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REACTOR FUEL WASTE DISPOSAL PROJECT
PERMEABILITY OF ROCK SALT AND CREEP
OF UNDERGROUND SALT CAVITIES

Final Report

By
T. D. Reynolds
E. F. Gloyna

December 30, 1960

Sanitary Engineering Research Laboratory
University of Texas
Austin, Texas

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The University of Texas
Department of Civil Engineering
Sanitary Engineering Research Laboratory

Final Report

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E. F. Gloyna, Prof. Sanitary Engr., Proj. Director

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U. S. Atomic Energy Commission

Contract AT-(11-1)-490

REACTOR FUEL STORAGE PROBLEM

RESEARCH CONCEPTS FOR STORING

WASTE

ACKNOWLEDGMENT

This investigation was sponsored by the U. S. Atomic Energy Commission under the guidance of Dr. Joseph A. Lieberman, Sanitary Engineer, of the Commission staff.

The assistance given by Dr. Ed Struxness and staff of the Oak Ridge National Laboratory and by the personnel of both the Carey and Morton Salt Companies is gratefully acknowledged.

Recognition is extended to Dr. Shosei Serata, Civil Engineering Department, Michigan State University; Dr. Ronald Drynan, Research Associate, Balcones Research Center, The University of Texas; Mr. Chander Bhagat, Research Assistant; and Mr. Verachai Suwannakarn, Research Assistant. All these people have been directly associated with the research.

ABSTRACT

Safe disposal of high level radioactive wastes is one of the most important problems of our time. Concentrating such wastes and isolating them from our environment presents the most practical solution. Such isolation can be obtained by storage underground in salt cavities. This study is devoted to a consideration of two of the several problems of salt-cavity storage, namely, seepage of wastes out of the formations and closure of cavities due to plastic flow of salt.

Although past experience in storage of liquefied petroleum products in salt formations and in operations of salt mines has shown that underground salt is impermeable, the possibility of seepage of radioactive wastes from such formations must be considered. Therefore, permeability tests were run on rock salt obtained from two major geological formations. Under test conditions, dome salt exhibited extremely low permeability, and most of the tests on bedded salt showed it to be highly impermeable. Under actual mine conditions, there would be no seepage through any homogeneous salt mass as long as the pressures were maintained at a level below that which would cause fracturing of the rock-salt structure. More fractures were found in dome than in bedded salt, due, probably, to the lower elastic strength of dome salt. It can be expected that dome salt contains less impurities than bedded salt. Fractures of such origin will be localized in and confined to the vicinity of an excavation leaving the remaining portions of the salt formation undisturbed.

In the creep studies, closure rates of cavities were measured. The values are in agreement with data previously reported, and plastic flow presents no serious problem.

CONCLUSIONS

Based upon the theoretical analyses and experimental investigations in this report, the following conclusions have been reached:

1. The storage of radioactive wastes in salt cavities is feasible.

Laboratory permeabilities for the dome salt varied from zero to $1.7 \times 10^{-9} \text{ cm}^2$ whereas the laboratory permeabilities for the bedded salt varied from zero to $2.3 \times 10^{-13} \text{ cm}^2$. Although the measured permeabilities are real, the permeability in situ must obviously be much less than those measured in the laboratory; the laboratory tests did not involve the extended consolidation that would occur over a geological time period, and, also, the laboratory specimens were fractured when they were removed from the mine.

2. The permeabilities of the bedded salt specimens were smaller than those of the dome salt.

Four of the seven tests registered no permeability. Only one specimen having a permeability of $1.2 \times 10^{-13} \text{ cm}^2$ was comparable to the dome salt.

3. Rock salt is relatively plastic and elastic but relaxes when it is mined. The rapid relaxation and the disturbance due to the mining operations produced localized fractures in the specimens.

Such specimens can be reconsolidated again, but the laboratory consolidation time will be very small compared to the geologic time involved during the formation of the salt mass.

4. Tests made on a solid crystal showed that no flow can occur through the crystals themselves.
5. The effective porosity of the dome salt was 1.71 per cent whereas that of the bedded salt was 0.59 per cent.
6. The nonreactive liquid permeability of the dome salt could be correlated with the net confining stress, $\sigma_m - p_f$, where

σ_m = mean confining stress in psi

p_f = average fluid pressure in psi

For net confining stresses between 1 to 1,000 psi, the nonreactive liquid permeability, k_L , can be estimated from the formula

$$k_L = 7.1 \times 10^{-10} (\sigma_m - p_f)^{-0.212}$$

where

k_L = nonreactive liquid permeability in cm^2

7. Tests on the dome salt showed kerosene to be nonreactive whereas the brine solutions showed some interaction.

The kerosene permeabilities approached the nonreactive liquid permeabilities obtained from the helium gas tests. The brine solutions, however, had permeabilities which averaged 32 per cent of the nonreactive liquid permeabilities; thus, some interaction occurred.

8. The dome-salt permeabilities to brine (NaCl), calcium sulfate and brine ($\text{CaSO}_4 + \text{NaCl}$), and the synthetic aluminum nitrate waste ($\text{Al}(\text{NO}_3)_3 +$

NaCl) were in the order of $2.8 \times 10^{-12} \text{ cm}^2$ and were all approximately equal. These were less than the equivalent nonreactive liquid permeability.

9. Superficial cracks in a cavity can be sealed effectively by the use of a diatomaceous earth suspension or other similar inert material.

Laboratory tests using pulverized diatomaceous earth suspended in a brine solution reduced the dome salt's permeability to zero within an hour's time

10. The proper selection of the piezometric head in a cavity (its internal pressure) can provide an additional safety factor in assuring that no leakage from a cavity will occur.

No flow will occur if the piezometric heads inside the cavity and outside the salt mass are equal although fracturing may have occurred within the salt. In the case where no liquid exists above the formation, no flow will occur vertically upward if the piezometric head in the cavity is maintained below the top of the formation and proper allowance is made for capillary action.

11. The solved hypothetical problem of a waste cavity in a salt bed shows that wastes can be confined in salt beds for over 500 years even if the formations had permeabilities of the same magnitude as the laboratory test results indicated. Such computations are on the ultra safe side since the permeability of underground salt is much smaller than the values obtained in the laboratory tests.

12. Measurements in the Grand Saline mine indicate that the creep rate decreases as the tunnel's age increases.

Cavities having an age of 5 years showed current creep rates which were 35 times greater than those now measured in a cavity which was 10 years old. About 95 per cent of the total deformation appears to occur during the first 5 years. The total deformation is not expected to exceed 5 per cent of the height of the tunnels that were measured.

13. Measurements in the Hutchinson mine indicate that the creep rate is less than that experienced in the Grand Saline mine.

The overburden and the room sizes are approximately the same. The relative tunnel ages, corrected for analysis, were 1.9 and 5.0 years for the Hutchinson and Grand Saline mine respectively.

14. The operation of the test storage pit in the older section of the Hutchinson mine caused an appreciable increase in the temperature of the surrounding salt mass and, consequently, an increase in the creep rate.

The additional creep resulting from the furnace operation at 82° C was 0.40 and 0.16 inch at 10 and 20 feet from the center of the furnace. The normal creep which would have occurred if the furnaces had not been operated would have been 0.13 and 0.09 inch respectively for the 10- and 20-foot distances.

15. The vertical creep rate at the center of the 1.9-year-old tunnel in the Hutchinson mine was found to be about 14 per cent greater than that near the wall.

16. The vertical creep rate at the center of the 1.9-year-old opening in the Hutchinson mine was approximately four times that of the horizontal rate. The actual deformations which had occurred were approximately equal, being 0.29 and 0.27 inch respectively in the vertical and horizontal directions.

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LIST OF SYMBOLS

A	constant	V, V_s	velocity
"	cross sectional area	V	volume
A_s	area at distance s from cavity	V_{s_a}	actual velocity
C	constant	V_p	pore volume
F	Fahrenheit degrees	V_t	total volume
K	constant	W_s	weight of specimen
L	length	a	radius of cavity
P	hydrostatic structural stress	b	Klinkenberg constant
"	vertical confining load	dh	incremental change in piezometric head
P_o	overburden pressure	dp	incremental change in pressure
P_i	internal pressure in a cavity	dr	incremental change in radius
Q	flow rate	ds	incremental change in distance
Q_b	gas flow rate at base pressure	dt	incremental change in time
p_b		dV	incremental change in volume
R	Rankine degrees	h	piezometric head
S_r	elastic radial stress	h_o	depth to center of cavity
S_t	elastic tangential stress	h_1	piezometric head in a cavity
S_v	specific surface area	h_2	piezometric head outside a cavity
T	temperature	k	specific permeability
T_o	temperature rise in a cavity	k_B	specific permeability of salt to brine
T_r	temperature rise at radius r	k_C	specific permeability of salt to calcium sulfate and brine
T_1	initial temperature in salt		
T_2	temperature in a cavity		

k_G	specific permeability of a medium to a gas	Δs	increment of distance
"	specific permeability of salt to helium gas	Σ	summation
		γ	unit weight
k_K	specific permeability of salt to kerosene	θ	angle
k_L	specific permeability of a medium to a nonreactive liquid	μ	absolute or dynamic viscosity
k_O	specific permeability of salt to oil	μ_s	absolute or dynamic viscosity at distance s from cavity
		σ_m	mean confining stress
k_S	specific permeability of salt to a synthetic waste of aluminum nitrate and brine	σ_r	plastic radial stress
		σ_t	plastic tangential stress
k_r	specific permeability at radius r	ϕ	effective porosity
m	constant	ϕ_s	effective porosity at distance s
p	pressure	ϵ	unit deformation
p_b	base pressure for the measurement of gas flow	$d\epsilon$	incremental change in unit deformation
p_c	vertical confining stress		
p_f	fluid pressure		
p_m	mean gas pressure $\frac{p_1 + p_2}{2}$		
p_1	influent pressure		
p_2	effluent pressure		
t	time		
"	tortuosity factor		
Δh	increment of piezometric head		
Δp	difference between influent and effluent pressure, $p_1 - p_2$		

INTRODUCTION

General

The accumulation of radioactive waste has been progressing at an accelerated rate yet no method for a permanent, economical, and safe disposal has been developed. The disposal of radioactive wastes has thus become one of the most important problems in the use of atomic energy for peaceful purposes. The storage of such wastes in cavities created within underground salt formations appears to be the most practical solution. This thesis deals with some of the aspects involved in salt-cavity storage.

The troublesome reactor-fuel processing wastes produced since the introduction of the first nuclear reactor have been stored in artificial containers up to the present date. The use of such storage is temporary because the lifetime of these containers is much shorter than that of the radioactive portion of the wastes. For example, radioactive waste has been stored in stainless-steel containers which have a 50-year life expectancy whereas high levels of the radioactivity may remain for considerably longer periods of time. The use of such containers will require perennial replacement and, consequently, may cause unusual safety problems to arise.

The particular problems involved in the actual disposal of the waste are: intense radiation levels which require thick shielding and remote handling; heat generation from radioactive isotope disintegration which requires an adequate cooling system; and corrosive tendencies which dictate the use of special containment.

The recommendation that storage in salt cavities represented the most promising permanent solution was made in 1955 by the Committee on Waste Disposal of the Division of Earth Sciences, National Academy of Science⁹. This committee consisted of leading scientists in interrelated fields such as Sanitary Engineering, Chemistry, Physics, Geology, Geophysics, Oceanography, and Economics. They concluded that the principle of concentrating the waste and then isolating it from our environment was more practical than the principle of diluting it in our environment to an allowable level of radioactivity. For high-level radioactive waste, the dilution principle would be impossible.

The disposal of radioactive wastes in salt formations involves numerous problems which require investigation. Some of these are: (1) radiation effect, (2) chemical effect, (3) time effect, (4) stress distribution, (5) geological study, (6) creep, (7) thermal heat effect, (8) structural stability, (9) permeability, and (10) cost. The study of these phases at The University of Texas was authorized by the U. S. Atomic Energy Commission under Contract AT-(11-1)-490. The investigations completed under this contract have been presented in a series of technical reports. The reports submitted are:

1. "Geology of Salt Domes and Storage Possibilities," January 1, 1959
2. "Development of Design Principle for Disposal of Reactor-Fuel Waste into Underground Salt Cavities," January 1, 1959
3. "Pressure-Temperature Effect on Salt Cavities and Survey of Liquefied Petroleum Gas Storage," January 15, 1959

4. "Thermal Considerations in the Storage of Radioactive Wastes in Salt Formations," June 1, 1960

These reports included investigations of all of the ten previously mentioned aspects involved in salt-cavity disposal, however, the study of salt permeability was very basic; and the creep studies were concerned mainly with laboratory tests and a few measurements in one mine. This study presents a detailed study of the permeability aspect and its consideration in the design of salt storage cavities and of the actual creep or closure rates occurring in existing salt mines.

In this report, many references are made to the previous reports since many relationships were taken from this literature.

Purpose

This report has two purposes: (1) to investigate the permeability of salt and evaluate it in terms of salt cavity storage and (2) to measure and evaluate the actual creep rates in salt mines.

