MASTERTECHNICAL MEMORANDUM REPORT RSI-0067**RECEIVED BY TID JUN 4 1979**

QUASI-STATIC STRENGTH AND CREEP
DEFORMATIONAL CHARACTERISTICS OF BEDDED SALT
FROM THE CAREY MINE NEAR LYONS, KANSAS

Submitted To

*Office of Waste Isolation
Oak Ridge, Tennessee*

operated by

*Union Carbide Corporation
Nuclear Division*

for the

Department of Energy

By

Francis D. Hansen

June 7, 1978

(Revised and Resubmitted on October 13, 1978)

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Rapid City, South Dakota*

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FOREWORD

This report was prepared under a subcontract with Union Carbide Corporation, Nuclear Division, a DOE contractor. The subcontract was administered by the Office of Waste Isolation and is part of the National Waste Terminal Storage (NWTS) Program. The principal objective of the NWTS Program is to provide facilities in various deep geologic formations at multiple locations in the United States which will safely dispose of commercial radioactive waste, which must be delivered to a Federal Repository for terminal storage. Some of the expected wastes produce both heat and radioactivity. This situation leads to many unique problems in rock mechanics. This report addresses a particular problem relative to the Rock Mechanics Program.

The overall objective of the OWI Rock Mechanics Program is to predict the response of a rock mass hosting a waste repository during its construction and operation, as well as the post-operational phase. The operational phase is expected to be approximately 20 years while the post-operational phase will last until the repository no longer poses any potential hazard to mankind, a period that may last several hundred thousand years. The Rock Mechanics Program is concerned with near field effects on mine stability as well as far field effects relative to the overall integrity of the geologic containment of waste.

In order to accomplish the objectives of the Rock Mechanics Program, numerical simulation, laboratory (including bench scale), and field studies are under way. The laboratory and field studies provide input to the numerical simulations and also the opportunity for validation of the predictive capabilities of the computer codes. Ultimately, the computer codes will provide the predicted response of the host rock mass and thereby form as essential part of the overall Rock Mechanics Program.

This report presents the results of a laboratory effort which was undertaken to determine mechanical properties of salt from Lyons, Kansas. In addition, it was a goal of the experimental work to define testing procedures, calibrations and data reduction during the process of generating strength data. Mechanical properties such as modulus of deformation and principal strain ratio were incorporated into simulations of Project Salt Vault using finite element methods. Deformational behavior of Lyons salt subjected to constant stress levels for extended periods of time was also evaluated in this experimental effort and compared to results determined for salt from other locations. Strength data and empirical relationships of strain as a function of time, stress and temperature were reduced for application to finite element analyses.

This work could not have been completed without the unselfish cooperation of Dr. Wolfgang R. Wawersik presently at Sandia Laboratories. Almost all of the experimental techniques were tailored after suggestions by Dr. Wawersik, which were patiently described during conversations or gleaned from publications. The author is indebted to Mr. Leslie A. Wagner who assisted in assembly of the testing machines after they were transported from the University of Utah. Mr. Wagner spent many hours preparing specimens and monitoring tests. The author is also indebted to Dr. Paul F. Gnirk

FOREWORD (CONT'D)

who recognized the need for a laboratory and lent his efforts toward implementation of the apparatus, and provided input to the data interpretation. The technical contents of this report have been reviewed by Dr. Gnirk and Mr. Gary D. Callahan. Ms. Julie S. Annicchiarico typed this manuscript and her careful work is gratefully acknowledged.

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June 6, 1978

TECHNICAL MEMORANDUM REPORT RSI-0067

TO: Office of Waste Isolation
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Oak Ridge, TN 37830

Attn.: Dr. James E. Russell
Dr. William C. McClain

FROM: Mr. Francis D. Hansen
RE/SPEC Inc.
P. O. Box 725
Rapid City, SD 57709

SUBJECT: "Quasi-Static Strength and Creep Deformational Characteristics of Bedded Salt from the Carey Mine Near Lyons, Kansas".
(Ref.: Union Carbide Corporation, Nuclear Division Subcontract No. 89Y-22303C (RSI-001000/FY78)).

