on Stability

Since no major water inflows are anticipated, no stability problems from such water are possible.

5.7.3 Excavation Techniques

The sylvinite at Cane Creek was mined by drilling and blasting, continuous ripper miners and boring machines. The opening size was generally 8-10 feet high by 14-18 feet wide. Rock bolts were used for ground control. Main entries were mined at extraction ratios ranging from 29 to 44 percent and production panels between 49 and 70 percent. The mine was a typical room-and-pillar layout⁴. However, large deformations were experienced and minor folds with wave lengths of 100 to 400 feet and

amplitudes of 20 to 100 feet caused difficulties in keeping the mining horizon within the ore zone. Gas pockets were also encountered at the contact of the ore zone with overlying roof shales. During the development work, 18 men were killed in a gas explosion and resulting fire. The mine has now been modified to a solution mining operation ¹¹.

5.7.4 Temporary and Permanent Support

Mining conditions in the Cane Creek Mine were difficult. Closure rates were high even with lower extraction ratios. Rock bolts were used for ground control. Four feet of roof salt was also left in place to reduce deformation.

5.7.5 Extraction Ratios

The Cane Creek Mine was a room-and-pillar operation at a mining height of 8 to 10 feet and a depth of more than 3000 feet. Extraction ratios ranged from 29 to 70 percent. In similar potash mines in Canada extraction ratios are 40 percent or less. It is important to note that the Cane Creek Mine is no longer operated as an underground mine.

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EXPLANATION

- APPROXIMATE LIMIT OF PARADOX BASIN
- APPROXIMATE LIMIT OF UNCOMPAGHRE TROUGH
- ANTICLINE OR ELONGATED DOME
- 2-3 TRACE OF SECTION, FIGURE 3
- A-A' TRACE OF SECTION, FIGURE 5
- B-B' TRACE OF SECTION, FIGURE 6
- C-C' TRACE OF SECTION, FIGURE 7

0 15 30 MILES

FIGURE 5-1 Index Map of Paradox Basin Showing Major Structures and the Trace for Figure 5.4 and 5.5 (Hite and Lohman, 1973)

FIGURE 5-2 Generalized Stratigraphic Chart of Northeastern Paradox Basin
(Hite and Lohman, 1973)

FIGURE 5-3 Typical Evaporite Cycle of Paradox Member
(Hite and Lohman, 1973)

A'

DRY CREEK SYNCLINE

SKEIN
MESA.
Kd Kbc

NUCLA SYNCLINE

FIGURE 5-4 Cross-Section Through Paradox Valley Anticline (Trace Shown on Figure 5.1)
(Hite and Lohman, 1973)

FIGURE 5-5 Cross-Section Through Cane Creek Anticline, Utah. Dark zones are clastic-penesaline marker beds. Inter-veining units are salt. (Hite and Lohman, 1973)

FIGURE 5-6 Vertical Closure Rates vs. Percentage Extraction (Weiselmann, 1972)

FIGURE 5-7 Comparison of Predicted and Measured Closure of 10-inch Opening in Moab Mine (Winkel, Gerstle, and Ko, 1972)

FIGURE 5-8 Deformation of Pillar Models from Various Localities at 4000 psi and 100 °C (Lomenick and Bradshaw, 1969)

FIGURE 5-9 Deformation of Pillar Models from Various Localities at 4000 psi and 22.5 °C (Lomenick and Bradshaw, 1969)

FIGURE 5-10 Natural Strain vs. Time at 80°F
(King and Acar, 1969)

FIGURE 5-11 Natural Strain vs. Time at 110°F
(King and Acar, 1969)

TABLE 5-1 Description of Structures in the Moab Sylvinite

Mineralogy: Intergrowth of halite and sylvite crystals 2-50mm in diameter.
2-3% impurities

Lithology: 1-6 inch layers, anhydrite laminae, occasional

Major Structures: Salt anticline structure, faulting and folding complex

Weathering/Alteration: No

Hydrology/Water Content: 0.093 - 0.144%

Jointing:

	Set A	Set B	Set C	Set D
Type of Joint	Bedding			
Filling	Anhydrite-Shale			
Orientation (dip dir/dip)	Various			
Opening Width	Nil			
Spacing	1 to 6"			
Waviness	Yes			
Extent of Joints (lengths)	100's of feet			

Typical RQD: 70 to 90%

Typical Fracture Frequency: 1-3/ft.

TABLE 5-2
TYPICAL ROCK MASS PROPERTIES SYLVINITE

BASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	132 lbs/ft ³
	. Natural moisture content (intact)	0.1 %
	. Porosity (total)	less than 0.5%
Stress-strain	. Young's Modulus	0.8×10^6 lbs/in ²
	. Poisson's Ratio	0.35 --
	. Bulk Modulus	0.9×10^6 lbs/in ²
	. Shear Modulus	0.3×10^6 lbs/in ²
Strength	. Cohesion 1500-3500 Friction Angle psi range	900-1200 lbs/in ² 20-30 degrees
	. Uniaxial Compressive Strength	3500 lbs/in ²
	. Tensile Strength	250 lbs/in ²
	. (Plastic Behavior?)	
Thermal	. Coefficient of Linear Thermal Expansion	22.2×10^{-6} °F
	. Heat Capacity	0.22 BTU/lb-F°
	. Thermal Conductivity	2.4 BTU/hr-ft-F°
Hydrological	. Horizontal permeability	
	. Vertical permeability	

6.0 PROPERTIES OF DOME SALT

6.1 INTRODUCTION

This section presents the various rock-mass properties of the Gulf Coast salt domes of Texas, Louisiana and Mississippi. The areal extent of the salt dome region is shown in Figure 6-1 ¹.

6.2 DESCRIPTION OF ROCK MASS

6.2.1 Lithology

The source of the Louann salt dome underlies parts of southern Arkansas, Mississippi, Alabama, Texas and Louisiana. The most prominent areas of salt dome intrusion from this thick salt layer are southern and northern Louisiana, Mississippi and southeast and northeast Texas (Figure 6-2).

The Louann salt is in the Eagle Mills Formation of Jurassic or Permian age. The Eagle Mills Formation contains red shale, sandstone, anhydrite and salt. The thickness of salt ranges from 76 to 1300 feet. The bedded salt is found in southern Arkansas and northern Louisiana ².

The general characteristics of salt domes are much the same regardless of their location. Idealized sections are shown in Figure 6-3.

As can be seen in Figure 6-2, there are more than 300 salt domes in the Gulf Coast Embayment, and more than 260 onshore domes in the Texas-Louisiana-Mississippi-Alabama portion of the embayment. This study will be confined to domes that are presently being mined by underground room-and-pillar methods.

In 1963, Kupfer listed ten operating or planned subsurface salt mines of the Gulf Coast. These are listed in Table 6-1. The depths to salt in these domes range from 15 feet (Avery Island) to 1880 feet (Bruinsburg) ³. Depths to salt domes can be as much as 10,000 feet or more. The height of the domes above their base is extremely variable, depending on the amount of piercement into the overlying sediments. In domes that have risen to near the present land surface, the height is on the order of 10,000 to 20,000 feet.

At the top of the near-surface salt domes is a caprock composed of anhydrite, gypsum and/or limestone. The limestone is generally at the top of the caprock, anhydrite at the base and gypsum, anhydrite and calcite in the middle. Anhydrite is also draped down the sides like a hood. The caprock is normally 300 to 400 feet thick, but may be as much as 1000 feet thick². Two examples of salt domes will be detailed below.