Scope

The permeability study has included: a literature survey; the testing of dome- and bedded-salt samples; an analysis and application of the results; and an evaluation of underground rock salt as a material for cavity storage.

The creep study has included: the installation of equipment to measure creep in dome- and bedded-salt mines; the collection of data; and an evaluation of the creep rates that occurred.

The salt for the permeability study was obtained from the same mines where the creep measurements were made. The dome-salt mine was the Morton Company's Grand Saline, Texas mine and the bedded-salt mine was the Carey Company's Hutchinson, Kansas mine.

Plan of Presentation

Its twofold purpose necessitates the division of this report into two independent sections. The first section, titled "The Permeability of Salt" presents the permeability study. A general description of the permeability aspect in salt-cavity storage is given at the beginning of Chapter II, "Basic Considerations."

The section titled "Creep Measurements in Salt Mines" presents the creep study. An introduction to this section is given at the beginning of Chapter VII, "Basic Considerations, Procedure, and Measuring Stations Descriptions."

An abstract of the study and conclusions has been placed at the beginning of the report in order to facilitate reading for those interested in the overall objectives and findings.

PART ONE: PERMEABILITY OF SALT

BASIC CONSIDERATIONS

The disposal of radioactive wastes in underground salt formations is based on the principle of isolating the wastes from human environment until the decay process has reduced the radioactivity to a safe level. Therefore, no significant amount of hazardous radionuclides must be permitted to move around in an uncontrolled manner.

Part One of this report presents an investigation and analysis of the seepage factors in the design of underground waste-storage cavities in salt formations. This chapter presents the background theory underlying the analysis and a major portion of the literature on previously related work. Most of the previous research on flow characteristics of deep formations has been done for petroleum production or for ground-water hydrology studies. Consequently, much of the literature survey has been taken from these two fields.

Seepage Analysis in Cavity Design

The seepage analysis consists of checking the proposed cavity for seepage and, if any does occur, checking to see if sufficient time will elapse for the leakage waste to decay to a safe level before it passes out of the salt formation into other strata.

The permeability of a medium is a measure of its percolation capacity. Actually, nearly every substance has permeability, even the solid metals; however, below certain permeability values, substances are considered impervious. Ordinarily, shale is thought of as being impervious since it has a very low

permeability It is shown later in Chapter IV, "Results," that some of the salt tested exhibited no permeability whereas some had a very low permeability, less than shale. A previous survey³ on the use of salt formations for the storage of liquefied petroleum-gas products indicates that the majority of the storage cavities in use are apparently in impervious formations. For the purpose of analysis, however, it is assumed that enough permeability exists to permit fluid flow.

A simplified, hypothetical storage cavity located in a bed of salt is shown in Figure 2-1. As previously mentioned, the controlling factor in checking a cavity for seepage is the length of time that would be required for any of the waste to infiltrate out of the formation. In the formation shown, it is assumed that flow downward through the bottom of the bed will not be of importance since no ground water exists below the shale layer. The upward flow to the top of the formation is assumed to be the critical flow.

Both unsteady and steady flow may exist. Unsteady flow is defined as flow where the velocity at a given point changes with respect to time whereas, in steady flow, the velocity does not change with respect to time. Unsteady flow would occur when a cavity is first filled with fluid and would continue until the frontal zone of the fluid has passed upward to the top of the bed. Steady flow would occur once the frontal zone has reached the top of the bed.

The variables, some of which are found experimentally, that are required to determine the time of flow for the steady and unsteady-flow cases are the permeability, designated k ; the fluid's absolute viscosity, μ ; and the porosity of the formation, ϕ .

FIG. 2-1. WASTE STORAGE CAVITY
IN A SALT BED.

All of the variables were investigated in the project research, and methods to evaluate them are presented in subsequent sections of the report.

Salt Deposits in the United States

Natural rock salt is widely distributed in several areas of the United States, and it generally occurs either in bedded formations or in dome-like structures. Both types of salt were used in the project testing program and were obtained from mines which were believed to be representative of the respective types. The bedded salt came from the Carey Salt Company's Hutchinson, Kansas mine; and the dome salt came from the Morton Company's Grand Saline, Texas mine.

Rock salt, commonly called halite, is sodium chloride (NaCl) and, if pure, would have a specific gravity of 2.164. In its natural occurrence, however, it contains impurities. Rock salt of both types is usually 89 to 99 per cent pure NaCl with a range in specific gravity of 2.1 to 2.6 depending upon the amount of impurities.

The geology of salt beds and domes has been fully described by previous investigators^{12,18}. However, for familiarization, a brief of the geology of each type is given in the following discussion along with a description of the salt tested.

Bedded salt occurs in strata of varying thicknesses which may be interbedded with shale or sandstone.

The beds are believed to have been formed by successive trapping and evaporation of sea water in low areas during past geologic ages. As the water evaporated, the salt concentration became great enough to cause

crystallization and precipitation. The beds in the process of forming were frequently covered by material transported by erosion or other means which accounts for the impurity layers of shale and sandstone. In the final stage of their development, the beds were covered with transported materials which formed the overlying layer.

The beds in Kansas are a portion of a large deposit lying in Kansas, Oklahoma, Texas, and New Mexico. The Hutchinson, Kansas mine proper is 645 feet below the earth's surface. The salt from the mine had a dark color due to the shale impurity and had some cracks interlaced throughout its volume. Both the color and cracks can be seen in the photographs of one of the test specimens, Figures 3-9 and 3-14. The cracks in the bedded salt were not as numerous as those in the dome salt, and, consequently, the bedded salt was less fragile. Surface fractures of the salt were also observed in both the mines. There is reason to believe that they were not present in the original undisturbed salt but were produced by the redistribution and relaxation of stresses when the mines were created. Also, they may be partially due to the impact from the blasting used in nearby mining operations.

Dome salt occurs in dome-like salt masses which have intruded upward from deeper bedded deposits in the earth. As the original bedded deposits were formed they became covered with thick overlying stratum. When the overlying material became of sufficient weight it caused the underlying salt to flow plastically upward through weaker places in the overlying material. The upward intrusions were in plug- or dome-like shapes.

The domes are rather widespread through Texas, Louisiana, and Mississippi. The average dome diameter is 2.0 miles although it may range from 0.5 to 4.0

miles, and the top of the dome may be at or very near the earth's surface. The Grand Saline, Texas dome is 1.5 miles in diameter, and its top is about 300 feet below the earth's surface. The salt taken from the mine had a white color, was relatively free from impurities, had cracks throughout its volume, and was rather fragile. Both the color effect and cracks of one of the test specimens can be seen in Figures 3-10 and 3-13.

Laboratory Permeability Testing

Darcy's Law for flow through porous and semi-porous media served as a basis for the permeability tests. The law, although originally derived from studies on sands for water-purification filters⁸, applies to many instances of flow through a porous media as long as certain criteria for its validity are maintained.

The best laboratory simulation of salt in its natural state in the ground was obtained by removing undisturbed rock salt samples and reconfining them with an external pressure equivalent to the natural overburden pressure. It has been found that 1.0 foot of overburden depth is approximately equal to 1.0 psi of overburden pressure, and, thus, the laboratory simulation of salt at a 1,000-foot depth would require 1,000 psi.

The permeability of a medium decreases with an increase in the confining pressure. Therefore, the permeability for a formation in the earth will decrease as the depth from the earth's surface gets greater. Permeabilities can be found for various depths by selecting the appropriate confining pressure, and a correlation can be made between permeability and depth. This procedure has been previously used on oil-bearing sandstones¹⁹

Most of the laboratory permeability-test procedures for samples from deep underground formations were developed by research for the petroleum industry, therefore their standardized procedures²⁰ were used as much as possible in the test program.

Definitions

1. Permeability is a measure of the capacity of a porous medium to transmit fluids.
2. Specific permeability is the permeability of a medium when the fluid flow consists of only one homogeneous, single-phase fluid. This permeability was the type tested in the program, and tests were conducted for several liquids and a gas. Specific permeability is usually simply called permeability and is designated by the symbol k . The specific permeability is a property of the medium and is theoretically independent of the type of fluid. Effective and relative permeability are expressions for the permeability of one of the fluids in a two-phase liquid system. This type of permeability was not tested in the program.
3. Effective porosity, ϕ , is the ratio of the volume of interconnected pore space to the total volume of the medium. Since fluid flow can only occur through interconnected pore space, the effective porosity is important in analyzing certain cases of fluid flow and was tested in the program. The total porosity, which is the ratio of the total pore volume to the total volume of the medium, was not tested because of its unimportance in fluid flow.

Darcy's Law

Liquids: Darcy's Law²² states that the volume rate of flow of a liquid per unit cross-sectional area of the medium is directly proportional to the unit weight of the liquid and the piezometric gradient and inversely proportional to the fluid's absolute viscosity. The permeability is the coefficient of proportionality. Darcy's Law, given as a formulation, is

$$\frac{Q}{A} = \frac{k\gamma}{\mu} \frac{dh}{ds} \quad (2-1)$$

where k = coefficient of proportionality or permeability

Q = volume rate of flow

A = cross-sectional area perpendicular to the flow

γ = unit weight of the liquid

μ = absolute viscosity

dh = change in piezometric head

ds = distance over which the change in piezometric head, dh , occurs.

For the special case of horizontal flow, the terms γdh become the change in pressure head, dp . This change, dp , is equivalent to the pressure differential, Δp , that was measured in the tests. Making these substitutions in Equation 2-1 and solving for the permeability, k , gives

$$k = -\mu \frac{Q}{A} \frac{L}{\Delta p} \quad (2-2)$$

This is the equation used to reduce the test data.

It can be seen from Equations 2-1 and 2-2 that the rate of flow is proportional to the first power of the piezometric or hydraulic gradient and

indicates that the flow must be laminar for Darcy's Law to be valid²².

Gases: Darcy's Law for gases is a modification of the liquid law. It can be given by several different equations, however, the form used to reduce the data from the gas tests which were run is

$$k = \frac{2\mu Q_b p_b L}{A(p_1^2 - p_2^2)} \quad (2-3)$$

where

Q_b = flow rate at the base pressure, p_b .

p_b = base pressure

p_1 = absolute pressure at entrance

p_2 = absolute pressure at exit

The other variables, μ , A , and L are the same as in the law for liquids.

In order for the modified Darcy formula for gases to be valid, the gas velocity must fall within a certain range which is analogous to laminar flow in liquids.

Permeability Units: An inspection of Equation 2-2 and 2-3 shows that the dimension of the permeability unit should be length squared (L^2), which, in the c.g.s. system, is the cm^2 . Unfortunately, this unit has been adopted only by some physicists. In most branches of applied science, some other unit has been adopted specifically for that branch. Thus, the oil industry uses the "darcy," and ground-water hydrologists express permeability in terms of velocity of water per unit decrease in hydraulic gradient. For the purposes of this report, the permeabilities are expressed in units of the

c.g.s. system, the cm^2 , and in darcys. The units are defined as follows:

1. The centimeter-squared, cm^2 , is the absolute dimensional unit of permeability in the c.g.s. system.
2. The darcy is the permeability of a medium when a single-phase fluid of one centipoise absolute viscosity flows in laminar flow at a rate of one cubic centimeter per second per square centimeter of cross-sectional area under a piezometric gradient of one atmosphere (76.0 cm Hg) per centimeter.

Conversions from darcys to centimeters-squared or vice-versa can be made by the relationship

$$1 \text{ darcy} = 9.87 \times 10^{-9} \text{ cm}^2$$

Deviations: Certain deviations from Darcy's Law may occur in permeability testing and require understanding before the test results can be properly evaluated.

The basic requirement for the validity of Darcy's Law is that the flow must be laminar or viscous. This requires relatively low flow velocities. If the velocities for laminar flow are gradually increased, a velocity will be reached where turbulence occurs and Darcy's Law becomes invalid. Some investigators have determined the upper limit of the region of laminar flow in terms of the Reynolds Number. Their experiments were on sands and the relationships derived were in terms of grain diameter. This concept could not be applied to the salt tests because the shape of the flow passages in the salt is different from that in sands.

Certain deviations even for laminar flow may occur in permeability testing. Some of these are: (1) Tests on the same type salt using two different liquids or a liquid and a gas may yield differing results, (2) Tests on a sample using a single liquid may show a variation of permeability with time.

The permeability, according to Darcy's Law, is a property of the medium and is theoretically independent of the test fluid. This is true because the fluid's flow properties, which are its viscosity and density, are incorporated into the Darcy formula, Equation 2-1. This means that the permeability value for salt, using two different test liquids, should be the same. As previously mentioned, however, there may be a difference, and it is customary in such cases to make reference to the test fluid in reporting the permeability values.

These deviations do not make Darcy's Law invalid for the particular fluid being tested; however, they do show that the permeability, in some cases, is dependent upon the fluid being tested¹¹. Deviations from Darcy's Law may be due to one or more major causes²⁰, which are:

1. Physical or chemical reactions of the fluid with the medium.
2. Phenomenon of "slip" in gas flow.
3. Molecular effect of gases.
4. Electrokinetic or electrical effects.