1. INTRODUCTORY REMARKS

Production creep and quasi-static testing of salt from the Carey Salt Mine at Lyons, Kansas, the site of Project Salt Vault^{(1)*}, was initiated in May, 1976. During the remainder of 1976, a majority of the tests covered in this report were completed. The results were analyzed concurrently with the experimental investigation, but not formally reported. The purpose of testing Lyons salt was twofold. The primary purpose was to provide requisite experimental input to the constitutive law development for modeling Project Salt Vault situations by the finite element method. In that regard, a letter containing results from the quasi-static tests was prepared for and submitted to Dr. William G. Pariseau in February, 1977⁽²⁾. The secondary purpose was to develop the procedural details of testing, including sample preparation, experimental procedure, system calibrations, and evaluation of the reliability of generated data.

*Numbers in parentheses refer to references given at the end of this report.

In order to accomplish the primary objective, specimens of salt from the Lyons Salt Mine Floor (LSMF) were prepared and tested to determine tensile, unconfined compressive, and triaxial compressive strengths. In addition, compressive creep experiments were conducted and the results compared to those reported by Lomenick⁽¹⁾. With the exception of tensile strength, the tests were conducted at both ambient and elevated temperatures up to 100°C.

As a result of the limited quantity of core available, the test matrices do not encompass as many parameter variations as desirable. However, the test results are no less valuable, as the limited number of tests simply precludes drawing extensive conclusions. The report is organized in a manner which presents background information first. The various phases of the experimental program are encompassed in Section 2. The subsequent sections present experimental results for the Lyons salt, as well as relevant results from experimental efforts on salt from other areas of the USA, including both bedded and domal salt (3,4,5,6,7,8,9).

2. EXPERIMENTAL PROGRAM

2.1. Specimen Preparation

Specimens prepared for this testing effort were recovered from several six-inch diameter samples that had been collected by Dr. Paul F. Gnirk and Dr. Earl R. Hoskins from the Carey Salt Mine, near the site of Project Salt Vault, in March, 1972.⁽¹⁰⁾ These core samples were retained since that time in the Mining Department laboratory at South Dakota School of Mines and Technology. No special containment nor protection was afforded these samples during this period, except that they were contained in plastic bags and did not experience a freeze-thaw situation.

Coring was accomplished by using a thin-walled diamond impregnated bit and saturated brine solution. Coring apparatus consisted of a Rockwell drill press modified with a water swivel and base plate chuck. Core drilling was not very successful initially. However, with proper care, specimens were successfully drilled from the centers of the larger field samples.

End preparation was accomplished with a rock lapping machine, which ground the ends parallel by means of a high speed grinding wheel. The lapping was done in a dry condition; a vacuum hood was used to evacuate the dust. This procedure resulted in some chipping around the circumference of the specimen ends due to wheel impact on crystals. Usually, chipping

was not severe. The chip cavities were filled with epoxy and refinished in an effort to provide uniform end surfaces for piston load application.

Generally, the Lyons salt contained significant amounts of clay which tended to wash out during the coring process. The salt specimens were inspected prior to testing and pits were filled with silicone rubber to prevent the jacketing membrane from being punctured while under confinement.

2.2. Apparatus and Procedure

2.2.1. Testing Apparatus

The compression tests (quasi-static and creep) in this experimental effort were performed utilizing three machines. Two of these machines were designed by Dr. Wolfgang R. Wawersik (currently with Sandia Laboratories) while at the University of Utah. These machines are referred to as Machine 1 and Machine 2. The third machine, referred to as Machine 3, was designed and built in house at RE/SPEC Inc. A description of these machines has been presented in detail in a previous report ⁽³⁾, which includes hydraulic schematics and operational details. Photographs of these machines are included herein in Figures 1 and 2.

The test machines are equipped with transducers which measure axial stress, confining stress, temperature, and axial strain. Machines 1 and 2 are also capable of measuring volumetric (lateral) strain. Axial displacement is measured by an opposing pair of LVDT transducers. Axial load (stress) is measured with a strain-gauge load cell or Heise pressure gauge, and confining pressure is measured with an in-line strain gauge pressure transducer or Heise pressure gauge. On the two machines designed by Wawersik, i.e. Machines 1 and 2, the lateral strain is measured and the lateral pressure controlled through a reversible motor system. An LVDT in a bellows senses the differential pressure change from the active to reference side and excites the motor which corrects the pressure. A potentiometer measures the turns of the motor shaft and consequently the volume change of the confining pressure liquid; this volume change is a measure of the volumetric strain ^(11,12). For an explicit description of the relationships of volumetric measurements to lateral strain, the reader is referred to Reference 3.