The Avery Island salt dome in Iberia Parish, Louisiana, is one of the "Five Islands" of the Louisiana Gulf Coast Area. A generalized block diagram of the Avery Island Dome is shown in Figure 6-4. The dome is circular in outline and the sediments dip steeply away from the dome. The country rock is the upper Miocene interval of soft, thick sand bodies and gravels with clay beds. The caprock is anhydrite, gypsum and calcite in ascending order and reaches a thickness in excess of 400 feet^{4, 5}.

Tatum Dome in Lamar County, Mississippi is approximately 1550 feet deep. A cross-section is shown in Figure 6-5. The dome is nearly circular in areal plan and nearly flat. The country rock is Miocene and Oligocene clays and sands and the contacts on the flanks are nearly vertical. The caprock ranges from 530 to 675 feet thick and consists of limestone, gypsum and anhydrite².

6.2.2 Mineralogy

The salt-dome deposits are almost pure sodium chloride except for the caprock. Anhydrite is the principal impurity and usually occurs as black bands in the salt. Bands of sandstone are known to exist as well as fragments of country rock². Layering is the most distinctive physical feature. Most layers average 1-10 inches thick and consist of interbedded light and dark bands. The darker layers are usually anhydrite. Grain-size is coarse, distinctly crystalline, with prominent cubic cleavage. Most crystals range between 1/4 to 1/2 inch in diameter. Fine to very fine-grained salt is rare. Pods of extremely coarse-grained salt occur with crystals 1 to 2 inches across.

6.2.3 Structure

Kupfer (1963, 1970, 1976)¹, 6, 7 and Muehlberger (1959, 1968)^{8, 9} have conducted studies or collected (from Balk and others) the results of extensive studies of the structure of some existing underground salt mines (Grand Saline, Jefferson Island, Winnfield, Weeks Island, Avery Island and Hockey Domes).

The layers in the salt all stand essentially vertical and are isoclinally folded around vertical axes. The roof and floor of the workings show transverse cross-sections of the folds which display varied pattern complications of the fold. Figure 6-6 exhibits block diagrams showing salt layering in the walls and the roof of the Weeks and Jefferson mines. The axial planes are vertical and parallel to the limbs of the folds. Detailed mapping shows microfaults and complex folding (Figure 6-7). Typical attitudes of the features are shown in Table 6-2. Closures are more common in the South Louisiana domes (Figure 6-8).

Fractures are uncommon but natural exfoliation fractures develop as rooms remain open. Faulting is rare and, when found, is very minor. However, shear zones are very common on the periphery of the dome and smaller shear zones occur within the dome. The larger shear zones delineate the "spines" of the salt's upward movement.

Discontinuities of domal rock salt are considerably different from those of bedded salt. A description of the dome salt structure is given in Table 6-3. Much of the information is from Kupfer (1963)¹, in which he summarized structures of the six salt domes with subsurface mines.

6.3 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

No testing of individual discontinuities of dome rock salt has been found in the literature.

Triaxial compression testing of salt rock cores (4-15/16-inch-diameter) from Tatum Dome, Jackson, Mississippi was conducted by the Division of Engineering Laboratories, Bureau of Reclamation. Shear strengths were determined during these tests as well as stress-strain curves.

The cores were taken from depth intervals of 1,650 to 2,700 feet. Eighteen specimens were tested. Eight analyses were conducted from the set of data. These analyses are shown in Table 6-4. Figure 6-9 shows the curve for the maximum load obtained when corrected for area. At $X = 0$ the cohesion equaled 564 psi and the friction angle equaled 63 degrees. Over the stress range of 1000 to 2000 psi the cohesion is 1100 psi and the friction angle is 36 degrees ¹⁰.

Hansen (1977) ¹¹ conducted triaxial tests and obtained the failure envelope shown in Figure 6-10. The average shear strength parameters in the normal stress range of 2000 to 3000 psi were a cohesion of 1700 psi and a friction angle of 33 degrees.

6.4 PHYSICAL PROPERTIES FOR OVERALL ROCK MASS

The physical properties for domal salt are shown in Table 6-5. Much of the data was obtained from Bradshaw, et al. (1968) ¹², Deere and Miller (1966) ¹³ and Project Dribble (1962) ¹⁰. Project Dribble provided data for cohesion and friction angles (see Section 6.3) and uniaxial compressive strength. Young's moduli were found in all of the above references. Bradshaw et al. (1968) ¹² obtained values of 0.5×10^6 psi for tangent moduli.

Thermal properties were obtained from Gera (1972) ¹⁴ and hydrological properties (moisture content and porosity) were obtained from Gloyna and Reynolds (1961) ¹⁵ and Hansen (1977) ¹⁶.

Rock salt is essentially isotropic, i.e. strength properties are similar when tested parallel or perpendicular to bedding.

Hansen (1977) ¹⁶ performed extensive tests on salt from Jefferson Island. Included in the tests are triaxial compression tests, triaxial creep tests and tensile strength tests. Indirect tensile strength tests averaged 220 psi. Mohr's envelope of Jefferson Island Salt is presented in Figure 6-11. A standard triaxial compression test result is shown in Figure 6-12. Average tangent modulus over a stress range of 2000 to 3000 psi was 10^6 psi.

In situ elastic properties were determined by Christensen, 1966 ¹⁷ utilizing a 3-Dimensional velocity log. These values are shown in Table 6-6.

6.5 ENVIRONMENTAL FACTORS

6.5.1 Time (Creep)

Some in situ and laboratory testing of rock salt from domal salt mines has been conducted by various investigators. Laboratory studies included those reported by Project Dribble (1962)¹⁰, Lomenick and Bradshaw (1969)^{18, 19} and Thompson and Ripperger (1964)²⁰.

Lomenick and Bradshaw conducted extensive tests of model pillars from bedded and domal salt. Included in these studies were rock salt from the Grand Saline and Cote Blanche Domes. Creep tests were conducted at varying temperatures and axial loads, and with different pillar shapes. It was observed that there is an initially high rate of deformation, that diminishes and becomes constant for the various rock salt types. An empirical relationship was developed from the tests for strain rate and cumulative deformation.

$$\begin{aligned}\dot{\epsilon} &= 0.39 \cdot 10^{-37} T^{9.5} \sigma^{3.0} t^{-3.0} \\ \epsilon &= 1.30 \cdot 10^{-37} T^{9.5} \sigma^{3.0} t^{0.30}\end{aligned}$$

where: $\dot{\epsilon}$ = strain rate (in/in/hr)
 ϵ = cumulative deformation (in/in)
 T = absolute temperature ($^{\circ}\text{K}$)
 σ = average pillar stress (psi)
 t = time (hr)

This relationship appears to be the best creep law with respect to temperature.