Certain physical or chemical reactions between the fluid and the medium can occur which cause a change in pore pattern and, in effect, create a new medium. A physical reaction which may occur in the testing of salt with an undersaturated brine solution is the dissolving of the medium by the test fluid. This will increase the area of the pore passage and thus increase the

permeability. Another example is the plugging of the pore passage by finely suspended material in the test solution or by salt recrystallized from a super-saturated brine test solution. This causes a reduction in the pore passage area and, consequently, a reduction in permeability. A chemical reaction which may occur is that of ion-exchange^{5,6}. This is supposed to take place when a brine solution is passed through a medium containing sodium ions such as a salt medium. The sodium ions are believed to be exchanged for the chloride ions in solution, and the deposition of the larger chloride ions causes the reduction in permeability. Later investigations^{2,23,31}, however, have shown that the ion-exchange may be rather small in comparison to the electrokinetic effects.

The phenomenon of "slip" in gas flow causes the permeability of a medium to a gas to be greater than the permeability of the same medium to a liquid⁴. This is due to a fundamental difference in the flow characteristics of the two fluids. In normal liquid flow there exists a liquid layer having a zero velocity next to the passage wall. However, in gas flow through a medium where the diameter of the pore passage is approaching or is smaller than the "mean free path" of the gas, the gas near the wall will have a finite velocity, and the flow is said to have slippage. The reason for the absence of the laminar layer is that the gas molecules are in constant motion. The molecules within the mass of gas are continually striking the walls and are bouncing off, and, in such a situation, a laminar layer is not possible. Since the gas will have a higher velocity near the passage walls than a liquid, the gas permeability will be larger than the liquid.

The molecular effect of gases causes the permeability of a medium to a gas to be dependent upon the mean pressure of the gas, and, also, it causes the permeabilities of a medium to two different gases to differ. The spacing of the individual molecules of a gas causes the molecular effects. Each gas has a characteristic "mean free path" which is the average distance a molecule has to travel before it collides with another. When the mean free path is of the same magnitude as or is greater than the pore passage width, the permeability becomes dependent upon the mean free path of the molecules⁶. As the pressure of a gas decreases the mean free path increases, and the permeability, in turn, increases. The permeability increase is believed to be due to the increased kinetic energy and diffusion of the gas molecules. At large mean free paths, the diffusion becomes of sufficient magnitude to add a contribution to the fluid flow. The permeability of a medium to a gas, therefore, is dependent upon the factors that affect the mean free path. These factors are: the individual gas under consideration; the temperature; and the pressure.

Electrokinetic effects sometimes occur in the flow of ionic solutions through a porous medium and cause the permeability to be less than that of a non-ionic solution. This phenomenon is due to the generation of a small electromotive force as an ionic solution is forced through a small pore passage. This self-generated potential causes a small electro-osmotically motivated resistance to the flow to occur²³.

Liquids that undergo any reaction with the porous medium or have electrokinetic effects are classified as "reactive" liquids whereas those that do not undergo any reaction or do not have any electrokinetic effects are classified as "nonreactive."

Gas and Nonreactive Liquid Permeability Relationship

The Klinkenberg formula¹⁵ relates the gas permeability of a medium to its nonreactive liquid permeability. Also, it relates the gas permeability of the medium at a given mean pressure to its gas permeability at a different mean pressure. The formula in its most common form is:

$$k_L = \frac{k_G}{1 + \frac{b}{pm}} \quad (2-4)$$

where

k_L = nonreactive liquid permeability

k_G = gas permeability

b = Klinkenberg constant

pm = mean gas pressure or $\frac{p_1 + p_2}{2}$

A plot of typical data from a Klinkenberg test is shown by Figure 2-2. The nonreactive permeability, k_L , is the ordinate intersection of an extrapolated line through the test points. This corresponds to an infinite mean pressure which causes the mean free paths of the gas molecules to become a minimum and equal to that of a liquid.

The constant, b , which can be determined from the plot, is dependent upon the gas used and the porous medium. Once determined for a type medium, it allows subsequent testing on samples under different loading conditions to be conducted at one mean pressure. The single values obtained can be then converted to gas permeabilities at other pressures or to non-reactive liquid permeabilities.

FIG. 2-2. KLINKENBERG EFFECT.

FIG. 2-3. STRESS DISTRIBUTION AROUND AN EMPTY CAVITY.

FIG. 2-4. STRESS DISTRIBUTION IMMEDIATELY AFTER FILLING.

FIG. 2-5. STRESS DISTRIBUTION AFTER SALT IS HEATED.

The Klinkenberg formula and constant, can be used in determining whether a liquid is reactive or nonreactive to a medium. This can be done by first testing the permeability with a gas and then with the liquid under consideration. The gas permeability can then be converted to the equivalent non-reactive liquid permeability. If this permeability does not equal the actual liquid permeability, some interaction or other effects have occurred, and the liquid is classified as reactive.

Permeability and Confining Pressure Relationship

A formula has been developed that gives a relationship between the liquid permeability, liquid pressure, and the confining pressure. The confining pressure, for present purposes, is considered as the overburden pressure when hydrostatic stress distribution exists and as the mean of the stresses in the three principal axes when the stress distribution is not hydrostatic. By hydrostatic stress distribution, it is meant that the structural stresses in all directions from a point are equal.

A relationship²⁹ which has been developed for hydrostatic stress conditions is

$$k = C(P - p_e)^{-m} \quad (2-5)$$

where

k = permeability

C = constant, determined experimentally

P = hydrostatic structural stress

p_f = fluid pressure

m = exponent constant, determined experimentally

Separate studies on oil-field sandstones have verified this relationship¹⁹.

The difference between the structural stress, P , and the fluid pressure, p_f , is the effective stress. This stress, $P - p_f$, is the stress that produces deformation of a porous medium²⁷.

Previous investigators²⁶ have found that hydrostatic stress distribution exists in confined salt when the vertical stress is 300 psi or more. Therefore, the stress distribution in undisturbed salt will be hydrostatic for depths of 300 feet or greater. The hydrostatic stress, P , will be equal to the overburden pressure, P_o , and Equation 2-5 will become

$$k = C(P_o - p_f)^{-m} \quad (2-6)$$

The construction of a cavity causes the rearrangement of stresses in the vicinity of the cavity, and, for that region, the stress distribution will not be hydrostatic. For this reason, it was decided that the best correlation could be obtained by using the mean of the three principal stresses, σ_m , as the stress parameter. The mean stress for a point in the vicinity of a spherical cavity would be

$$\sigma_m = \frac{S_r + 2S_t}{3} \quad (2-7a)$$

where

σ_m = mean stress or mean confining stress

S_r = elastic stress in radial direction

S_t = elastic stress in tangential direction

Substituting the mean stress, σ_m , in Equation 2-5 gives

$$K = C(\sigma_m - p_f)^{-m} \quad (2-8)$$

Equation 2-8 was used as the relationship for the permeability, liquid pressure, and confining pressure in this report.

A complete treatise on the structural analysis involved in cavity design has been done by previous investigators²⁶. The solution of a hypothetical cavity of 30-foot diameter and 1,000-foot depth is shown in Figures 2-3, 2-4, and 2-5 to illustrate the previously derived concepts. When an empty cavity is first constructed, Figure 2-3, elastic stress conditions will exist around the cavity unless it is at a great depth. The radial stress, S_r , and the tangential stress, S_t , are approximately equal at a distance of several radius lengths from the cavity. Near the cavity, however, the radial stress, S_r , decreases; and the tangential stress, S_t , increases. Up to the cavity wall, the mean stress, σ_m , is constant and is equal to the overburden pressure, P_o . In the case of a cavity at a great depth, there may be a plastic zone immediately surrounding the cavity and elastic stress conditions will exist outside of the plastic region.

Immediately after the cavity is filled, Figure 2-4, the radial stress, S_r , at the cavity wall, becomes equal to the internal pressure, P_1 ; and the

tangential stress, S_t , in the vicinity of the cavity, is slightly decreased. The mean stress, σ_m , however, remains the same as that of the empty cavity.

As the heat from the waste builds up and is transferred out into the salt, considerable stress changes occur. A plastic zone, Figure 2-5, is formed around the cavity, and the thermal stresses cause increases in the tangential and radial stress.

In keeping with previous notations²⁶, the radial and tangential stresses in the plastic zone are given by σ_r and σ_t . The mean stress, σ_m , therefore, in the plastic zone, will be

$$\sigma_m = \frac{\sigma_r + 2\sigma_t}{3} \quad (2-7b)$$

where

σ_m = mean stress or mean confining stress

σ_r = plastic stress in radial direction

σ_t = plastic stress in tangential direction

The mean stress, σ_m , is maximum at the border of the plastic zone and has a distribution as shown in Figure 2-5.

The mounting of the specimens tested in the laboratory was done in such a manner that hydrostatic pressure distribution was obtained and the vertical pressure, p_c , placed on top of the specimen was equal to the mean stress, σ_m .

Permeability and Porosity Relationship

There is a definite correlation between permeability and effective porosity for a given medium under different confining pressures. Such a relation is useful in determining one of the two quantities when the other is known. In the analysis of a storage cavity design problem, as presented in Chapter V, it is necessary to know the porosity of salt at various confining pressures. This could not be determined experimentally because of the complex equipment that would be required. Therefore, it was computed from permeability values at various confining pressures which were easily measured.

The relationship between permeability and porosity is most commonly expressed by the Kozeny^{7,16} equation or one of its modifications. The form which served as the basis for the relationship developed for this study is

$$k = \frac{C\phi^3}{tSv(1 - \phi)^2} \quad (2-9)$$

where

k = permeability

C = coefficient depending upon the shape of the pores cross-sectional area

Sv = specific surface area or the ration of the pore's surface area to the mineral volume of the medium

t = tortuosity factor

The equation is based on Poiseuille's law of flow through capillary tubes and on the assumption that ideal straight capillary tubes extend through the medium. The actual flow paths, however, will not be straight,

but, instead, sinuous and much longer than the ideal path. The tortuosity factor, t , compensates for this deviation.

The factors c , t , and S_v may be combined into a single constant for the special case of a medium under different confining pressures. This is valid since these factors do not vary much under different pressures. The varying confining pressures merely increase or decrease the width of the flow passages.

Combining these factors into a single constant, K , gives

$$k = K \frac{\phi^2}{(1 - \phi)^2} \quad (2-10)$$

which is the equation used herein as the relationship between permeability and porosity.

TEST PROCEDURE

This chapter describes the procedures used in the permeability tests. The tests were performed at the Sanitary Engineering Research Laboratories, Balcones Research Center, Austin, Texas, and were performed in accordance with accepted standards²⁰ for testing of porous media.

Liquid-Permeability Test

The liquid-permeability test utilized Darcy's Law in the form given by Equation 2-2 in the previous chapter. A schematic diagram of the liquid test is shown in Figure 3-1. For the test, the salt specimen was mounted in the permeability test cell, and the confining pressure, p_c , was applied to the top of the specimen. The permeating liquid was stored in the pressure-exchange cylinder. When the desired permeating-fluid pressure, p_1 , was applied by the permeating-liquid pressure pump, the permeating fluid flowed from the exchange cylinder into and through the salt specimen. The flow from the specimen continued into the graduated glass measuring cylinder which allowed the flow rate, Q , to be measured. The cross section area, A , and the length, L , depended upon the specimen's size. The pressure differential, Δp , was, for practical purposes, equal to the gage pressure, p_1 , since the gage pressure at the salt's exit was almost zero. The viscosity, μ , was a function of the fluid and temperature and was determined by viscosity tests.

The equipment, Figure 3-2, consisted of the permeability test cells, test stands, the confining load hydraulic rams and pump, the permeating-fluid

Note: Permeability Test Cell is shown at an exaggerated scale.

FIG. 3-1. PERMEABILITY TEST USING A LIQUID

FIG. 3-2. ASSEMBLY OF COMPREHENSIVE TEST DEVICE.

FIG. 3-3. PERMEABILITY TEST CELL ASSEMBLY.

FIG. 3-4. ARRANGEMENT FOR PERMEABILITY TESTING.

FIG. 3-5.
PRESSURE
CONTROL
SYSTEM

FIG. 3-6. PERMEABILITY TEST CELLS.

pressure exchange cylinder and pump, and the graduated measuring cylinders. Three test cells and stands were used permitting simultaneous testing. The entire test equipment was housed in a room having a thermostatically controlled heating and cooling system to maintain a temperature of $79^{\circ} \pm 2^{\circ}$ Fahrenheit during the tests.

After the porous filters were placed over the ends of a specimen, it was inserted in the lower chamber of a test cell, Figures 3-1, 3-3, and 3-6. A plastic cement was then cast around the specimen to confine the flow to the specimen itself and to allow uniform application of the confining pressure, p_c , Figure 3-1, to the specimen's top. The confining load, P , Figure 3-1, was applied to the piston rectangular compressor assembly, which, in turn, distributed the load uniformly as the confining pressure, p_c . When the confining pressure, p_c , is greater than 300 psi, the confining pressure will be equal to the mean stress, σ_m , of Equation 2-7a²⁶. This condition of hydrostatic stress has been found to exist at pressures above 300 psi²⁶.