The sensitivity of the axial displacement transducers is ± 0.0001 in., and the axial load cells and gauges are accurate to ± 10 psi (specimen stress). The confining pressure transducer is accurate to ± 5 psi, and the volumetric strain mechanisms on Machines 1 and 2 are accurate to ± 25 microstrains.

Figure 1. Photograph of Testing Apparatus Housing Machine 1 on the Right, Machine 2 on the Left.

Figure 2. Photograph of Machine 3.

2.2.2. Calibration of Apparatus

The three testing machines have been calibrated for axial and lateral displacements by use of metal specimens of steel, brass and aluminum. The elastic properties of the metals were predetermined by strain gauge analyses.

2.2.2.1. Calibration of Axial and Lateral Systems

Unconfined compression calibrations of metal specimens resulted in initially nonlinear displacement (LVDT) as a function of stress; direct strain gauge data, however, were linear and consistent. Triaxial compression calibrations resulted in linear stress-strain responses with the contribution of the assembly pistons consistent between metal types. Axial calibration consisted of a simple comparison of indirect displacement measurements with strain gauge results. Calibration of these machines was first performed by Dropek ⁽¹³⁾ and have been substantiated by two subsequent calibration programs performed by RE/SPEC, involving both ambient and elevated temperature. Calibration began by testing strain-gauged samples in uniaxial compression, making use of assembly pistons used for triaxial compression tests. The various calibration specimens were aligned with the actuator piston and loaded from zero to 12,500 psi. After unloading, the test column was reassembled in a different orientation and retested. In this manner, the strain gauge response yielded an indication of uniformity of load which in turn indicated whether the lower base plate and the load actuator piston were parallel. With a minimal amount of shimming of the columns holding the lower platen, the strain gauges were found to respond equally regardless of orientation and the alignment was considered satisfactory.

Triaxial calibrations involved evaluation of both the axial displacement and the volumetric measuring system. Metal samples undergo small axial strains ($\epsilon_1 \leq 0.2\%$ strain) in the calibration range of stress and the reduction of lateral strains can be simplified. However, irrespective of metal behavior, salt will undergo much larger strains. Computation of lateral strain through volume displacement for large rock deformation follows similar procedures to those published by Crouch ⁽¹¹⁾, Wawersik ⁽¹²⁾, and Dropek ⁽¹³⁾. The derivation assumes that the rock specimen initially has the shape of a right circular cylinder, and this shape is preserved as

deformation proceeds. A similar assumption is made for the initial and deformed shapes of the loading piston.

Calibration of axial displacement was accomplished by comparing results obtained directly (strain gauges) to results obtained by indirect measurements (LVDT). Uniaxial calibration was not very successful due to nonlinear response of the LVDT measurements. It is believed that uniaxial calibration including this nonlinearity could be achieved, but for the immediate concerns in our testing program, it was not done. Triaxial calibration tests resulted in linear force-displacement response of the system. Accordingly, the contribution of the piston assembly to the total axial displacement could be readily evaluated. By successively testing calibration specimens of steel, aluminum and brass of known moduli, the axial calibration factors for both machines were consistent between the three metals. Table 1 is a summation of the calibration results (1976 calibration effort) obtained for indirect determinations of Young's modulus of elasticity. These results are obtained by averaging all calibration tests and were considered adequate. As an indication of the accuracy of these axial measurements, an error of ± 0.0001 inches, which is the tolerance of the calibration specimens, will introduce a relative error in the modulus of elasticity of steel of ± 6.5 percent at a stress level of 11,500 psi.

Table 1

MODULI OF ELASTICITY OF CALIBRATION
SPECIMENS AS DETERMINED EXPERIMENTALLY

METAL SPECIMENS	STRAIN GAUGED VALUES	MACHINE NO. 1	ERROR (%)	MACHINE NO. 2	ERROR (%)
STEEL	30.20	28.88	-4.4	31.22	+3.4
ALUMINUM	10.31	10.47	+1.6	11.22	+8.8
BRASS	13.47	--	---	12.01	-10.8

Calibration of the lateral system involved reduction of volumetric measurements to lateral strain equivalents. The formulation of the calibration factor for lateral strains is:

$$L_p = \frac{\left[\frac{\Delta V}{A_c} \right] - L_c \left[1 - \frac{F}{E_c A_c} \right] \left[\left\{ 1 + \frac{\nu_c F}{E_c A_c} \right\}^2 - \left\{ 1 + \frac{\nu_p F}{E_p A_p} \right\}^2 \right]}{\left\{ 1 + \frac{\nu_p F}{E_p A_p} \right\}^2 - 1.0} \quad (1)$$

where:

L_p = The effective length of the test column inside the pressure vessel. (in.)