Most creep laws are a function of differential or axial stress and temperature. This is shown by Thompson and Ripperger in Figures 6-13 and 6-14 in tests on salt from Grand Saline Dome. The relationship derived was

$$\dot{\epsilon} = C \left(\frac{\sigma}{\sigma_0} \right)^n$$

where: $\dot{\epsilon}$ = strain rate (in/in/hr)
 σ = axial or differential stress
 σ_0 = characteristic stress
 C and n are constants

Project Dribble tests also exhibited creep under high axial and confining pressures, as shown in Figure 6-15. The axial strain of salt at 5,000 psi confining pressure is more than 10 times that with no confining pressure. Nair and Deere (1970) ²¹ derived the equation:

$$\epsilon_c = A \sigma^n t^m$$

where: A, n and m are constants

If temperature is considered

$$\epsilon_c = A \sigma^n t + B \sigma^m t$$

where: B is a function of temperature

Creep tests performed by Hansen (1977) ¹⁶ yielded typical curves for one-stage and multi-stage creep shown in Figures 6-16 and 6-17. The curves fit the power law formulation ($\epsilon = K t^n$) with different k and n values depending on differential stress. Maximum creep strain was up to 11 percent.

Baar (1975) ²² warns that theoretical calculations based on laboratory experiments must not be applied to in situ conditions, because of lack of strain-hardening in actual pillars and stress adjustment.

Reynolds and Gloyna (1961) ²³ conducted in situ creep measurements in the Grand Saline mine and found that the stress concentration of 4,000 psi on a room 66 feet in width and 23 feet in height at a depth of 700 feet was 0.001 in. per day. The time required for the deformation to be 95 percent complete was 4.7 years. The creep rate is shown in Figure 6-18 and can be approximated by

$$\frac{d\epsilon}{dt} = 0.03 e^{-0.635t}$$

where: $\frac{d\epsilon}{dt}$ = creep rate

0.03 = A = constant

-0.635 = K = exponential constant

t = time

This is the decay formula.

6.5.2 Temperature

The physical behavior of domal rock salt is drastically affected by temperature. Thermal conductivity, thermal diffusivity and strength decrease sharply with increasing temperature and the deformation rate increases sharply. These tests were conducted in the laboratory by Lomenick and Bradshaw (1965)²⁴. No in situ tests have been found in the literature.

Laboratory testing by Lomenick and Bradshaw indicate that higher temperatures with constant stress increase the amount of strain by seven times (Figure 6-19). Increasing temperature after loading also accelerates strain (Figure 6-20).

Bradshaw et al. (1968)¹² demonstrated that the compressive strength of dome salt from Grand Saline is reduced by approximately 35 percent when tested at 200°C.

6.5.3 Pressure

Increased pressure on model pillars causes increased strain. When compared to an increase in temperature however, the changes are small (Figure 6-21). Long-term applied pressure can produce very large strains in the laboratory^{18, 19}. Baar (1975)²² predicts that this is also possible in situ if measures are not taken to relieve the pressure.

6.5.4 Water/Moisture

Domal salt has moisture trapped internally in vesicles. The porosity of dome salt is approximately 1.7 percent¹⁵. Hansen found a water content of 0.02 percent in Jefferson Island salt¹⁶. Seeps have been reported in several mines in fault and shear zones and some anhydrite bands are permeable. However, these seeps are not major and are generally near the dome margins¹.

The trapped brine can be released with considerable energy when the rock is heated. Salt from Winnfield, Grand Saline and Weeks Island Domes was tested by Bradshaw, et al. (1968)¹². The salt did not fracture at temperatures of up to 400°C.

6.5.5 Irradiation

The effect of irradiation on domal salt was studied by Bradshaw et al. (1968) ¹². It was concluded that the compressive strength of irradiated dome salt was 30 to 40 percent less than that of nonirradiated dome salt. This is a significant reduction and could affect stability. The results are shown in Table 4-5.

6.6 ANTICIPATED ENVIRONMENT

The effect of irradiation and increased temperature is expected to be a major environmental factor in dome salt. Accelerated closure can be expected due to these factors. Stable openings to allow for retrievable wastes will require support.

6.7 EXCAVATION CRITERIA

6.7.1 Water Inflow

Domal salt contains very little interstitial water. However, excavations near the dome margins in mines have encountered higher seepages from the country rock ^{25, 26}.

6.7.2 Water Pressure Effects on Stability

As long as the excavation avoids the margins of the dome, no significant water pressure is expected.

6.7.3 Excavation Techniques

The dome salt of the Gulf Coast Plain have been mined by the room-and-pillar methods. The room height ranges from 75 to 130 feet at depths of 700 to 1400 feet. Mining conditions in the Gulf Coast domes are generally good. Ground conditions are continuous for great distances. Significant problems have been encountered when peripheral areas of the domes are mined. Spall and closure tend to decrease with time.

Mining is accomplished by conventional drilling and blasting techniques. Extraction ratios average 60 percent. Tunnelling machines however, could be utilized in the rock salt, because the salt is low in abrasion and has sufficient stand-up time.

6.7.4 Temporary and Permanent Support

Mining conditions in the salt mines of the Gulf Coast Domes is generally good. The roof is generally unsupported, with occasional use of rock bolts. Severe spalling is uncommon, and, when it does occur, is generally ignored.

6.7.5 Extraction Ratios

The mines of the Gulf Coast are room-and-pillar patterns with depths ranging from 700 to 1400 feet and mining heights of 75 to 130 feet. Estimated extraction ratios are 60 percent. Pillar loadings are on the order of 3000 to 4000 psi.

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FIGURE 6-1 Areas of Intrusive Salt (Stippled) and Location of Underground Salt Mines (Star) of the Gulf Coast Region of the United States (Kupfer, 1963)

FIGURE 6-2 Map of Gulf Coast Embayment Showing Location of Salt Domes and the Louann Salt (D'Appolonia, 1976)

FIGURE 6-3 Cross-Sections of Salt Domes
 A-C: idealized sections;
 D: La Rue Salt Dome;
 E: Weeks Island and
 F: Cote Blanche Island Salt Domes
 (Pierce and Rich, 1962)

FIGURE 6-4 Generalized Block Diagram of Avery Island Dome
(Bates, et al, 1969)

FIGURE 6-5 Cross-Section of the Tatum Dome in Mississippi (Pierce and Rich, 1962)

FIGURE 6-6 (Kupfer, 1963)

- Block diagrams showing salt layering in walls and ceiling of Weeks and Jefferson mines.
- Moderately complex fold pattern in ceiling of Weeks Mine (Room E 1-2). The approximate plunge of the folding is indicated by "Pl."; the true plunge, 81° , is unusually flat for this mine. Wierd apparent dips on left wall are caused by vertical uplift section essentially parallel to axial plane of minor fold; apparent dip pseudo-structures of this type are not uncommon in the walls in certain parts of the mine. Near ceiling is 50 feet high and far one is 25 feet high.
 - Isoclinal folds that have been folded around new axial planes and into more open structures. Continued vertical movement has stretched the limbs together to form closed structures ("closures"). Weeks Mine, Room I 7-8; ceiling is 25 feet high.
 - Multiple folded fold in Room D 7-8 of Weeks Mine. First isoclinal folding placed beds A_1 and B_1 on one limb and A_2 and B_2 on the other. A second folding on the indicated axial plane caused the present repetition of beds and continued vertical uplift removed some beds by thinning and attenuation. The ceiling is 50 feet high, but distortion has been introduced in the drawing in order to show all the beds. Total width of zone involved is about 15 feet. Note room and pillar method of mining with corridors 50 to 60 feet wide and pillars 100 feet on a side.
 - "Closures" in isoclinal folds of the Jefferson Mine, Room F 5. Ceiling is 100 feet high. Note the vertical axes of the folds.