The test stand with an inverted, mounted, hydraulic ram, shown in detail in Figure 3-4, furnished the confining load, P , to the test cell. The ram was operated by a hydraulic pump with a pressure operated control circuit, Figure 3-5. The control circuit kept the loading pressure at a constant value.

The permeating-liquid pressure exchange cylinder, Figure 3-1, consisted of a cylinder and free piston with the permeating fluid on one side and oil from the permeating-fluid pressure pump on the other side. The pressure was maintained constant by a pressure-control system similar to that shown for the confining pressure pump, Figure 3-5.

Gas-Permeability Test

The gas-permeability test utilized Darcy's Law in the form given by Equation 2-3. A schematic diagram of the gas test is shown in Figure 3-7. The salt specimen was mounted in the permeability test cell and the confining load, P , applied in an identical manner as in the liquid-permeability test. The gas from the high pressure gas cylinder was reduced to lower pressure by the pressure reducing and regulating device. The low pressure gas from the regulator flowed into and through the salt specimen. The flow from the salt specimen continued into the graduated glass measuring cylinder which allowed the flow rate, Q_b , to be measured. The gas flow rate was measured by displacement of water which originally filled the cylinder. As the water was displaced, the cylinder was gradually raised from the water to maintain the surface level in the cylinder at the same level with that in the tank. This gave the volume at atmospheric pressure. For Equation 2-3, Q_b represents the flow rate at the base pressure, p_b , which is the atmospheric pressure at the time Q_b was measured. The cross section, A , and length, L , depended upon the specimen's size. The entrance pressure, p_1 , and the exit pressure, p_2 , in Equation 2-3 represent the absolute pressures or the sum of the relative pressures and the atmospheric pressure. The relative pressure at the entrance to the specimen was measured by a mercury manometer when the pressure was below 20 psi and by the gage on the pressure reducing device when the pressure was greater than 20 psi. The relative pressure at exit of the specimen was measured at all times by a mercury manometer. The atmospheric pressure was obtained from a mercury

FIG. 3-7. PERMEABILITY TEST USING A GAS.

barometer. The dynamic viscosity, μ , was a function of the gas used and the temperature.

Some of the equipment used in the gas test, such as the test cells, test stands, and the confining load system, was the same equipment that was used in the liquid test. Other equipment required for the gas test consisted of the high pressure gas cylinder, the regulating device, the water tank, and the graduated glass measuring cylinder.

Test Operations

A flow chart of the test operations used is given in Figure 3-8. The procedure consisted of securing the salt samples, preparing specimens to a standard size and mounting them in test cylinders, loading the specimens, performing the actual tests, and reducing the test data collected.

The number of tests performed on each specimen followed one of these patterns:

1. One type of liquid per specimen.

The liquids generally used were either kerosene or saturated brine (NaCl) solution, and the permeability tests were conducted over a period of 7 to 14 days.

2. Two types of liquids per specimen.

The liquids generally used were kerosene and saturated brine (NaCl). Each liquid was tested over a 7- to 14-day period.

3. One gas test per specimen followed by one or more liquid tests.

Securing the Salt Samples from the Mines.
(Mining and shipping the "Mother Blocks")

Preparation of Specimens

1. Cutting crude specimens from Mother Blocks
2. Grinding crude specimens down to finished specimen size $1\frac{1}{4}'' \times 1\frac{1}{4}'' \times 1\frac{9}{16}''$
3. Fitting the porous filters
4. Placing the specimen and filters in the test cell.
5. Encasement of specimen in plastic cement.

Loading of Specimens in Test Stand

FIG. 3-8. FLOW CHART OF TEST PROCEDURE.

Helium gas was used and was tested for one day; then the two liquids were tested as described in Pattern 2 above.

Salt Samples and Permeating Fluids

The tests were performed on the two types of naturally occurring rock salt, the dome and bedded type, and a synthetically produced solid salt crystal.

The dome-type rock salt was obtained from the Morton Salt Company's mine located at Grand Saline, Texas. The portion of the mine where the salt was removed is 700 feet below the earth's surface. The salt was removed as a block (1 cubic meter). This "mother block" was removed with extreme care using power saws and drills to prevent excessive cracking or disturbances. The block, after removal, was sprayed with a plastic film to prevent moisture condensation and absorption at its surface.

The bedded salt was obtained from the Carey Salt Company's mine located at Hutchinson, Kansas. The portion of the mine where the "mother block" was removed is 645 feet below the earth's surface. The block was about 1.5-foot cubed and was mined and protected in a similar manner as the Grand Saline block.

The synthetically produced monocrystal was obtained from the Harshaw Chemical Company. The permeating fluids used were kerosene, a mineral oil, pure saturated brine solution (NaCl), saturated brine and calcium sulfate solution ($\text{NaCl} + \text{CaSO}_4$), a synthetic waste of saturated brine and aluminum nitrate ($\text{NaCl} + \text{Al}(\text{NO}_3)_3$), and helium gas.

The viscosity for all the fluids varied with the temperature; therefore, the temperature was kept constant during each test to maintain a constant viscosity.

The kerosene was obtained from the Magnolia Petroleum Company, and a table of its physical properties including viscosity at 100° Fahrenheit was furnished by the manufacturer. The viscosity at 100° Fahrenheit agreed closely to the viscosity given in standardized graphs²² of viscosity versus temperature. Since this was true, the viscosity for the test temperature of 79° F. was taken from standardized graphs.

All of the brine solutions were prepared at the test temperature of 79° Fahrenheit using distilled water and reagent grade chemicals. Viscosity tests were run at various temperatures, and viscosity-versus-temperature graphs were developed. The viscosity at the test temperature was then taken from the graph.

The helium gas was obtained in a 1,000-psi high pressure gas cylinder and was 98.7 per cent helium and 1.3 per cent butane. The viscosity, since the gas was relatively pure, was taken from standardized viscosity-versus-temperature tables¹³.

Sample Preparation and Loading

Both the dome-salt and bedded-salt specimens were prepared in the same manner except that the dome salt required more care in handling because it was found to be more fragile.

Crude salt specimens measuring approximately 1 3/4 inches by 1 3/4 inches by 2 1/2 inches were cut from the "mother blocks" with a handsaw.

The crude specimens were then ground down, using sandpaper, into finished specimens of $1\frac{1}{4}$ - by $1\frac{1}{4}$ - by $1\frac{11}{16}$ -inch size, Figure 3-10. The finished specimens were then stored in an air tight box.

The first step in preparing a finished specimen for a test was the fitting of the porous ceramic filters over the specimen's entrance and exit ends, Figure 3-11. These filters assured an even distribution of flow into and out of the specimen. The filters, which were originally $1\frac{1}{4}$ inches by $1\frac{1}{4}$ inches by $\frac{3}{8}$ inch, were ground down in thickness until the specimen with its two filters were fitted snugly lengthwise in the $2\frac{1}{4}$ -inch long confining chamber of the test cell, Figure 3-6.

The second step was the placing of the specimen with its two end filters in the confining chamber of the test cell. The specimen was located in the chamber in such a manner that a $\frac{1}{4}$ -inch thick cement encasement could be poured around it.

The third step was the encasement of the specimen by the plastic cement. For this operation, the cell was inverted and a Tefron plate which served as the lower form for the cement was placed in the confining chamber below the specimen. The plastic resin cement, Hysol, was mixed in such a proportion (8:1) with its hardening agent that the hardened cement had a stress-strain curve approximately equal to that of the salt. The hardening was complete in 24 hours after the pouring operation. The Tefron plate was then removed and the specimen was ready for the assembly of the cell. In order to give a more complete picture of the encasement operation, Figures 3-12, 3-13, and 3-14 are shown of specimens removed from the test cells

FIG. 3-9. CRUDE BEDDED
SALT SPECIMEN.

FIG. 3-10. FINISHED DOME
SALT SPECIMEN.

FIG. 3-11. FINISHED SPECIMEN
WITH END FILTERS.

FIG. 3-12. ENCASED SPECIMEN
AFTER TEST COMPLETION.

FIG. 3-13. ENCASED DOME
SALT SPECIMEN.

FIG. 3-14. ENCASED BEDDED
SALT SPECIMEN.

after completion of their tests. Figures 3-13 and 3-14 clearly show the difference in color and appearance of the dome and bedded salt.

The final step in the preparation of a sample consisted of the assembly of the test cell. The component parts of the cell, Figure 3-6, were put together to give the assembled cell shown in perspective section in Figure 3-3 and by photograph in Figure 3-6. The assembled cell was then placed in the test stand and was ready for application of the confining load.

The confining load was applied to the assembled cell after the dial gage and the necessary hoses were attached as shown in Figure 3-15.

The tests were conducted at 500, 1,000, 1,500, 2,000, and 2,500 psi confining pressures. Generally, only one confining pressure was used per specimen. Once the desired confining pressure was applied, the loading system was placed on automatic operation using the pressure regulated control system which maintained a constant loading. The specimen, if only liquid tests were to be made, was then placed under a 150- to 200-psi permeating fluid pressure and maintained at this pressure until the permeability tests were begun. The constant liquid pressure was accomplished by closing the exit valve from the test cell and leaving the permeating-fluid pressure on automatic operation. If, however, the specimen was to be tested by gas, no liquid was applied and the specimen was kept dry.

The creep, or vertical deformation, was recorded daily, and, when the total creep had reached a maximum value and the daily creep increase became zero, the permeability tests were begun. Generally, this occurred between 7 to 14 days after loading.

FIG. 3-15. PERMEABILITY TESTING STAND.
(Set-up for Liquid Test)

Collection and Reduction of Data:

Liquid Permeability: Daily permeability tests on a specimen were determined over the test period, and each test consisted of measuring the amount of flow per time interval. The daily tests were conducted at a constant permeating-fluid pressure between 100 to 400 psi or at a series of pressures of 100, 200, 300, 400, and 500 psi. The permeating-fluid pressure was always kept below a value of one-third the confining pressure.

The daily test, using the constant fluid pressure, consisted of recording the volume of fluid collected and the time of collection since the beginning of the flow. The test varied from one to four hours long depending upon the amount of flow.

The daily test, using the series of increasing pressures, consisted of recording the volume of flow at each fluid pressure for a one-hour duration. If five pressures were used, the total time required was five hours. At least four different pressures were used with five being the most common.

The permeability for a specimen at a given confining and fluid pressure was assumed to be the mean of the daily permeability values over the 7- to 14-day test period. The daily permeabilities were computed from Equation 2-2.

The daily permeability computations for each test using a constant fluid pressure utilized the average rate of flow as the term Q . The value of the pressure differential was, for practical purposes, equal to the gage pressure, p_1 .

The daily permeability computations for the tests using a series of liquid pressures required a graph of the average flow at each pressure versus the pressure. The slope of a straight line drawn through the points and the origin represented the terms $Q/\Delta p$.

Gas Permeability: The Klinkenberg constant, b , in Equation 2-4 was determined from the results of the first gas test conducted on each type of salt. Once this had been determined, it was possible to convert gas permeabilities from subsequent tests at a single pressure into nonreactive liquid permeabilities.

The tests for determination of the Klinkenberg constant were made daily for three days, and the constant was taken as the mean of the daily values. Each daily test involved testing at differential gas pressures of 10, 20, 30, 40, and 50 psi.

The gas tests, subsequent to the determination of the Klinkenberg constant, were conducted at one pressure in order to save gas.

The Klinkenberg constant, b , was taken as the mean of the daily constants from the three daily tests. The computations for the daily constant required the permeabilities at each test pressure. These were computed from Equation 2-3.

Once the daily permeabilities for the different mean pressures were determined, a plot similar to Figure 2-2 was made; and the Klinkenberg constant, b , and the nonreactive liquid permeability, k_L , were determined by the use of Equation 2-4.

The Klinkenberg constants for the three daily tests were then averaged and the mean value obtained was used to convert the gas permeabilities from

subsequent tests into nonreactive liquid permeabilities. The subsequent gas tests were all run at one pressure, and the gas permeabilities were computed using Equation 2-3. The gas permeabilities were then converted into non-reactive liquid permeabilities using Equation 2-4.

Effective Porosity and Density:

The effective porosity, ϕ , was determined by the gas expansion method³⁰ using a mercury pump porosimeter. The method requires the expansion of air filling the pores by means of a vacuum. The pore air volume at the vacuum pressure was converted into volume at atmospheric pressure, V_p , by Boyle's Gas Law. The total volume, V_t , both the salt and pore space, was determined by the volume of mercury displaced when the specimen was placed in the confining chamber of the porosimeters. The effective porosity, ϕ , was then computed from the formula

$$\phi = \frac{V_p}{V_t} \quad (3-1)$$

The density of the salt, γ , was determined from the specimen's weight, W_s , and its total volume, V_t . The density utilized the bulk volume and therefore did not represent the density of the solid crystals themselves. The specimens' weights were determined prior to the porosity tests. The density, γ , was then computed from the formula

$$\gamma = \frac{W_s}{V_t} \quad (3-2)$$

TEST RESULTS

This chapter presents the results of the permeability, porosity, density, and viscosity tests with their interpretation.