ΔV = Volume change of confining oil (in.³)

A_c = Initial area of calibration specimen (in.²)

L_c = Initial length of calibration specimen (in.)

F = Piston Force (lbs.)

E_c = Modulus of elasticity of calibration specimen (psi)

ν_c = Poisson's ratio of calibration specimen

ν_p = Poisson's ratio of loading pistons.

E_p = Modulus of elasticity of loading pistons. (psi)

A_p = Initial area of loading piston. (in.²)

Two calibration efforts were actually undertaken during the course of testing and reporting the Lyons experimental data, one in 1976 and one in 1977. The 1976 results were comparable to those previously determined for the apparatus by Dropek⁽¹³⁾ and to the theoretical values listed in Table 2.

TABLE 2

VALUES OF EFFECTIVE LENGTH, L_p ,
FOR MACHINE NO. 1 AND MACHINE NO. 2

CALIBRATION	L_p , MACHINE NO. 1	L_p , MACHINE NO. 2
THEORETICAL	7.375	8.125
DROPEK (13)	8.099	8.391
PRESENT EFFORT	7.383	7.813

More extensive calibrations were conducted in 1977 and despite the relatively large number of tests, refinement of a value for L_p was not possible due to scatter in the data. As an example, values of L_p for individual tests ranged from 7.0 to 9.0. Influences of L_p values in determination of lateral strain are basically a function of the magnitude of strain. That is, for small strain, such as obtained from calibration tests on metals, the value of L_p is more significant than it is for larger strains, such as experienced during triaxial compression tests on rock salt. This partially accounts for the scatter encountered during calibration. It was determined that errors in lateral strain calculations due to L_p for reduction of actual test data were minimal (< 1.0%). For reduction of experimental data in this report, L_p values determined for the present effort (Table 2) were used.

The equation used for reduction of volumetric measurements to lateral strains is:

$$\epsilon_{R2} = \sqrt{\left[\frac{1}{1 - (\Delta L_R / L_R)} \right] \left[1 + B_1 \Delta V - B_2 \{ (1 + B_3 F)^2 [B_4 + (\Delta L_R / L_R)] - B_4 \} \right]}$$

- 1.0 (2)

where the variables are the same as those listed for Equation (1) and a set of constants has been defined as:

$$B_1 = \frac{1}{A_R L_R}$$

$$B_2 = \frac{A_P}{A_R}$$

$$B_3 = \frac{V_P}{A_P E_P}$$

$$B_4 = \frac{L_P - L_R}{L_R}$$

A_R = Area of Rock Salt Specimen (in.²)

L_R = Length of Rock Salt Specimen (in.)

In order to correct for fluid contraction during non-ambient temperature tests, constant B_1 is modified as follows:

$$B_1' = \frac{B_1}{[1 - (T - T_o)\beta]} \quad (2A)$$

where T is the test temperature, T_o is the ambient temperature, and β is the fluid expansion coefficient.

2.2.2.2. Calibration of Temperature

Temperature of the tests conducted in Machines 1 and 2 is measured by means of a thermocouple probe inserted in the pressure vessel wall to a point flush with the inside diameter (Figure 3). This thermocouple also served as feedback for temperature control. Calibrations were performed in 1977 to evaluate the difference between the temperature at the pressure vessel wall and the temperature within the salt specimen at the top, middle, and bottom. To accomplish the calibration, three 0.020 in. diameter flexible thermocouples were inserted into a 1/16 inch diameter hole drilled in a specimen of Jefferson Island domal salt and arranged as illustrated in Figure 3. The vessel oil was heated from room temperature to 70°C and later to 100°C while measurements of temperature were taken. Tests were conducted with no confinement pressure and with 500 psi confinement pressure.

Figure 3. Temperature Calibration Assembly.

During thermal calibration tests, the heater controllers were preset at the desired calibration temperature and switched on. Temperature rise of the silicone oil from room temperature to 70 or 100°C required of the order of 20 minutes. Equilibrium was achieved within one hour.