FIGURE 6-7 (Kupfer, 1963)

Detailed map of layering in 13 foot high ceiling of tool room (Room G 7-8), Weeks Mine. Arrows indicate direction of probable younger beds as suggested by "graded bedding." Identically shaped structures are locally visible in floor and give accurate plunge of folds. Closure in northwest corner of room has identical dimensions in floor (i.e., it is tubular). In area marked "vague," layering is difficult to see, but the rendition is as accurate as possible (not diagrammatic).

A.

B.

C.

D.

FIGURE 6-8 (Kupfer 1963)

Comparison of closed structures or "closures" of various types. Note the shear folds in the upper left diagram and their "drag fold" character, characteristic of the Grand Saline Mine. This indicates a domal or basin type of structure in the initial stages of movement. The other three diagrams are from the Weeks dome and appear to represent the results of refolded folds and attenuation.

FIGURE 6-9 Mohr's Envelope, Normal vs. Shear Stress.
(Project Dribble, 1962)

FIGURE 5-10 Triaxial Stress-Strain Curves
(Hansen, 1977b)

FIGURE 6-11 Mohr's Circle of Stress for Jefferson Island Salt
(Hansen, 1977a)

FIGURE 6-12 Typical Quasi-Static Triaxial Compression Test Results: Differential Axial Stress as a Function of Axial Strain (Hansen, 1977a)

FIGURE 6-13 Creep curves for Halite
(Thompson and Ripperger, 1964)

FIGURE 6-14 Stress Creep Rate Curve for Halite
(Thompson and Ripperger, 1964)

FIGURE 6-15 Triaxial Stress-Strain Curves
(Project Dribble, 1962)

FIGURE 5-16 Axial Strain as a Function of Time for a Single Stage Creep Test (Hansen, 1977a)

FIGURE 6-17 Axial Strain as a Function of Time for a Multi-Stage Creep Test
(Hansen, 1977a)

FIGURE 6-18 Creep Rates in the Grand Saline Mine (Reynolds and Gloyna, 1961)

FIGURE 6-19 Deformation of Pillar Models from Various Localities at 4000 psi and 22.5°C (Lomenick and Bradshaw, 1969)

FIGURE 6-20 Deformation of Pillar Model at 4000 psi and (1) 22.5°C and (2) 100°C (Lomenick and Bradshaw, 1969)

FIGURE 6-21 Deformation of Pillar Models at Various Temperatures and Pressures (Lomenick and Bradshaw, 1969)

TABLE 6-1 (Kupfer, 1963)

**STATUS OF GEOLOGIC MAPPING IN SUBSURFACE SALT MINES OF THE
GULF COAST OF THE UNITED STATES**

NAME AND DESCRIPTION	MAPPED BY	COMMENTS
Grand Saline Dome Kleer Mine Morton Salt Co. Van Zandt Co., Tex.	Robert Balk AAPG, 1949	Classic paper Remapped by Muehlberger, Tex. Bur. Ec. Geol., 1959 Int. Geol. Cong., 1960
Jefferson Island Dome Jefferson Mine Diamond Salt Co. Iberia Parish, La.	Robert Balk AAPG, 1953 (Asstd. by G.T. Duvall)	Similar to Grand Saline Needs mapping in newer workings
Winnfield Dome Carey Mine Carey Salt Co. Winn Parish, La.	Hoy, Foose, and O'Neill AAPG, 1962	Stanford Research Inst.
Weeks Island Dome Weeks Mine Morton Salt Co. Iberia Parish, La.	Donald Kupfer AAPG, 1962	Lower level mapped, upper level to be mapped
Avery Island Dome Avery Mine International Salt Co. Iberia Parish, La.	McMullen and Duxey (Unpublished)	Mapped summer 1961
Hockley Dome Hockley Mine United Salt Co. Harris Co., Tex.	Muehlberger and students (1961) (Unpublished)	Reconnaissance map, structure is very simple (personnal communication, 1962)
Cote Blanche Dome Carey-Monsanto St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Belle Isle Dome Cargille Corp. St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Tatum Dome Lamar County, Miss.	?	Atomic Energy Commission
Bruinsburg International Salt Co. Claiborne Co., Miss.	Unmapped	Exploration drilling under lease and option

TABLE 6-2 (Kupfer, 1963)

TYPICAL ATTITUDES OF FEATURES IN THE SALT AT FIVE MINES

SALT DOME	DIP OF LAYERING	PLUNGE OF LINEATIONS	PLUNGE OF FOLDS
Grand Saline	51°-90°, Avg=80°	53°-90°, Avg=75°	78°-80° (two)
Jefferson	75°-90°, Avg=90°	70°-90°, Avg=88°	
Avery	66°-87°, Avg=77°		
Weeks	78°-90°, Avg=86°	(Ax. pl. of folds dip 80°-90°, Avg=85°)	79°-90°, Avg=83°
Winnfield	50°-90°, Avg=75°	55°-87°, Avg=75°	

SECURITY DATA WITH
RESTRICTED ACCESS

TABLE 6-3 Description of Dome Salt Structure

Mineralogy: $\frac{1}{4}$ to $\frac{1}{2}$ " crystals of halite, up to 1-2 inches
97-99% halite with traces of halite. Occasional
inclusions of 5-80% anhydrite, also trace dolomite
calcite, others

Lithology: Layers 1-10 inches thick of interbedded light and dark
salt. These layers are folded, stretched, recrystallized and
deformed.

Major Structures: Near vertical isoclinal folds, closures, occasional
faults (small), some shear zones (from shear folding)

Weathering/Alteration: Occasional weathering on edges of dome

Hydrology/Water Content: Near lateral edges of dome

Jointing:

Jefferson-Avery Is				
	Set A	Set B	Set C	Set D
Type of Joint	Bedding	Shear	Joints	
Filling	Salt Anhydrite	Anhydrite Salt	Anhydrite Salt	
Orientation (dip dir/dip)	77-90°/88°	Variable	90°/variable	
Opening Width	Nil	1-3"	Nil	
Spacing	1-10 in.	Variable	1/10'	
Waviness	Variable	Variable	0	
Extent of Joints (lengths)	100's of feet	2'-2000'	10-40'	

Typical RQD: 70-90% (estimated)

Typical Fracture Frequency:
Many blast induced
1 per 10 feet

TABLE 6-4
(from Ref. 10)

TATUM SALT ROCK CORES
Shear Strength Relationships--Curvilinear Analysis
Shear Stress and Slope of Mohr's Envelope at Zero Normal Stress

Analysis	(C) in psi	Tan ϕ
A = Maximum load obtained	696	1.91
A _c = Maximum load obtained, corrected for area	564	1.98
C = 2% deformation	885	0.96
C _c = 2% deformation, corrected for area	875	0.95
D = 10% deformation	975	1.65
D _c = 10% deformation, corrected for area	914	1.59
E = 20% deformation	903	1.82
E _c = 20% deformation, corrected for area	889	1.65

C = Y-intercept of Mohr's envelope, which is the unit cohesive strength or the shear stress at zero normal stress.

Tan ϕ = Slope of Mohr's envelope or coefficient of internal friction, computed in this case for X = 0.