The tests are numbered in sequence for each of the salts that were tested and use a letter to designate the type of salt. For instance, the thirteenth test on Grand Saline salt would be designated 13G. The permeability values for each test are designated by the letter k with a subscript to denote the fluid used. This system gives the following symbols for the respective fluids:

k_G	--	permeability to helium gas
k_K	--	" " kerosene
k_O	--	" " mineral oil
k_B	--	" " brine (NaCl)
k_C	--	" " calcium sulfate and brine ($\text{CaSO}_4 + \text{NaCl}$)
k_S	--	" " synthetic waste of aluminum nitrate and brine ($\text{Al}(\text{NO}_3)_3 + \text{NaCl}$)

The flow through the specimens was found to occur through the interconnected fractures and not through the crystals themselves. This was proven by testing a solid synthetically grown monocrystal obtained from the Harshaw Chemical Company. The test gave no flow showing that the flow cannot pass through the crystals. Therefore, any flow must pass through the fractures.

Special procedures were used on the Grand Saline specimen in Test 15G to determine if the plastic encasement cement was causing any

prestressing of the specimen. The sides of the specimen were coated with a thin layer of Duco cement, and it was then mounted in the test cylinder.

Prior to the pouring of the Hysol, the specimen was tested with helium gas and was found to have a nonreactive permeability, k_L , of $8.0 \times 10^{-10} \text{ cm}^2$.

Twenty-four hours after the Hysol had been poured, it had hardened. Another gas test was then made giving a nonreactive liquid permeability, k_L , of $9.7 \times 10^{-10} \text{ cm}^2$. Since the permeabilities compare favorably, it shows that the Hysol did not have any appreciable prestressing effect.

Grand Saline Salt

The permeability tests on the Grand Saline salt gave consistent results. The Klinkenberg constant for helium gas was determined. A relationship between permeability, confining pressure, and liquid pressure was developed. Also, various factors that reduce permeability were evaluated.

Klinkenberg Data: A series of helium tests at different mean pressures were conducted on specimen 11G to determine the Klinkenberg constant, b , in Equation 2-4. The results of the tests are shown in Figures 4-1 through 4-3 along with lines that were fitted to the data by the method of least-squares. The computed Klinkenberg constants were 0.19, 0.41, and 0.69 giving an average value of 0.43. Substituting this into the Klinkenberg formula, Equation 2-4, gives the equation for the nonreactive liquid permeability, k_L , as

$$k_L = \frac{k_G}{1 + \frac{0.43}{p_m}} \quad (4-1)$$

FIG. 4-1. KLINKENBERG DATA -
GRAND SALINE SALT.

FIG. 4-2. KLINKENBERG DATA -
GRAND SALINE SALT.

FIG. 4-3. KLINKENBERG DATA -
GRAND SALINE SALT.

Table 4-1

Comparison of the Brine, Kerosene, and Nonreactive Liquid Permeabilities of Grand Saline Salt

Test	Mean Stress σ_m (psi)	Permeability (cm ²)					
		k_G	k_L	k_K	$(k_K/k_L) 100\%$	k_B	$(k_B/k_L) 100\%$
11G	1,500	3.2×10^{-12}	2.3×10^{-12}	2.1×10^{-12}	92%	6.2×10^{-13}	27%
15G	500	9.0×10^{-11}	7.2×10^{-11}	5.7×10^{-11}	79%	2.6×10^{-11}	36%
		Average					89%
							32%

where

p_m = mean gas pressure in atmospheres

Reactivity of Kerosene and Brine Solutions:

The reactivity of kerosene and brine solutions was determined by testing two specimens, 11G and 15G, with helium gas followed by the two solutions.

Table 4-1 shows the results of the tests with a percentage comparison of the kerosene and brine permeabilities to the nonreactive liquid permeabilities. The kerosene and brine permeabilities shown were those that were obtained during the first one or two days of testing with the respective liquids. The permeability obtained at the beginning of a test has been designated the initial permeability. It will be shown in a subsequent section that the permeability in many of the tests decreased with the test duration.

The kerosene permeability, k_K , averaged 89 per cent of the nonreactive liquid permeability, k_L , whereas the brine permeability

k_B , averaged 32 per cent. This indicates that kerosene is relatively nonreactive whereas brine has some interaction.

It was suspected prior to the testing that kerosene would be nonreactive because it is a nonpolar liquid and does not dissolve salt.

The reactivity of brine is believed to be due to electrokinetic effects which may result from its ionic nature. Other investigators²³ have shown that saline solutions generate small electromotive forces which cause a retardation of the flow thus causing the permeability to be smaller than would normally occur.

In order to check for possible recrystallization and precipitation of salt from the brine solution, samples were taken of both the influent and effluent flows and were checked for salt content. This revealed that the salt content was the same in both so, apparently, no crystallization and deposition of crystals had occurred.

Nonreactive Liquid Permeability and Confining Pressure Relationship:

Figure 4-4 shows the results of all the nonreactive liquid-permeability values that were obtained in the tests. The permeability values at a net confining stress of one psi were found to be equal to those obtained from tests at zero overburden pressure. The results of these tests are found in Table 4-2. Curve 1 of Figure 4-4 represents the average permeability to mineral oil, k_O , for Test 1G. In this test the permeability was determined at increasing confining pressures from 10 to 8,500 psi. Since the permeability to kerosene was approximately equal to the nonreactive liquid permeability, it is assumed that the permeability to the oil will have the same relationship and could be considered equal to the nonreactive liquid permeability.

FIG. 4-4. NON-REACTIVE LIQUID PERMEABILITY -
GRAND SALINE SALT.

Table 4-2

Nonreactive Liquid Permeability of Grand Saline

Salt at Zero Overburden Pressure

Test	Gas Permeability k_G (cm^2)	Nonreactive Liquid Permeability k_L (cm^2)
12G	1.22×10^{-10}	9.3×10^{-11}
13G	7.90×10^{-10}	6.0×10^{-10}
14G	1.09×10^{-9}	8.3×10^{-10}
15G	1.28×10^{-9}	9.7×10^{-10}
17G	1.98×10^{-9}	1.5×10^{-9}
18G	5.80×10^{-10}	4.4×10^{-10}
19G	7.20×10^{-10}	5.4×10^{-10}
Average		7.1×10^{-10}

Curve 2 represents the average nonreactive liquid permeability, k_L , for three tests using helium gas, 14G, 15G, and 16G. The specimens for these tests were made from the same salt block; therefore, the results have been incorporated into the same curve. Curve 3 represents the nonreactive permeability for Tests 11G and 13G, specimens for which were made from the same block. Curves 4, 5, and 6 represent the average values for Tests 17G, 18G, and 19G. The variation between the results is apparently due to the differences between the individual specimens and may be caused by their small size.

It can be seen from these curves that the relationship of Equation 2-8

$$k_L = C(\sigma_m - p_f)^{-m} \quad (2-8)$$

will only be applicable for values of the net confining pressure from 1 to

about 1,000 psi. The breakdown of the relationship for large values of the net confining pressure is believed to be due to the plastic nature of salt and its low elastic strength. The equation is based on studies of elastic materials such as sandstones which have a much greater elastic strength and do not exhibit plastic flow at these pressures like salt does.

The isolated points on the plot represent tests made on random samples, therefore they do not show a close relationship to each other. The test fluids used were helium gas and kerosene. The nonreactive liquid permeability values for the kerosene tests were assumed to be equal to the kerosene permeability values.

The relationship between permeability, mean confining stress, and liquid pressure can be put in the form of an equation for net confining stresses below 1,000 psi. Applying the method of least-squares to the data from Curves 1 through 6 gives the relationship

$$k_L = 7.1 \times 10^{-10} (\sigma_m - p_f)^{-0.212} \quad (4-2)$$

where

k_L = nonreactive liquid permeability in cm^2

σ_m = mean confining stress or mean stress in psi

p_f = fluid pressure in psi

The relationship for net confining pressures above 1,000 psi was made by averaging the data from the curves for values above 1,000 psi. The curve representing this average is shown on the plot, Figure 4-4.

Initial Permeability of Kerosene and Brine Solutions: Figure 4-5 shows the initial permeabilities that were obtained in the beginning of each test

FIG. 4-5. INITIAL PERMEABILITY TO KEROSENE AND BRINE SOLUTIONS - GRAND SALINE SALT.

for ten samples using kerosene and brine solutions. The brine solutions used were: (1) pure brine (NaCl); (2) calcium sulfate and brine ($\text{CaSO}_4 + \text{NaCl}$); and (3) a synthetic waste of aluminum nitrate and brine ($\text{Al}(\text{NO}_3)_3 + \text{NaCl}$). The number of tests using each type of solution were;

Kerosene followed by brine--2

Kerosene --3

Pure brine --3

Calcium sulfate and brine --1

Synthetic waste --1

All of the tests with the exception of the calcium sulfate and brine, 3G, the synthetic waste, 4G, and Test 5G were consolidated for 7 to 14 days prior to the permeability determinations.

The two tests, 11G and 13G, which used kerosene followed by brine, were tested with helium gas prior to the liquid tests. It can be seen from Figure 4-5 that the nonreactive liquid permeabilities for these tests were approximately equal to their respective kerosene permeabilities and were several times greater than their brine permeabilities.

The calcium sulfate and brine test, 3G, and the synthetic waste test, 4G, were both run at a net confining pressure of 950 psi. The permeabilities obtained fell within the range of the brine permeabilities at the same net confining pressure.

Because kerosene was shown to be nonreactive, the kerosene permeabilities were incorporated in the previous section on nonreactive liquid permeability. The brine values, however, were so varied that no representative

equation could be developed. However, an approximation of the brine permeability at a given net confining pressure can be made by assuming it to be 32 per cent of the nonreactive liquid permeability as taken from the average curve in Figure 4-4.

Minimum Permeability of Kerosene and Brine Solutions: It was noticed in nearly all of the liquid tests that the permeability decreased with the duration of the test and finally reached a minimum value. Figure 4-6 and Table 4-3 show the minimum values obtained in the kerosene and brine testing.

All of the specimens with the exception of the first three in Table 4-3 had been under a confining load for 7 to 14 days prior to the permeability tests. Some minute consolidation was still occurring after the permeability tests were begun, and it was originally thought that this small consolidation was causing the reduction in permeability.

Subsequent tests, however, revealed that an appreciable amount of the reduction in permeability was due to a plugging or clogging effect in the upstream end of the specimens. In these tests the flow was reversed upon reaching the minimum permeability, and it was observed that an appreciable increase in permeability took place. Figure 4-7 shows the results of a typical test. In this test, 11G, the permeability using kerosene had decreased in ten days from an initial permeability of $1.9 \times 10^{-12} \text{ cm}^2$ to $5.4 \times 10^{-13} \text{ cm}^2$. Upon reversing the flow, however, the permeability almost reverted to its initial value as can be seen from Figure 4-7.

FIG. 4-6. MINIMUM PERMEABILITY TO KEROSENE AND BRINE SOLUTIONS - GRAND SALINE SALT.

FIG. 4-7. PLUGGING EFFECT AND REDUCTION IN PERMEABILITY, GRAND SALINE SALT

Table 4-3

Initial and Minimum Permeabilities of Grand Saline Salt

Test	Mean Stress σ_m , psi	Permeability	Initial Permea- bility (cm^2)	Min. Permea- bility (cm^2)	Min. k x 100% Initial k	Days Duration to Min.
3G	1,000	k_C	4.4×10^{-12}	1.5×10^{-12}	34.3	8
4G	1,000	k_S	1.4×10^{-12}	0	0	14
5G	1,000	k_B	4.5×10^{-12}	1.4×10^{-12}	31.0	3
6G	3,000	k_B	6.0×10^{-13}	2.0×10^{-15}	3.2	36
7G	2,300	k_K	5.0×10^{-12}	5.0×10^{-15}	0.001	22
8G	1,000	k_B	1.0×10^{-12}	2.8×10^{-13}	28.0	4
9G	500	k_K	1.0×10^{-11}	1.7×10^{-12}	17.0	9
10G	500	k_K	4.2×10^{-11}	3.2×10^{-11}	76.3	3
11G	1,500	k_K	2.1×10^{-12}	5.4×10^{-13}	2.1	10
11G	1,500	k_B	5.0×10^{-13}	0^+	0^+	9^+
13G	500	k_K	6.2×10^{-11}	1.7×10^{-11}	27.4	6
13G	500	k_B	4.0×10^{-11}	1.1×10^{-12}	2.7	4

⁺Supersaturated brine solution used.

The clogging effect was unsuspected because a membrane filter was used in the influent line on most of the tests. Apparently it was due to very fine suspended material that passed through the filter.

The test using the synthetic waste, 4G, had a minimum permeability of zero on the fourteenth day of flow. This was the largest reduction observed except for a supersaturated brine solution or a fine granular suspension in a saturated brine solution. Both of these tests are described in a subsequent section of this chapter. The test using the synthetic waste, 4G, was made prior to the discovery of the clogging effect, therefore no reversal of the flow was made.

Permeability Reduction by a Supersaturated Brine Solution: The effect of a supersaturated brine solution was tested in Test 11G, and Figure 4-7 shows the results of the test. The supersaturated solution was prepared by saturating distilled water at 160° F. with sodium chloride and then allowing the solution to cool to the test temperature of 79° F.