As a result of these calibration tests, the internal specimen temperature was found to be less than the vessel oil temperature by 6 to 8°C at 100°C and 3 to 5°C at 70°C. A temperature gradient of 2°C was found to exist within the specimen.

2.2.3. Quasi-Static Triaxial Compression Test Procedure

A specimen prepared for testing was first inspected for pits which sometimes result from coring. Any pits were filled with silicone rubber to prevent the jacket from puncturing. The sample was jacketed in a membrane fabricated of sheets of polyurethane. Membrane fabrication consisted of wrapping a sheet of polyurethane around a metal cylinder and bonding the overlapped areas with tetrahydrofuran. The jacketed specimen was carefully placed between the upper and lower pistons, and the jacketing stretched over a latex rubber ring which in turn was stretched over the pistons. The jacket-piston overlap was about 1/2 inch, and the jacket was clamped onto the piston using two strands of high-tension safety lock wire. The entire assembly of piston-specimen was placed in the pressure vessel and the vessel filled with silicon oil and sealed. The vessel was then placed on the lower platen and aligned with the load actuator piston. The specimen was subjected to increasing hydrostatic pressure until the desired confining pressure was reached. The assembly was allowed to achieve equilibrium.

For triaxial tests conducted at elevated temperatures, the assembly was loaded hydrostatically to check for leaks and unloaded hydrostatically. The heater was then switched on with the confining system open and the axial piston retracted to vent out pressure increases due to expansion of the oil, pistons, and specimen. When the desired temperature was achieved and had reached an equilibrium, the axial and confining pressures were again applied hydrostatically and allowed to equilibrate at the desired pressures. Axial load application to a specimen tested in quasi-static triaxial compression for this program was accomplished in a load-hold procedure, whereby the axial stress was increased in increments.

2.2.4. Triaxial Creep Test Procedure

A triaxial compressive creep specimen was prepared for testing and set up as described in Section 2.2.3. for triaxial compression tests. Creep test specimens were subjected to a hydrostatic stress for periods ranging from a few hours to a day. The creep experiments necessarily had to be leak proof. Leaks in the system or other potential problems were usually evident immediately. Very slow leaks could be discovered by means of hydrostatic stress application for longer periods of time. All creep tests were allowed to reach thermal equilibrium and were leak free prior to test initiation.

A nitrogen charged bladder accumulator with a volume of one gallon was precharged to the desired axial stress level for each creep test. With the accumulator isolated from the system, the axial stress was applied until the desired differential stress level was reached. The accumulator was then turned into the axial pressure line and the load was maintained constant for the duration of the test. Axial and lateral strains were monitored during each load application.

2.3. Matrix of Tests

A matrix of tests was not predetermined by contractual obligations; rather, the controlling factor as regards parameters and total number of tests was simply the amount of core available. At the outset, recovery of specimens from field core was not too successful (see Section 2.1). However, test parameter variations on the specimens that were recovered were governed by a need for constitutive material property input to computer codes for modeling purposes.

Table 3 contains a list of the tests completed on Lyons salt. The experimental program involved indirect tensile tests, uniaxial and triaxial compression tests and constant compressive stress creep experiments. With the exception of tensile tests, the experiments were conducted at ambient and elevated temperatures.

2.4. Physical Characterization of Salt from Various Sites

Several observations concerning the physical nature of salt specimens from sites in the U.S.A. should be noted as a preliminary to comparison of experimental results. The essence of this report is the evaluation of test results for Lyons, Kansas salt, but additional data are of interest as regards the variances of salt from site to site and significance of physical characterization. Impetus toward compiling this section was lent by comparisons made in ORNL 4555 (1) between Lyons salt results and results for Cote Blanche and Weeks Island salt which, coincidentally, were two of the several locations tested in the RE/SPEC laboratory for other projects (5,6).

The physical characterization of salt from six sites in the U.S.A. is itemized below in general terms. Photographs of representative specimens are presented in Figures 4 through 6 which should assist in conceptualizing the written description. Figure 4 shows six specimens of domal salt from Louisiana, of which three are undeformed and three have been deformed. Figures 5 and 6 are photographs of bedded salt. The relative amount of impurities is evident, as is the variation of grain sizes. Reference 14 contains one large plate showing a photograph of half-cylinders of Lyons and Jefferson Island salt.