TABLE 6-5
TYPICAL ROCK MASS PROPERTIES - DOME SALT

BASIC PARAMETERS

<u>Type of Property</u>	<u>Parameter</u>	<u>Customary English Units</u>
Index	. Unit Weight	135 lbs/ft ³
	. Natural moisture content (intact) est.	0.02 %
	. Porosity (rock mass intact)	1.7 %
Stress-strain	. Young's Modulus	0.6x10 ⁶ to 0.2x10 ⁶ lbs/in ²
	. Poisson's Ratio	0.35 --
	. Bulk Modulus	6.67x10 ⁵ lbs/in ²
	. Shear Modulus	2.22x10 ⁵ lbs/in ²
Strength	. Cohesion 1500-3500	1100-1700 lbs/in ²
	. Friction Angle psi range intact.	36-33 degrees
	. Uniaxial Compressive Strength	3300-5600 3900 avg. lbs/in ²
	. Tensile Strength	250 lbs/in ²
	. (Plastic Behavior?)	
Thermal Intact	. Coefficient of Linear Thermal Expansion Est.	22.2x10 ⁻⁶ °F
	. Heat Capacity	0.47 BTU/lb-F°
	. Thermal Conductivity	1.8 BTU/hr-ft-F°
Hydrological Intact	. Horizontal permeability	4.6x10 ⁻¹⁸ ft/min
	. Vertical permeability	4.6x10 ⁻¹⁸ ft/min

TABLE 6-6 Anisotropic Dynamic Elastic Moduli
(Christensen, 1966)

REFERENCE	σ	μ Units $\times 10^{11}$	B	E dynes/cm ²
Lab: Anisotropic	0.219	1.32	2.45	4.13
In-Situ Anisotropic	0.215	1.34	2.56	4.29
In-Situ Isotropic	0.310	1.34	3.07	3.51

7.0 SPECIAL CHARACTERISTICS OF SALT

7.1 GENERAL

The question of the relationship between the intact properties and the rock-mass properties for salt has yet to be resolved. For instance, the general reduction factors which are typically employed when establishing constitutive laws for general rock masses (e.g., igneous and sedimentary formations) are probably inappropriate in the case of salt. This is due to several factors including the relatively huge size of halite crystals; these are on the order of several feet as compared to grains in typical rocks, which are of the order of millimeters. The most significant factor influencing rock-mass behavior, however, is probably the extreme susceptibility of halite to visco-elastic and visco-plastic behavior. The introduction of thin clay and shale seams further complicates the analysis. The following section presents the current attitude of the scientific community with respect to this material, as found in the literature.

7.2 SUMMARY OF FINDINGS ON THE SALT PROBLEM

There is a great deal of literature which pertains to salt in general but very little which has a direct bearing on engineering with this curious material. It is believed that the fifteen papers which have been briefly reviewed genuinely represent the most important literature on the subject --if some of these have been discussed as "irrelevant" it simply means that they do not concentrate on aspects of engineering importance: their value as corroborating evidence may still be quite high.

The literature can be divided into four classes:

- 1) Laboratory tests on single crystals of salt (usually artificially grown)^{1, 2, 3}.
- 2) Laboratory tests on polycrystalline samples machined for use in uniaxial or triaxial tests^{2, 4, 5, 6, 7, 8, 9}.
- 3) Field tests conducted in salt or potash mines^{2, 6, 7, 9, 10, 11, 12}.

- 4) Theoretical papers concerned with analyses using various constitutive relations derived from field or lab tests 13, 14, 15, 16.

Rather surprisingly, there is often a close correlation between values of physical properties produced by 1) and 2). However, the more important mechanical properties found in the lab are at variance with the ones found in the field. The theoretical analyses of underground structures are simply curve-fitting exercises: parameters have to be "revised" or "improved" to fit the measured data.

The basic error in the published analyses has been pointed out by Baar (1973). At the present time most of the models of the bulk creep behavior of salt are based on laboratory experiments. Unfortunately the laboratory tests are inappropriate because the samples become work hardened and the elastic regime is extended by an order of magnitude. Consequently the proposed creep models require large octahedral stresses before flow begins. The theorists, however, assume that the stress field around the excavation is simply the one for the virgin ground with the normal stresses on the walls, roof and floor reduced suddenly to zero. Thus $\sigma_3 = 0$ and σ_1 has its initial value -- this naturally makes the initial octahedral stress enormous. Flow occurs (in the models) with a combination of large shearing stress versus a large shearing strength. Initially the stress is greater than the strength but after a while the creep leads to a reduction in shearing stress and ultimately it falls below the threshold value (which all the models have) and creep ceases. Thus the typical model prediction is of rapid initial creep followed by an asymptotic approach to some limiting strain. This leads to the conclusion that some openings in deep mines will never close.

According to Baar this situation is the exact opposite of the truth. Plastic flow begins at shearing stresses less than 100 psi. Consequently, within a few hours of mining "stress relief creep" has reduced the octahedral stresses around the excavation to values not far beyond the elastic region. Afterwards, creep proceeds slowly but continuously, with a small shearing stress just overcoming a small shearing strength. In other words, the period of very rapid creep is over almost before the excavation is completed. This leads to the type of discrepancy shown in Figure 7-1.

The trouble is that the field data are of very poor quality. There do not seem to be any generally accepted measurements for the theories to be tested against -- each investigator has his own set of data obtained from the field by unspecified means and his own lab data as well. Under these circumstances most theorists are able to fit a few curves to a few points and thereby "verify" their theories.

So it seems to be the case that constitutive laws connecting (strain), (strain rate) and τ_{oct} are being falsely applied to field conditions. In particular, it will be seen that the general functional dependence of creep rate on stress, temperatures (and time) is well accepted, but that the exact form of the relationship is still in dispute.

Numerical Results of Lab Tests

The following section indicates the current state-of-the-art with respect to various properties of halite formations.

Thermal Properties

- 1) Conductivity - according to Bradshaw et al. (1962)⁵ we can use the values for single crystals. He quotes the graph, shown in Figure 7-2.

Note: There is no mention anywhere of variation of thermal conductivity with pressure so presumably it is not significant.

- 2) Specific Heat - Sources agree that this changes very little with temperature or pressure.
Kay and Laby give $C_p = 0.88 \text{ Jg}^{-1}\text{C}^{-1}$ @ 10°C .
- 3) Coefficient of Expansion - Varies from 2.0×10^{-5} to 2.2×10^{-5} in/in/ $^\circ\text{F}$.
- 4) Disintegration Temperature - Natural salt contains small brine inclusions which cause shattering at elevated temperatures. The main reference is Bradshaw, et al. (1962) where shattering temperatures are in the range $250\text{-}350^\circ\text{C}$ for bedded salt and $\geq 400^\circ\text{C}$ for dome salt.

Mechanical Properties

- 1) Elastic Constants
 - (a) Young's modulus: Adachi et al. (1969)⁸ have measured this and given a range from 0.8 to 2.3×10^6 psi.

- (b) Bulk modulus: Adachi gives 0.55 to 0.85×10^6 psi.
- (c) Poisson's ratio: Adachi says this can vary from 0 to 0.5 according to applied stress.
- 2) Yield and Failure - This is the point which is in dispute, since it depends on rate of loading and instrument sensitivity. Baar (1973)¹¹ (representing the mining engineers) thinks that the elastic limit of salt is reached at stresses <100 psi. In contrast Adachi (1969)⁸, Winkel et al. (1972)¹⁴ and Hofer (1969)⁹ are producing yield points of the order of 1000 psi or more. The curves presented by Carter and Heard (1970)¹⁷ suggest strongly that this discrepancy is a result of the short time scale of the laboratory tests.
- 3) Creep Behavior - Obviously the form in which a creep law is framed depends strongly on the view taken in 2). The important references are Adachi et al. (1969)⁸, Carter and Heard (1970)¹⁷ and Lomenick and Bradshaw (1965), (1969)^{4, 6, 7} and Bradshaw, et al. (1962)⁵. Having chosen a law from lab tests one must then be very careful about how to apply it to salt in bulk.