The supersaturated solution was substituted for the saturated solution on the eighteenth day of the test. The permeability rapidly decreased and reached a value of $2.0 \times 10^{-14} \text{ cm}^2$ on the sixth day after the substitution as can be seen in Figure 4-7. The flow was reversed on the sixth day and the permeability increased to $6.0 \times 10^{-14} \text{ cm}^2$. This increase was due to the unclogging of the plugged material in the upstream end of the specimen. It may be noted that the permeability did not return to its original value of $5.0 \times 10^{-13} \text{ cm}^2$ which existed on the day when the supersaturated solution was first substituted. After the brief rise on the sixth day, the

permeability began decreasing again and reached zero permeability on the ninth day after the substitution.

The reduction in permeability was mainly due to the recrystallization and precipitation of salt from the solution which caused a plugging of the pore passages. Supersaturated solutions are unstable, and, apparently, the velocities that occurred as the solution passed through the specimen caused the recrystallization to occur. The blocking of the passages was complete throughout the specimen's length and was not confined to the upstream end since a reversal of the flow would not reestablish a permeability value near the original permeability.

Permeability Reduction by a Fine Granular Suspension: After completion of Test 16G which used helium gas, the sample was tested at 500 psi net confining pressure using a fine granular suspension in a saturated brine solution. The suspension was prepared by mixing pulverized diatomaceous earth in a saturated solution. It was not a true colloidal solution since settling of the suspended particles did occur in four or five days under quiescent conditions.

The results from the test are shown in Table 4-4. The nonreactive liquid permeability from a helium gas test prior to the liquid test was $2.4 \times 10^{-12} \text{ cm}^2$. The permeability of the suspension after seventeen minutes of flow was $4.7 \times 10^{-13} \text{ cm}^2$ which is about 20 per cent of the nonreactive liquid permeability. After sixty minutes of flow, however, the flow ceased, and the permeability became zero.

Table 4-4

Reduction of Permeability by Fine Granulated Suspension

Time of Flow (min)	Permeability (cm^2)
17	4.7×10^{-13}
43	1.3×10^{-13}
60	0

Permeability Reduction by Strain Hardening: Three tests were run to determine the effect of strain hardening on permeability. Strain hardening results from the alternate increase and decrease of the mean confining stress.

The results of the first of these tests, Test 2G, are shown in Figure 4-8. The test was loaded for seven days prior to the permeability testing, and a calcium sulfate and brine solution was used as the test fluid. The permeability was determined at each loading pressure, and the order of loading was 850, 1,700, 2,800, 1,700, and 850 psi. The loading at any pressure was maintained only long enough to make the permeability test. The permeability at 850 psi before and after the increase in loading was $3.1 \times 10^{-12} \text{ cm}^2$ and $2.0 \times 10^{-12} \text{ cm}^2$ as can be seen from Figure 4-8. The reduction in permeability was 35 per cent.

The second test employed six cycles of increasing and decreasing stresses up to a maximum of 2,000 psi, and mineral oil was used as the test fluid. The permeability at 2,000 psi after the six cycles was $5.0 \times 10^{-15} \text{ cm}^2$, which is only 0.067 per cent of the permeability of another specimen, 1G, using the same confining pressure and the same test fluid.

FIG. 4-8. EFFECTS OF STRAIN HARDENING - GRAND SALINE SALT.

FIG. 4-9. VISCOSITY OF MINERAL OIL, SYNTHETIC WASTE, AND BRINE.

The third test, 14G, was loaded for seven days prior to the permeability test at the confining pressure of 900 psi and helium gas was used as the test fluid. The permeability at 900 psi before and after an increase in the confining load to 8,500 psi was $3.3 \times 10^{-10} \text{ cm}^2$ and $2.8 \times 10^{-11} \text{ cm}^2$. The reduction in permeability was 92.5 per cent.

The decrease in permeability due to strain hardening is believed to result from several phenomena. The plastic nature of salt is bound to be one of the causes. This would allow the salt to flow plastically under high stresses and close the pore passages. Also the low elastic strength is another possible cause. This would allow a breaking down of the ridges in the pore passage walls and allow the walls to come closer together closing the pore passages and filling them with granulated material.

Hutchinson Salt

The results of the permeability tests on Hutchinson salt showed it to have a much lower permeability than the Grand Saline salt. The data varied over an appreciable range, and, consequently, no relationship was developed between the permeability, confining pressure, and liquid pressure.

Helium gas tests that were made in Test 4H for the determination of the Klinkenberg constant showed the specimen to have no permeating flow. The specimen therefore had a zero permeability, and the determination of the Klinkenberg constant was not possible.

Seven tests were run on Hutchinson salt at various confining pressures using helium gas, pure brine solutions, and kerosene as test fluids. The

permeabilities obtained, Table 4-5, were less consistent than those from the Grand Saline salt. Of the seven tests, four showed no permeability, two showed a permeating flow on some of the test days, and only one gave a permeating flow on all days during the test period.

Table 4-5

Permeabilities of Hutchinson Salt

Test	Mean Stress σ_m (psi)	Permeability	Max. Permeability (cm ²)	Min. Permeability (cm ²)	Test Period (days)	Days of Flow	Days of no Flow
1H	2,300	k_K	2.3×10^{-13}	5.0×10^{-15}	23	23	0
2H	1,000	k_B	0	0	7	0	7
3H	1,000	k_B	7.2×10^{-14}	0	9	3	6
3H	2,000	k_B	1.5×10^{-14}	0	11	6	5
4H	1,500	k_G	0	0	2	0	2
5H	500	k_G	0	0	2	0	2
5H	500	k_K	0	0	2	0	2

Only one of the tests, Test 1H, had a permeability that was approximately equal to the Grand Saline salt under the same conditions of confining pressure. All of the remaining tests had permeabilities smaller than the Grand Saline salt.

The lower permeability of the bedded salt is related to its lower porosity. The porosity, which is discussed more fully in the following section of this chapter, was only about one-third of that of the Grand Saline salt.

Porosity and Density

Porosity tests were run on eleven Grand Saline and six Hutchinson salt samples. Also, density tests were run on all but three of the samples. The results of the tests are shown in Tables 4-6 and 4-7.

The average porosity and density of the Grand Saline salt was 1.71 per cent and 2.139 gm/cm^3 whereas that of the Hutchinson salt was 0.59 per cent and 2.153 gm/cm^3 . It may be noted that the bedded salt porosity was only about one-third that of the dome salt. This lower porosity is one of the main reasons for the lower permeability. The slightly greater density of the bedded salt is probably due to its greater impurity content.

Since the average permeability and porosity at zero overburden pressure are known, these can be substituted in Equation 2-10 and the constant K can be evaluated. Substitution of the permeability value of $7.1 \times 10^{-10} \text{ cm}^2$ and the porosity of 0.0171 gives the constant as 1.37×10^{-4} . Thus the porosity-permeability relationship will be

$$k_L = 1.37 \times 10^{-4} \frac{\phi^3}{(1 - \phi)^2} \quad (4-3)$$

where

k_L = nonreactive liquid permeability in cm^2

ϕ = effective porosity as a fraction

The porosity-permeability relationship of Equation 4-3 is for the Grand Saline salt.

Table 4-6

Porosity and Density of Grand Saline Salt

Sample	Bulk Volume Vt (cm ³)	Pore Volume Vp (cm ³)	Weight, Ws (gms)	Porosity, ϕ (%)	Density (gm/cm ³)
1	40.32	0.645	85.847	1.74	2.14
2	30.62	0.470	65.285	1.54	2.14
3	30.05	0.432	64.249	1.47	2.14
4	34.05	0.635	72.168	1.88	2.12
5	35.92	0.478	65.965	1.31	1.94
6	21.68	0.350	46.370	1.61 ⁺	2.14
7	34.58	0.258	74.293	0.76 ⁺	2.15
8	35.70	0.635	76.292	1.75	2.14
9	28.91	0.670	-	2.25	-
10	30.68	0.430	-	1.41	-
11	32.96	0.720	-	2.17	-

Average

1.71

2.139

Table 4-7

Porosity and Density of Hutchinson Salt

Sample	Bulk Volume Vt (cm ³)	Pore Volume Vp (cm ³)	Weight, Ws (gms)	Porosity, ϕ (%)	Density (gm/cm ³)
1	32.76	0.202	70.566	0.61	2.15
2	33.60	0.230	72.519	0.68	2.15
3	29.35	0.165	63.656	0.56	2.16
4	28.78	0.193	61.870	0.67	2.15
5	30.90	0.129	66.721	0.42	2.16
6	31.05	0.193	66.937	0.62	2.15

Average

0.59

2.153

Viscosity

The results of the viscosity tests at various temperatures for three of the solutions used, the pure brine, the mineral oil, and the synthetic waste, are shown in Figure 4-9. The ordinate of the plot represents the viscosity in centipoises and the abscissa is $1,000/\text{Temperature}$ in Rankine degrees.

The pure brine and the synthetic waste were saturated at the test temperature of 79° F., however, for temperatures above this, they will be undersaturated.

APPLICATION OF RESULTS

This chapter presents an application of the test results. Because of the many variables involved such as the geometry of the salt formation, the various conditions of piezometric head, and the location of a cavity in a formation, it is not possible to derive general formulas that will solve all cases. Therefore, in order to present an application of the data, a hypothetical problem for a specific case has been selected and solved.

Although some degree of permeability was measured in the test samples, it is recognized that these specimens were reconsolidated and were not truly representative of a plastic medium which has been subjected to consolidation over a geological time period. From various mining operations and the experience in the storage of liquefied petroleum products in salt cavities, it is obvious that there is no flow of liquids through a massive salt structure. Consequently, any computations using the laboratory results will be on the ultra-safe side.

The test results obtained in this study can be used for the preliminary location of a cavity. Before a final location can be selected, however, an extensive permeability test study should be made on the salt formation under consideration.

Hypothetical Problem

A cavity is located in a salt bed, Figure 5-1, that has the same permeability characteristics as the Hutchinson salt which was tested in the project. The given conditions are:

FIG. 5-1. HYPOTHETICAL CAVITY
IN A SALT BED.

Overburden pressure, P_o --600 psi

Internal pressure in the cavity, P_i --200 psi

Cavity radius, r_1 --30 feet

Depth to center of the cavity, h_o --600 feet

Initial salt temperature, T_1 --70° F.

Temperature in the cavity, T_2 --300° F.

Temperature rise, T_c --230° F.

Specific weight of waste, γ --64 lb. / ft³

Piezometric head in the cavity, h_1 --450 feet

It is desired to determine the time required for the frontal zone of the waste to pass from the cavity to the top of the formation if ten feet of ground water lie above the bed, Figure 5-1, and to see if the travel time is sufficient for the waste to decay to an acceptable level.

The assumptions required for the solution are:

- (1) A confining time of 500 years is required for the waste to decay to an acceptable level.
- (2) The viscosity of the waste at elevated temperatures is the same as the viscosity of the synthetic waste solution shown by Figure 4-9. Although the curve gives the viscosity at elevated temperatures, the solution was undersaturated since it was originally saturated at 79° F.
- (3) The effect of the elevated temperature on the permeability will only be due to the increase in stresses around the cavity if the waste is saturated. This assumption allows the permeability

values obtained at the test temperature of 79° F. to be used in the problem.

- (4) The waste solution will be saturated at any distance from the cavity. Actually, if the solution is saturated at the elevated temperature in the cavity, it will become supersaturated as it moves outward and its temperature is reduced. This will cause recrystallization of the salt in solution which, in turn, will reduce the permeability of the salt. No reduction, however, was made in the solution of the problem.
- (5) The permeability is assumed to be isotropic at any point.
- (6) Since no correlation between permeability and confining pressure was found for the bedded salt, it is assumed that the permeability is uniform throughout the bed and is equal to the maximum value found in the bedded-salt tests.

Solution

When the wastes are placed in the cavity, a frontal zone of the waste will start penetrating outward. The frontal zone will first make contact with the ground water at a point vertically above the cavity. The time required for the frontal zone to travel this distance represents the minimum confining time for the wastes, i. e., the length of time the wastes will actually be confined in the formation.

This problem represents a case of steady flow if it is assumed that no liquid goes into storage in the formation. Actually, some liquid would go

into storage because the salt is compressible. However, ignoring this effect will be on the safe side because the travel time will be shorter than that which would result if the storage were taken into consideration.

The streamlines away from the cavity can be determined by the relaxation technique^{17,23}. Using this method gives a vertical stream tube from the cavity as shown in Figure 5-2. The discharge through the tube will be constant and will be equal to the area A_s at any section times the average velocity, V_s , at the section. The velocity is given by Eq. 2-1 which is a form of Darcy's Law.

$$Q = V_s A_s = - \frac{k\gamma}{\mu_s} A_s \frac{\Delta h}{\Delta s} \quad (5-1)$$

The area, A_s , will be tangent at all points to the equipotential lines for the flow and perpendicular at all points to the streamlines.