Conclusions

There is still a great deal of fieldwork in mines to be done and still many unresolved theoretical problems. Several very basic questions are still in dispute.

Of the papers mentioned, the following appear to be the key references: Adachi et al. (1969)⁸ and Serata (1964)¹⁸ produces some interesting laboratory results and an elaborate theory. Lomenick and Bradshaw (1965) (1968) (1969)^{4, 5, 6, 7} gives field results and Baar's work from project salt vault (Baar, 1973)¹¹ briefly indicates possible pitfalls for the analyst.

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FIGURE 7-1 Diagram Showing the Baar vs. Sereta, et al Position on Creep

FIGURE 7-2 Variation of Conductivity with Temperature in Halite (Bradshaw, et al, 1962)

8.0 ROCK MASS PROPERTIES OF A TYPICAL SALT

8.1 GENERAL

It is often difficult to distinguish between the properties of an intact specimen and the rock-mass formation of salt. The principal difference is that intact samples are often machined to small sizes and contain no physical discontinuities. Rock masses of salt, however, contain discontinuities in the form of joints, fractures and thin clay and shale seams which are often planes of weakness.

8.2 INTACT PROPERTIES FOR A TYPICAL SALT

In order to obtain a feel for the range of property values for intact salt, a literature search was carried out. Where possible, specific test values were obtained and these were entered in a "specific" list. Where only summaries of test programs were reported these were entered in a "generic" list. The maximum and minimum values from both lists were used to find the range of the data. The actual data are included in Appendix A. The mean was calculated from the specific list and from those data in the generic list that were accompanied by the number of samples tested. The values of properties of typical intact salt are presented in Table 8-1.

8.3 ROCK MASS PROPERTIES FOR A TYPICAL SALT

When considering rock properties it is important to distinguish between the properties of a small intact piece of rock (dimensions typically in inches) and the behavior of the rock mass (dimensions typically in hundreds of feet). The difference in behavior is due to the presence of flaws, cracks and discontinuities that exist in the rock mass that do not exist in an intact block. Consequently, an intact piece of rock will generally be many times stronger than the rock mass.

Unfortunately, it is not easy to obtain the rock mass values. Few field tests are carried out on scale greater than a few feet and few structures excavated in rock have been monitored sufficiently well to enable the rock-mass properties to be deduced. In some fields, such as

rock-slope stability, a large number of failures have been back-analyzed and rock-mass properties have been derived. Underground design, however, has not yet reached this stage of development, and confidence (usually expressed in terms of the factor of safety) is not as high in underground design as in slope stability.

The fact that it is difficult to measure or estimate rock-mass properties does not mean that an attempt should not be made. Otherwise a structure based on the intact properties, which can easily be determined in the laboratory, would almost certainly fail (during or after construction) since the strength of the rock mass is less than the intact strength.

Before rock-mass properties can be derived, the local geological structures must be mapped and their influence understood. This is particularly true of the joint patterns, which largely control the behavior of the rock mass.

Although bedded-salt formations may be several thousand feet in overall thickness, they consist of irregular sequences of clear to white halite with thin laminae of shales, siltstones, clay, gypsum and anhydrite. The salt layers range from a few inches to 30 feet in thickness. The significant features in the salt are layering of clear and cloudy salt, seasonal layering of shale and anhydrite with occasional thicker beds of shales, anhydrite and other materials.

Basin salts are characterized by gentle dips. However, they can be folded or faulted. Jointing or fracturing is commonly due to partings along impurity layers. Otherwise, jointing is rare, since salt is a relatively plastic material and joints within the halite tend to selfheal. For this reason, salt beds are generally impervious, since there are few vertical joints through which the water can penetrate.

A partial summary of the structures found in a typical salt formation is included as Table 8-2. Due to the relative lack of structure in salt compared to other rock types, the rock-mass properties do not vary markedly from the intact properties. However, it is more appropriate to express the constitutive relationships in terms of an equation, and this has been included in Table 8-3.

TABLE 8-1

PROPERTIES OF INTACT SALT

Type of Property	Parameter	Mean*	Range	Customary English Units	
Index	. Unit Weight	130 (39)	103-152	lbs/ft ³	
	. Natural moisture content	.08 (12)	0-1.1	%	
	. Porosity	3.3 (11)	1.4-10.0	%	
Stress-strain	. Young's Modulus	1.8x10 ⁶ (18)	0.9x10 ⁶ -7.25x10 ⁶	lbs/in ²	
	. Poisson's Ratio	.34 (12)	.22-.50	--	
Strength	. Uniaxial Compressive Strength	3530 (16)	2300-7250	lbs/in ²	
	. Tensile Strength	225 (15)	120-4580	lbs/in ²	
Thermal	. Coefficient of Linear Thermal Expansion	21.6x10 ⁻⁶ (4)	20x10 ⁻⁶ -22x10 ⁻⁶	°F ⁻¹	
	. Heat Capacity	.28 (4)	.19-47	BTU/lb-°F	
	. Thermal Conductivity	TEMPERATURE		CONDUCTIVITY	
		32°F		3.53 BTU/hr-ft °F	
122		2.90			
212		2.43			
302		2.08			
392		1.80			
572		1.44			
752		1.20			

*Number of tests used to derive mean and standard deviation as shown in parenthesis.

TABLE 8-2

PARTIAL DESCRIPTION OF TYPICAL STRUCTURES IN BEDDED SALT

	<u>SET A</u>	<u>SET B</u>	<u>SET C</u>
Type of Joint	Bedding	Joint	Joint
Filling	Clay or Anhydrite	Calcite/Anhydrite	Calcite Anhydrite
Orientation (Dip Dir/Dip)	Horizontal	Dip 80-90°	Dip 80-90° Perpendicular to Set B
Opening Width	Tight	0	0
Spacing	Max. 1/ft.	Rare	Rare
Waviness	0	Slight	Slight
Extent of Joints (Lengths)	10 to 50 ft.	1 to 30 ft.	1 to 30 ft.
Typical RQD: 90 to 100%	Typical Fracture Frequency: 1/foot or less		

TABLE 8-3

ESTIMATED ROCK MASS PROPERTIES FOR GENERIC SALT

<u>Type of Property</u>	<u>Parameter</u>	<u>Value</u>	<u>Customary English Units</u>
Index	. Unit Weight	133	lbs/ft ³
	. Natural moisture content	0.08	%
	. Porosity (rock mass)	0.5	%
Stress-strain	. Young's modulus	1.6×10^6	lbs/in ²
	. Poisson's ratio	0.35	---
Strength	. Unconfined Compressive Strength	3200	lbs/in ²
	. Tensile Strength	50	lbs/in ²
Example of Creep Law	. Creep Law	$B = 0.5 \times 10^{-6}$ at 1000 psi	Note: This equation excludes temperature and pressure variations
	$\epsilon = B + C \ln t + D t$	$C = 300 \times 10^{-6}$ at 1000 psi	
		$D = 9 \times 10^{-8}$ at 1000 psi	
		$t = \text{time in days}$	
Thermal	. Coefficient of Linear Thermal Expansion	22.2×10^{-6}	$^{\circ}\text{F}^{-1}$
	. Heat Capacity		
	<u>TEMPERATURE</u>	<u>HEAT CAPACITY</u>	
	32 [°] F	0.20 BTU/lb- [°] F	
	212	0.21	
	392	0.22	
	. Thermal Conductivity		
	<u>TEMPERATURE</u>	<u>CONDUCTIVITY</u>	
	32 [°] F	3.53 BTU/hr-ft [°] F	
	122	2.90	
	212	2.43	
	302	2.08	
	392	1.80	
	572	1.44	
	752	1.20	

APPENDIX A TYPICAL PHYSICAL PROPERTIES OF SALT

This appendix is provided to indicate the range of various properties of salt and to provide the reader with specific references in these areas. The different test conditions show how certain characteristics may or may not change. Generic values indicate trends and specific values are results of individual tests.

DENSITY

<u>GENERIC (pcf)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
Rock Salt 136	2 samples	Clark, 1966
Rock Salt 131	2 samples	Clark, 1966
135		Callahan and Ratigan, 1975
130	from 1900' depth	Ratigan, et al, 1976
130	from 2100' depth	Ratigan, et al, 1976
130	from 2700' depth	Ratigan, et al, 1976
135		Ratigan, 1976
135		SAI, 1976
135		PBQD, 1976
144		OWI, 1976
Rock Salt	6 samples	Deere, et al, 1966

SPECIFIC (pcf)

152		Gnirk, et al, 1974
135		Callahan and Rutigan, 1975
131	from 2700' depth	Hansen and Gnirk, 1975
131	from 2700' depth	Hansen and Gnirk, 1975
131	from 2704' depth	Hansen and Gnirk, 1975
131	from 2704' depth	Hansen and Gnirk, 1975
131	from 2704' depth	Hansen and Gnirk, 1975
130	from 2706' depth	Hansen and Gnirk, 1975
130	from 2706' depth	Hansen and Gnirk, 1975
132	from 2709' depth	Hansen and Gnirk, 1975
132	from 2709' depth	Hansen and Gnirk, 1975
130	from 2714' depth	Hansen and Gnirk, 1975
132	from 2720' depth	Hansen and Gnirk, 1975
132	from 2720' depth	Hansen and Gnirk, 1975
130	from 2727' depth	Hansen and Gnirk, 1975
130	from 2727' depth	Hansen and Gnirk, 1975
130	from 2727' depth	Hansen and Gnirk, 1975
131	from 2730' depth	Hansen and Gnirk, 1975

DENSITY (Con't)

<u>SPECIFIC (pcf)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
132	from 2714' depth	Hansen and Gnirk, 1975
133	from 2742' depth	Hansen and Gnirk, 1975
133	from 2742' depth	Hansen and Gnirk, 1975
133	from 2748' depth	Hansen and Gnirk, 1975
133	from 2748' depth	Hansen and Gnirk, 1975
133	from 2748' depth	Hansen and Gnirk, 1975
133	from 2763' depth	Hansen and Gnirk, 1975
133	from 2763' depth	Hansen and Gnirk, 1975
134	from 2767' depth	Hansen and Gnirk, 1975
134	from 2767' depth	Hansen and Gnirk, 1975
133	from 2796' depth	Hansen and Gnirk, 1975

UNCONFINED COMPRESSIVE STRENGTH

<u>GENERIC (psi)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
4,580		Gnirk, et al, 1974
3,050		Gnirk, et al, 1975
2,445	from 1900' depth	Ratigan, et al, 1975
2,445	from 2100' depth	Ratigan, et al, 1975
3,725	from 2700' depth	Ratigan, et al, 1975
3,750		Ratigan, 1976
7,250		PBQD, 1976
4,200	68°F parallel to bedding	Parker, et al, 1960
3,900	392°F parallel to bedding	Parker, et al, 1960
4,000	68°F normal to bedding	Parker, et al, 1960
3,600	392°F normal to bedding	Parker, et al, 1960
3,000		Parker, et al, 1960
Rock Salt 3100	5 samples	Deere, et al, 1966
 <u>SPECIFIC (psi)</u>		
Rock Salt 4,305	from 2700' depth	Hansen and Gnirk, 1975
Rock Salt 4,340	from 2704' depth	Hansen and Gnirk, 1975
Rock Salt 4,650	from 2706' depth	Hansen and Gnirk, 1975
Rock Salt 3,940	from 2709' depth	Hansen and Gnirk, 1975
Rock Salt 4,260	from 2714' depth	Hansen and Gnirk, 1975
Rock Salt 4,486	from 2727' depth	Hansen and Gnirk, 1975
Rock Salt 3,545	from 2730' depth	Hansen and Gnirk, 1975
Rock Salt 3,200	from 2741' depth	Hansen and Gnirk, 1975
Rock Salt 3,350	from 2748' depth	Hansen and Gnirk, 1975
Rock Salt 3,600	from 2767' depth	Hansen and Gnirk, 1975
Rock Salt 2,300	from 2796' depth	Hansen and Gnirk, 1975

TENSILE STRENGTH

<u>GENERIC (psi)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
4580		Gnirk, et al, 1974
250		Hansen and Gnirk, 1975
200	from 1900' depth	Ratigan, et al, 1975
200	from 2100' depth	Ratigan, et al, 1975
240	from 2700' depth	Ratigan, et al, 1975
250		Ratigan, 1976
145		PBQD, 1976
120	2 samples	Deere, et al, 1966

SPECIFIC (psi)

Rock Salt 280	from 2700' depth	Hansen and Gnirk, 1975
Rock Salt 245	from 2706' depth	Hansen and Gnirk, 1975
Rock Salt 230	from 2709' depth	Hansen and Gnirk, 1975
Rock Salt 280	from 2720' depth	Hansen and Gnirk, 1975
Rock Salt 260	from 2720' depth	Hansen and Gnirk, 1975
Rock Salt 215	From 2727' depth	Hansen and Gnirk, 1975
Rock Salt 260	from 2727' depth	Hansen and Gnirk, 1975
Rock Salt 220	from 2742' depth	Hansen and Gnirk, 1975
Rock Salt 235	from 2742' depth	Hansen and Gnirk, 1975
Rock Salt 220	from 2748' depth	Hansen and Gnirk, 1975
Rock Salt 260	from 2748' depth	Hansen and Gnirk, 1975
Rock Salt 220	from 2763' depth	Hansen and Gnirk, 1975
Rock Salt 210	from 2767' depth	Hansen and Gnirk, 1975