Rearranging Eq. 5-1 in terms Δh and summarizing the expression gives

$$\Sigma \Delta h :: h_2 - h_1 = - \frac{Q}{k\gamma} \Sigma \left(\frac{\mu_s \Delta s}{A_s} \right) \quad (5-2)$$

Rearranging Eq. 5-2 gives the expression for the discharge, Q .

$$Q = \frac{k\gamma (h_1 - h_2)}{\Sigma \left(\frac{\mu_s \Delta s}{A_s} \right)} \quad (5-3)$$

The increment of time, Δt , required for the flow to travel through an increment of distance, Δs , is given by the expression

FIG. 5-2. STREAMLINES FROM WASTE CAVITY.

FIG. 5-3. STREAMLINES FROM WASTE CAVITY.

$$\Delta t = \frac{\Delta s}{V_{s_a}} \quad (5-4)$$

where V_{s_a} is the actual velocity through the pore passages. The actual velocity through the pores will be much larger than the velocity as given by Darcy's Law because the velocity in Darcy expression represents the average velocity through the gross cross sectional area. The actual velocity will be approximately equal to the average velocity, V_s , divided by the effective porosity, .

$$V_{s_a} = \frac{V_s}{\phi} = \frac{Q}{\phi A_s} \quad (5-5)$$

Combining Eqs. 5-4 and 5-5 gives the expression for the increment of time, Δt , as

$$\Delta t = \frac{\phi A_s}{Q} \Delta s \quad (5-6)$$

The time required for the frontal zone of the waste to pass from the cavity to the top of the formation will be the summation of the individual increments, Δt , over the given distance.

$$t = E \Delta t = \frac{\phi}{Q} \sum (A_s \Delta s) \quad (5-7)$$

Substituting the expression for Q , Eq. 5-3, gives the time expression as

$$t = \frac{\phi}{k\gamma(h_1 - h_2)} \sum \frac{\mu_s \Delta s}{A_s} \sum (A_s \Delta s) \quad (5-8)$$

In order to carry out the step integration, the values of the viscosities, μ_s , of the liquid at various distances from the cavity must be known. The viscosities will depend upon the temperature of the liquid. The distribution of the temperature around a spherical cavity under a steady state of heat flow can be approximated from the Fourier conduction equation^{14,24}.

$$T_r = \frac{a}{r} T_c \quad (5-9)$$

where

T_r = temperature use at a distance r

T_c = temperature rise in the cavity above the initial temperature in the salt

a = radius of the cavity

r = distance from the cavity

The temperature at the distances, r , can be computed by determining the temperature rise from Eq. 5-9 and adding it to the initial temperature of the salt. The viscosities, μ_r , can then be taken from the viscosity-temperature curve, Figure 4-9, once the temperatures are known.

Since the Hutchinson salt test results did not allow a correlation between the confining pressure and permeability, the nonreactive liquid permeability has been taken on the maximum kerosene permeability obtained in the

testing. The permeability to the wastes is assumed to be 32 per cent of the nonreactive liquid permeability. The porosity is assumed to be constant throughout the formation, and an estimate of the porosity under the confining pressure involved has been made by reducing the Hutchinson salt atmospheric porosity by the same percentage reduction that would occur for the Grand Saline salt.

Substituting the summations and the variables into Eq. 5-8 gives a travel time of 6,500 years. This time is considerably more than the allowable time of 500 years.

These computations give results which are extremely conservative because:

1. Undisturbed underground salt has a much lower permeability than found in the laboratory tests. In some cases, it may be for all practical purposes impermeable.
2. If the underground salt does have any permeability, the waste will become supersaturated as it passes outward from the cavity causing recrystallization and precipitation of the salt. This, in turn, will block the pore passage and reduce the permeability to zero.
3. The permeability values used in the problem were the maximum obtained in the tests. Many of the tests showed the salt to be impermeable.

The method of loading in the tests may have reduced the permeability more than would result from a true triaxial stress because, at the beginning of loading on a specimen, no stress existed on the specimen's ends where the filters were located. As compression occurred from the vertical stress, the

salt had to expand in the direction of the filters before a confining pressure existed in this direction. This, perhaps, may have caused the pore volume to be reduced more than would otherwise occur if triaxial stress existed at the beginning of the loading. Possibly, future tests using a different method of loading could determine if this is a real factor or not.

DISCUSSIONS

The utilization of salt formations for the storage of radioactive wastes appears to be a feasible and practical method of disposal. The application of the data from the permeability and porosity tests has revealed that the travel time involved in the hypothetical problem was greater than the required range. Also, the tests have indicated that a cavity may be effectively sealed by several methods to create a region of zero permeability immediately surrounding the cavity.

There is evidence that undisturbed rock salt in its natural state in underground formations may not have any permeability. A previous survey³ on the use of cavities for the storage of liquefied petroleum gas products has shown that the majority of existing cavities had no pressure drop when pressure tested. Also, this study disclosed that salt mines in Germany have been excavated to within thirty feet of high pressure hydrocarbon gas formations yet no gases were ever detected in the mines. It is indicated from these data that undisturbed rock salt in underground formations is impermeable.

The pressure tests on the cavities for the liquefied petroleum gas products consisted of filling the cavities with brine and sealing them for 24 to 72 hours under pressures as high as 1,400 psi. The pressures used were usually 0.75 psi per foot of depth down to the cavities. Any leakage should have resulted in a loss in pressure since water is relatively incompressible. Preliminary calculations using the permeability and porosity data obtained in the test program indicate that some noticeable pressure drop should have

occurred if the permeability of the salt in the ground is of the same magnitude as the results from the laboratory testing.

Other permeability investigators using different test methods have found permeability values that are similar to those obtained in this study which indicates a satisfactory test procedure was used. It is believed, therefore, that the salt which was obtained from the mines was interlaced with more cracks than would be found in natural undisturbed underground salt.

These cracks might be due to: (1) the relaxation or redistribution of stresses which occurs when the mine openings were created or when the individual blocks were removed from the mines, and (2) the blasting operations which are used in the mining operations.

Several of the oil companies in the previously mentioned survey³ performed permeability tests on salt samples from underground formations that gave no pressure drop when pressure tested. The oil companies' tests showed the salt to have some permeability which indicates that the salt developed cracks due to the stress relaxation.

Future permeability studies will give more representative results if the samples are obtained from locations that are a considerable distance away from any mines. Core drilling could possibly be used to obtain these samples.

Permeability testing of salt in place in a relatively undisturbed state could possibly be made in the mines themselves. This could be done by drilling into the mine floor and creating a model cavity some distance below the mine and using pressure tests to determine the permeability.

If salt does have some permeability in its undisturbed underground state, a cavity could possibly be sealed by: (1) filling the cavity with a hot supersaturated brine solution under high pressure which would force the fluid into the surrounding salt. This would cause recrystallization and cause a plugging of the pore passages. (2) filling the cavity with a brine solution containing a fine granular suspension and placing the cavity under high pressure. This would cause a plugging of the pores due to the suspension. (3) filling the cavity with a brine solution and alternately increasing and decreasing the pressure to cause strain hardening which would reduce the permeability. It is believed that the second method offers the greatest promise and warrants further investigation.

Also, if salt in underground formations does have permeability and the wastes in the cavity are kept saturated at the elevated temperature in the cavity, a reduction of the surrounding salt's permeability will occur as the waste penetrates outward. The penetration will result in lowering the solution's temperature which will cause it to become supersaturated and recrystallize. This will cause a plugging of the pore passages.

An inspection of the permeability values of salt from other mines shows that the permeability varies greatly between different mines. Therefore, permeability studies over a large distribution of mines would give useful data. Certainly, a comprehensive permeability study should be completed on a particular formation before actual waste cavities are constructed.

The use of helium gas as a test fluid in permeability studies provides a basis for evaluating the results from tests using various liquids.

Correlating liquid permeability values to the nonreactive liquid permeability values and then performing gas tests on future samples to obtain the nonreactive liquid permeability will probably give the quickest method to study the permeability of salt.

Since the dome salt from the Grand Saline mine had a higher porosity than the bedded salt from the Hutchinson mine, it was suspected that it would also have a higher permeability. The permeability tests showed this to be true. The lower permeability of the bedded salt does not necessarily imply that it would be a better formation for the storage of wastes. Both of the salts tested had cracks which probably resulted from the mining operations and the stress relaxation.

The breakdown of Equation 4-2 for the Grand Saline salt at net confining pressures greater than 1,000 psi is apparently due to the plastic nature of salt and its low elastic strength. This type of equation which relates permeability to confining and liquid pressure was developed from studies on sandstones. These stones have high elastic strengths and are not plastic in nature. The permeability of salt was greatly reduced at high confining stresses and is apparently due to the salt's plastic nature and low elastic strength.

The simplest method to assure that no seepage will occur from a cavity is to maintain the piezometric head level in the cavity below or at the same level as the piezometric head level outside the formation. This, however, may not always be possible. In the case where no liquid exists outside the formation, no flow will occur in the vertical direction if the

piezometric head in the cavity is maintained below the top of the formation and proper allowances are made for capillary action.

PART TWO: CREEP MEASUREMENTS IN SALT MINES

BASIC CONSIDERATIONS; PROCEDURE AND MEASURING STATION DESCRIPTIONS

A storage cavity in salt formations may undergo a decrease in volume after it is created due to the plastic nature of salt. This closure, if great enough, will be of importance in the design of the cavity. A previous study⁴ considered the structural analysis of cavities including the volume-reduction aspect. In that investigation, creep measurements were initiated in the Morton Company's mine at Grand Saline, Texas, to verify the theory of plastic flow of salt and to give actual measurements showing what rate of closure might be expected. These measurements have been continued since the completion of the study, and, in addition, new measurements were begun in the Carey Salt Company's mine at Hutchinson, Kansas. The rate of closure is more commonly called the creep rate or plastic flow rate, and either of these terms will be used in subsequent sections of this report.

The purpose of this section of the report (Part Two) is to present the measurement data and to develop, where possible, an empirical equation to express the closure rate or creep rate as a function of time. This chapter presents the background theory underlying the creep process and a description of the measuring procedure and stations.

Basic Considerations

The initial study showed that salt undergoes permanent deformation without fracture at a stress less than its yield point. This deformation is termed the creep or plastic flow.

When a cavity or tunnel is created, large stress concentrations are developed adjacent to the opening. For instance, the stress concentration in the 700-foot-deep Grand Saline mine would be over 4,000 psi. If the salt were an elastic material possessing no plastic properties this stress would be sufficient to cause failure.

The high stress concentration is relieved by the development of a plastic zone in the immediate area. In this area, the salt undergoes plastic flow or creep which causes a gradual reduction in stress until an equilibrium condition is reached.

Laboratory studies and, also, the creep measurements from the Grand Saline mine confirmed that salt acts in this manner and flows plastically under these conditions.

Several other investigations and observations have shown the plastic nature of salt. Muehlberger, et al.,² cite many of these in their report on the geology of salt domes.

Creep measurements were made in the Neu-Strassfurt Mine in Germany as early as 1907¹. Attention to the salt's movement in the mine was aroused by the inward bending of the walls of a newly excavated shaft. Measurements in 300-foot-wide rooms at a depth of 2,640 feet showed the plastic flow rate to be as high as 0.13 and 0.9 millimeters per day. Holes 40 millimeters in diameter and 50 centimeters deep were drilled in the walls and filled with lead bars that fitted closely upon insertion. The time was recorded when they jammed: At 1,650 feet, the bars jammed after a few months; at 984 feet they jammed after two years; and above 820 feet the holes stayed open. This clearly illustrates that the creep rate becomes greater at greater depths.

Creep measurements in the Grand Saline mine in 1952 also have shown creep to exist. The vertical creep rate in a newly created room 66 feet in width and 23 feet in height at a depth of 700 feet was 0.025 millimeters per day.

Some of the concepts derived from previous investigations regarding creep rate are:

1. The rate of creep for an opening decreases with age.
2. The rate of creep increases with the depth of the opening from the earth's surface.
3. The plasticity of salt increases with increasing temperature, and, therefore, creep rates would be greater for higher temperatures.
4. Immersion of samples in a reactor-fuel waste substitute or a saturated brine solution did not materially affect the creep rates.
5. Fine-grained materials are more creep resistant than coarse-grained at lower temperatures; however, the elevation of temperature reverses the case.
6. Certain concentrations of impurities can increase the cohesive force in salt, and thus impure halite may be stronger than pure halite.

Previous investigators⁴ found that the actual creep rate in a mine can best be expressed by an empirical formula. It was found in Chapter VIII, "Measurement Results and Discussion," that an equation of the following form was most applicable.

$$\frac{d\mathcal{C}}{d\,t} = A e^{-k\,t} \quad (7-1)$$

where

$$\frac{d \epsilon}{d t} = \text{creep rate}$$

$d \epsilon$ = change in unit deformation

$d t$ = change in time

A = constant

k = exponential constant

t = time

A direct comparison can be made between the data from the two mines where the measurements were made since the mines are at approximately the same depths.

Measurement Procedure

The method of measuring the creep for the Grand Saline, Texas, and Hutchinson, Kansas, mines was basically the same. For each measurement, the distance between two pins set in the salt was measured by the use of dial gages. For a vertical creep measurement between the floor and the ceiling the floor pin was set directly below the ceiling pin whereas, for horizontal creep between two walls, the pins were set directly opposing each other.