YOUNG'S MODULUS

<u>GENERIC (psi)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
$.46 \times 10^6$		Gnirk, et al, 1974
$.8 \times 10^6$		Callahan and Ratigan, 1975
$.8 \times 10^6$		Callahan and Ratigan, 1975
1.94×10^6	from 1900' depth	Ratigan, et al, 1975
1.94×10^6	from 2100' depth	Ratigan, et al, 1975
2.02×10^6	from 2700' depth	Ratigan, et al, 1975
$2. \times 10^6$		Ratigan, 1976
7.25×10^6		PBQD, 1976
$.35 \times 10^6$	68°F Parallel to bedding	Parker, et al, 1960
$.09 \times 10^6$	392°F Parallel to bedding	Parker, et al, 1960
$.36 \times 10^6$	68°F Normal to bedding	Parker, et al, 1960
$.11 \times 10^6$	392°F Normal to bedding	Parker, et al, 1960
$.71 \times 10^6$	5 samples 50% σ_A (ult)	Deere, et al, 1966
6.0×10^6		Christensen, 1966
0.7×10^6		Muir, 1966
Halite 5.4×10^6		Spencer, 1969
Rock Salt 1.62×10^6	from 2700' depth	Hansen and Gnirk, 1975
Rock Salt 1.37×10^6	from 2704' depth	Hansen and Gnirk, 1975
Rock Salt 2.06×10^6	from 2706' depth	Hansen and Gnirk, 1975
Rock Salt 1.71×10^6	from 2709' depth	Hansen and Gnirk, 1975
Rock Salt 1.50×10^6	from 2714' depth	Hansen and Gnirk, 1975
Rock Salt 1.41×10^6	from 2727' depth	Hansen and Gnirk, 1975
Rock Salt 1.51×10^6	from 2730' depth	Hansen and Gnirk, 1975
Rock Salt 3.05×10^6	from 2741' depth	Hansen and Gnirk, 1975
Rock Salt 2.64×10^6	from 2748' depth	Hansen and Gnirk, 1975
Rock Salt 2.04×10^6	from 2763' depth	Hansen and Gnirk, 1975
Rock Salt 0.97×10^6	from 2767' depth	Hansen and Gnirk, 1975
Rock Salt 3.47×10^6	from 2796' depth	Hansen and Gnirk, 1975

SHEAR MODULUS

GENERIC (psi)

Low

1.9×10^6

TEST CONDITIONS

REFERENCE

PBQD, 1976

Christensen, 1966

SPECIFIC (psi)

Halite 2.2×10^6

Spencer, 1969

POISSON'S RATIO

GENERIC

TEST CONDITIONS

REFERENCE

.40		Gnirk, et al, 1974
.40		Callahan and Ratigan, 1975
Rock Salt .28-.48		Gnirk, et al, 1975
.33	from 1900' depth	Ratigan, et al, 1975
.33	from 2100' depth	Ratigan, et al, 1975
.31	from 2700' depth	Ratigan, et al, 1975
.33		Ratigan, 1976
.50		PBQD, 1976
.73(?)	5 samples 50% $A_{(ult)}$	Deere, et al, 1966
.22		Christensen, 1966

SPECIFIC

Rock Salt .26	from 2700' depth	Hansen and Gnirk, 1975
Rock Salt .38	from 2704' depth	Hansen and Gnirk, 1975
Rock Salt .24	from 2706' depth	Hansen and Gnirk, 1975
Rock Salt .28	from 2709' depth	Hansen and Gnirk, 1975
Rock Salt .38	from 2714' depth	Hansen and Gnirk, 1975
Rock Salt .34	from 2727' depth	Hansen and Gnirk, 1975
Rock Salt .42	from 2741' depth	Hansen and Gnirk, 1975
Rock Salt .35	from 2748' depth	Hansen and Gnirk, 1975
Rock Salt .32	from 2763' depth	Hansen and Gnirk, 1975
Rock Salt .40	from 2767' depth	Hansen and Gnirk, 1975
Rock Salt .34	from 2796' depth	Hansen and Gnirk, 1975

MOISTURE CONTENT

<u>GENERIC (%)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
Block Salt 0.75		Gnirk, et al, 1974
Block Salt 0.10		Gnirk, et al, 1974
Block Salt 0.07		Gnirk, et al, 1974
Low		PBQD, 1976
0-3.5		Wawersik, et al, 1977
.048-1.08		Bradshaw, et al, 1968
<u>SPECIFIC (%)^A</u>		
Block Salt .03		Gnirk, et al, 1974
Block Salt .03		Gnirk, et al, 1974
Block Salt .04		Gnirk, et al, 1974
Block Salt .04		Gnirk, et al, 1974
Block Salt .05		Gnirk, et al, 1974
Block Salt .05		Gnirk, et al, 1974
Block Salt .10		Gnirk, et al, 1974
Block Salt .11		Gnirk, et al, 1974
Block Salt .13		Gnirk, et al, 1974
Block Salt .13		Gnirk, et al, 1974
Block Salt .26		Gnirk, et al, 1974

^AMoisture content measured at end of triaxial compression test.

POROSITY

<u>GENERIC (%)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
Block Salt 10		Gnirk, et al, 1971
Block Salt 6.1		Gnirk, et al, 1971
Block Salt 5.0		Gnirk, et al, 1971
Non-porous		PBQD, 1976
1.7		Gloyna and Reynolds, 1961
<u>SPECIFIC (%)^A</u>		
Block Salt 1.4		Gnirk, et al, 1974
Block Salt 1.6		Gnirk, et al, 1974
Block Salt 1.9		Gnirk, et al, 1974
Block Salt 2.1		Gnirk, et al, 1974
Block Salt 2.7		Gnirk, et al, 1974
Block Salt 3.0		Gnirk, et al, 1974
Block Salt 3.6		Gnirk, et al, 1974
Block Salt 3.6		Gnirk, et al, 1974
Block Salt 3.8		Gnirk, et al, 1974
Block Salt 5.2		Gnirk, et al, 1974
Block Salt 7.2		Gnirk, et al, 1974

PERMEABILITY

GENERIC (ft/yr)

1.1×10^{-2}

1.7×10^{-15}

TEST CONDITIONS

REFERENCE

Parker, et al, 1960

Gloyna and Reynolds, 1961

LINEAR COEFFICIENT OF THERMAL EXPANSION

GENERIC ($^{\circ}\text{F}^{-1}$)

Rock Salt 20×10^{-6}

22.2×10^{-6}

22.2×10^{-6}

22×10^{-6}

TEST CONDITIONS

86 and 167°F

104°F

REFERENCE

Clark, 1966

Gnirk, et al, 1974

Ratigan, 1976

PBQD, 1976

THERMAL CONDUCTIVITY

<u>GENERIC (BTU/hr-ft-°F)</u>	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
3.53	32°F	Clark, 1966
2.90	122°F	Clark, 1966
2.43	212°F	Clark, 1966
2.08	302°F	Clark, 1966
1.80	392°F	Clark, 1966
1.60	482°F	Clark, 1966
1.44	572°F	Clark, 1966
1.33	662°F	Clark, 1966
1.20	752°F	Clark, 1966
Rock Salt 3.1	68°F 2 samples	Clark, 1966
Rock Salt 3.1	68°F 2 samples	Clark, 1966
3.54	32°F	Gnirk, et al, 1974
1.80	392°F	Gnirk, et al, 1974
Rock Salt 4.16	63°F	Callahan and Ratigan, 1975
2.43		Callahan and Ratigan, 1975
2.90		Ratigan, 1976
Rock Salt 2.9-4.1		Weaver, 1976
.52		OWI, 1976
2.8		Parker, et al, 1960
1.81		Gera, 1972

HEAT CAPACITY

<u>GENERIC</u> (BTU/lb-°F)	<u>TEST CONDITIONS</u>	<u>REFERENCE</u>
.22		Ratigan, 1976
.22		SAI, 1976
.19		PDQD, 1976
.47		Gera, 1972

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