Description of Measuring Stations in the Grand Saline, Texas, Mine

Two measuring stations, designated G-A and G-B, were set in the mine in April, 1957. Each station consisted of one pair of pins to measure the vertical creep. A profile through the salt dome is shown in Figure 7-1 and a plan of the mine in Figure 7-2. Figure 7-2 shows the location of the two stations.

FIG. 7-1. PROFILE OF GRAND SALINE SALT DOME.

FIG. 7-2 PLAN OF THE GRAND SALINE SALT MINE

FIG. 7-3. SCHEMATIC DIAGRAM OF STATIONS AND MEASURING DEVICES IN THE GRAND SALINE MINE.

The measuring equipment, Figure 7-3, consisted of a measuring rod with a dial gage attached to one end and a standard-length reference rod 22.0 feet long. The distance between two pins was determined by comparing the dial gage reading between the pins to the reading for the standard-length rod.

Station A, Figure 7-3, was located in a room which was 10 years old at the beginning of the measurements in 1957. The room is 66 feet wide and 23 feet high. The pins were set at a position of one-sixth of the room's span from the room's center to allow the passage of mining equipment.

Station B, Figure 7-3, was located in an opening that was 5 years old at the beginning of the measurements. The room is 35 feet wide and 23 feet high, and the pins were set approximately in the center of the room.

Description of Measuring Stations in the Hutchinson, Kansas, Mine

Two measuring stations, designated H-A and H-B, were set in August, 1959. A plan of the mine, Figure 7-4, shows the locations of the stations. A reference rod was not used in making the measurements as was done at Grand Saline. Instead, a long rod was attached to one pin of each pair as shown in Figure 7-5 for a vertical creep measuring setup. This made a gap of about 9 inches that allowed the creep to be measured by a dial gage. A pair of pins with the extension rod will be referred to as a "rod" in subsequent discussions.

Station H-A, which was located in the Oak Ridge National Laboratories furnace test room, is in an opening that is approximately 30 years old. The station, shown schematically in Figure 7-6, consisted of three rods to measure the vertical creep and one rod to measure the horizontal creep.

FIG. 7-4. PLAN OF THE HUTCHINSON SALT MINE.

FIG. 7-5. VERTICAL CREEP MEASURING APPARATUS IN THE HUTCHIN MINE.

FIG. 7-6. SCHEMATIC SECTION OF STATION H-A IN HUTCHINSON, KANSAS MINE.

FIG. 7-7. SCHEMATIC SECTION OF STATION H-B
IN HUTCHINSON, KANSAS MINE.

FIG. 7-8. INTERNAL CREEP MEASURING DEVICE, HUTCHINSON MINE.

Station H-B was located in an opening that was only 9 months old when the rods were installed. The station, shown schematically in Figure 7-7, consisted of four vertical rods, one horizontal rod, and four internal creep-measuring devices. The internal creep, for the purposes of this report, is the creep between the surface of the salt and points at various depths in the salt. These devices, one of which is shown in detail in Figure 7-8, measured the creep at depths of 4, 7, and 10 feet. The devices were designated BC, BF, BS, and BW according to their location.

MEASUREMENT RESULTS AND DISCUSSIONS

This chapter presents the results and interpretation of the creep measurements. The Grand Saline mine data were reduced into a formula giving the creep rate for a given-age tunnel. The Hutchinson mine data, however, had not been collected over a sufficiently long time to permit the development of a formula. It was possible, though, to compare the present Hutchinson creep rate to that in the Grand Saline mine as well as to collect useful data concerning the thermal expansion of salt.

Grand Saline Mine Results

The Grand Saline creep rates followed the general relationship given by Equation 7-1. The unit deformation, ϵ , in the equation represents the change in length between two points divided by the distance between them, therefore it will have a unit of length per length or L/L.

Equation 7-1 will give a straight line on a semi-log plot if the log of the creep rate is plotted versus time. A plot using the rates from the data for Station G-A and G-B is shown in Figure 8-1. Station G-A is over 10 years old therefore the creep rate was very small. Station G-B was only six years old, and, consequently, it had a much larger creep rate. The constant, A, in Equation 8-1 is the intersection of the line with the y-axis and the rate constant, k, is the line's slope divided by 0.434. The resulting equation for the line is

$$\frac{d\epsilon}{dt} = \text{Creep Rate} = 0.03 e^{-0.635t} \quad (8-1)$$

FIG. 8-1. CREEP RATES IN THE GRAND SALINE MINE.

Since the data in Figure 8-1 are localized in two groups, future measurements will verify the accuracy of Equation 8-1. It is believed, however, that the equation gives a good approximation of the creep rate since the rate for Station G-A at 5 years of age closely corresponds to that of Station G-B at the same age.

An estimation of the total amount of deformation which will occur can be made by integrating Equation 8-1 between the limits of $t = 0$ and $t = \infty$, giving

$$\mathcal{E} = \int_{t=0}^{t=\infty} d\mathcal{E} = 0.03 \int_{t=0}^{\infty} e^{-0.635 t} dt = 4.7\%$$

This corresponds to a reduction of 13 inches in the height of a room that is 23 feet high.

The time required for the deformation to become 95 per cent complete can be determined by solving for t_2 as follows:

$$\mathcal{E} = 95\% \times 4.7\% = 0.03 \int_0^{t_2} e^{-0.635 t} dt$$

The time required to obtain 95 per cent deformation is 4.7 years.

Hutchinson Mine Results

Station H-A: This station which was located in the Oak Ridge National Laboratories' furnace test room is in an opening about 30 years old. The test furnace located at the station was placed into operation on the 138th day of creep measurement, and it gave an insight as to what magnitude of thermal

expansions may occur. The plots of the unit deformation versus time for Station H-A are shown on Figures 8-2 through 8-5.

The creep rates for all rods were relatively uniform prior to the furnace operation. The rods, Figure 7-6, had creep rates as shown in Table 8-1.

Table 8-1
Creep Rates at Station H-A in the Hutchinson Mine

Rod	Position	Rate
AV-1	Vertical	9.9×10^{-4} in/in/yr
AV-2	Vertical	9.5×10^{-4} in/in/yr
AV-3	Vertical	6.1×10^{-4} in/in/yr
AH-1	Horizontal	1.05×10^{-4} in/in/yr

The average of the two vertical rates near the room's center, rods AV-1 and AV-2, is 9.7×10^{-4} in/in/yr which is about 50 per cent greater than that nearer the walls. The vertical rate is about 9 times as great as the horizontal rate.

A comparison of the creep rate in Station H-A to that in the Grand Saline mine was made by the use of Equation 8-1 which revealed that the creep rate at Station H-A was much greater than that of a tunnel of the same age in the Grand Saline mine. This is not a true comparison, however, because the conditions were not the same. It is believed that the creep of Station H-A is much larger than would normally be expected. The higher creep rate is believed to be due to the construction of Test Pit No. 2 and the operation of the furnace

FIG. 8-2. CREEP RATES AT STATION H-A,
HUTCHINSON MINE, ROD AV-I.

FIG. 8-3. CREEP RATES AT STATION H-A,
HUTCHINSON MINE, ROD AV-2.

FIG. 8-4. CREEP RATES AT STATION H-A,
HUTCHINSON MINE, ROD AV-3.

FIG. 8-5. CREEP RATES AT STATION H-A,
HUTCHINSON MINE, ROD AH-I.

at Test Pit No. 1. The construction of the test pit may have caused a redistribution of existing stresses and thus may have caused movement of the salt. Also, the operation of the furnace at the other pit, even though it was 40 feet away, may have caused thermal expansion of the salt at the measuring rods.

An appreciable increase in the creep rate occurred when the test furnace was placed into operation due to the thermal expansion of the salt, as shown in Figures 8-2 through 8-5. The creep rate was maximum when the furnace was first started up and since then has been gradually decreasing. The furnace operation was stopped on the 335th day of measurement. Attempts were made to fit several exponential equations to the data with no success. The expansion of the salt at the room's center was about 0.53 inch at the last reading made on the 335th day of measurement. If the furnace had not been operated, the deformation would have been 0.13 inch which shows that the thermal expansion was 0.40 inch.

Station H-B, Vertical and Horizontal Rods: This station, located at a considerable distance from the ORNL furnace test room, was in an opening that was only 9 months old when the measuring equipment was installed.

The creep rates for the vertical rods and the horizontal rod were relatively constant with some of the rods showing a gradual reduction in rate during the latter days of measurement. The plots of the unit deformation versus time for the rods are shown in Figures 8-6 through 8-14. Between the 280th and the 418th day of measurement, a malfunctioning of the measuring gage occurred which caused the variation in the data during this period. The

FIG. 8-6. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, ROD BV-1.

FIG. 8-7. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, ROD BV-2.

FIG. 8-8. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, ROD BV-3.

FIG. 8-9. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, ROD BV-4.

FIG. 8-10. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, ROD BH-1.

FIG. 8-II. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, RODS BC.

FIG. 8-12. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, RODS BF.

FIG. 8-13. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, RODS BS.

FIG. 8-14. CREEP RATES AT STATION H-B,
HUTCHINSON MINE, RODS BW.

rods, which are located in Figure 7-7, had creep rates between the 1st and the 200th day of measurements as shown in Table 8-2.

Table 8-2

Creep Rates at Station H-B in the Hutchinson Mine

Rod	Position	Rate
BV-1	Vertical	15.2×10^{-4} in/in/yr
BV-2	Vertical	17.8×10^{-4} in/in/yr
BV-3	Vertical	17.8×10^{-4} in/in/yr
BV-4	Vertical	16.2×10^{-4} in/in/yr
BH-1	Horizontal	4.2×10^{-4} in/in/yr

A noticeable decrease in the creep rates should occur in the future measurements, and the plots of the deformation versus time should start forming a curve.

The vertical creep rate at the center of the room was greatest at rod BV-3, and it was about 14 per cent greater than that measured at the rods BV-1 and BV-4 which were 5 feet from the wall.

The vertical creep rate at the room's center was about 4.3 times the horizontal rate. This is a much smaller ratio than that observed at Station H-A. At Station H-A, the vertical creep was greater than would normally be expected because of the construction and operation of the test furnaces. The actual deformations that occurred at Station H-B in the vertical and horizontal directions were approximately equal, being 0.29 inch vertically at the room's center and 0.27 inch horizontally across the room.

A comparison of the vertical creep rate measured at Station H-B to that which would be expected in the Grand Saline mine was made by the use of Equation 8-1 as was done for Station H-A. The creep at the center of the room at Station H-B which is in a 1.9-year-old opening has been about 0.30 inch since the room was created. The total creep in a tunnel of the same age in the Grand Saline mine would be about 8.7 inches. This shows that the creep rate of a relatively new opening in the Hutchinson mine is much lower than that of a new opening in the Grand Saline mine. Station H-A showed the converse relationship; however, Station H-A more than likely did not give data which would be representative of an undisturbed opening.

Subsequent studies³ have shown that Hutchinson salt has a greater compressive strength than Grand Saline. It is believed that this is the cause of the lower creep rate in the Hutchinson mine. The greater elastic strength could result in a smaller plastic zone which, in turn, could cause a smaller creep rate. The higher strength could be due to the higher impurity content. The smaller plastic zone could also be due to the lower average temperature that exists in the Hutchinson mine. The Hutchinson mine has a year-round temperature of about 67° F. whereas the Grand Saline mine maintains a temperature of about 81° F. Muehlberger's² report cites several previous investigations that show that impure halite is stronger than pure halite and that a decrease in temperature decreases the plasticity. Previous studies⁴ also demonstrated the temperature-plasticity relationship.

Future measurements in the Hutchinson mine will help to shed more light on the effect of age on the creep rate and will allow a relationship similar to Equation 8-1 to be developed.

Station B: Internal Creep Measuring Devices: The plots of the unit deformation versus time for the internal creep measuring devices are shown in Figures 8-11 through 8-14. The devices located in the floor, designated BS, and in the wall, BW, gave consistent results during the first 200 days of measurement which indicates that the design of the apparatus was satisfactory. The creep rates of these rods during this period are shown in Table 8-3.

Table 8-3

Internal Creep Rates in the Hutchinson Mine

Rod	Position	Depth	Rate
BS-1	Floor	4 feet	2.7×10^{-4} in/in/yr
BS-2	Floor	7 feet	2.4×10^{-4} in/in/yr
BS-3	Floor	10 feet	2.8×10^{-4} in/in/yr
BW-1	Wall	4 feet	6.6×10^{-4} in/in/yr
BW-2	Wall	7 feet	7.3×10^{-4} in/in/yr
BW-3	Wall	10 feet	5.8×10^{-4} in/in/yr

These show that the horizontal creep in the wall was about 2.5 times the vertical creep in the floor near the wall.

All the internal creep measuring devices gave inconsistent results after the 280th day of measurement which was apparently due to the malfunctioning of the measuring gage. However, the devices located in the ceiling, BC, and in the floor, BF, at the room's center gave inconsistent results since the beginning of the measurements. Future measurements will help clarify the internal creep movements.

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