TABLE 3

MATRIX OF MECHANICAL PROPERTIES TESTS COMPLETED ON
BEDDED SALT FROM LYONS, KANSAS

SAMPLE IDENTIFICATION	GENERAL TEST CONDITIONS	MAXIMUM* $\sigma_1 - \sigma_2$ (PSI)	$\sigma_2 = \sigma_3$ (PSI)	TEMPERATURE (°C)
LSMF 1T through LSMF 19T	Indirect Tension Indirect Tension	225 ± 55	0	Ambient
LSMF - 1/1	Unconfined w/Strain Gauges	3785	0	Ambient
LSMF - 1/2	Unconfined w/Strain Gauges	3460	0	Ambient
LSMF - 2/1	Unconfined w/ Strain Gauges	3720	0	Ambient
LSMF - 3/2	Unconfined w/Strain Gauges	3060	0	95
LSMF - 2/3	Unconfined w/Strain Gauges	2750 (EST)	0	95
LSMF - 1/5	Triaxial Compression	7300	500	Ambient
LSMF - 1/6	Triaxial Compression	6300	500	Ambient
LSMF - 1/7	Triaxial Compression	10500	500	Ambient
LSMF - 1/3	Triaxial Compression	8600	1000	Ambient
LSMF - 1/4	Triaxial Compression	11100	2000	Ambient
LSMF - 1/9	Triaxial Compression	8200	3000	Ambient
LSMF - 2/5	Triaxial Compression	9200	5000	Ambient
LSMF - 2/9	Triaxial Compression	3200	500	100
LSMF - 2/2	Triaxial Compression	4000	1000	100
LSMF - 3/7	Triaxial Compression	4600	1500	100
LSMF - 2/4	Triaxial Compression	5600	2000	100
LSMF - 3/4	Triaxial Compression	4700	2000	100
LSMF - 2/6	Multistage Triaxial Comp.	4500	Variable	Ambient
LSMF - 2/7	Multistage Triaxial Comp.	4500	Variable	Ambient
LSMF - 1/8(1)	Creep, Stage 1	1500	500	Ambient
LSMF - 1/8(2)	Creep, Stage 2	3000	500	Ambient
LSMF - 1/8(3)	Creep, Stage 3	4500	500	Ambient
LSMF - 1/8(1)	Creep, Stage 1	1500	500	100
LSMF - 2/8(2)	Creep, Stage 2	3000	500	100
LSMF - 3/1	Creep, Single Stage	4500	500	Ambient
LSMF - 4/1	Creep, Single Stage	3000	500	Ambient
LSMF - 3/6(1)	Creep, Stage 1	1700	1800	Ambient
LSMF - 3/6(2)	Creep, Stage 2	3000	1500	Ambient
LSMF - 3/6(3)	Creep, Stage 3	4500	1500	Ambient
LSMF - 3/5(1)	Creep, Stage 1	1500	500	70
LSMF - 3/5(2)	Creep, Stage 2	3000	500	70
LSMF - 3/8(1)	Creep, Stage 1	1500	500	Ambient
LSMF - 3/8(2)	Creep, Stage 2	3000	500	Ambient

*Maximum does not necessarily mean failure strength.

Physical characterization of salt specimens from each site is given as follows:

Lyons (Bedded) Salt: Obtained from the Carey Salt Mine floor at approximately 1000 ft. depth. This salt is appreciably coarse grained, 0.4 in. average diameter, and contains a considerable amount of clays in layers. Impurities are laminated; i.e. alternating layers of relatively pure salt with interbeds of gray layers of variable thicknesses. A mineralogical description of the impurities has not been determined, but it appears to be clay.

S.E. New Mexico (Bedded) Salt: Cores have been tested in the RE/SPEC laboratory from drillholes AEC #7, AEC #8, and ERDA #9. Considerably more mineralogical studies have been performed on this salt in an independent study (15). Most samples are predominantly halite with various amounts of anhydrite, polyhalite, and clays. The cores were obtained throughout a stratigraphic section from about 1800 feet to 3300 feet depth, and as a consequence exhibited highly variable mineralogical contents and crystal sizes (7).

Jefferson Island (Domal) Salt: Obtained from the 1500 ft. level of the Diamond Crystal Mine. This salt is very clean in appearance, although small needles of anhydrite are scattered throughout along halite crystal boundaries. The grain size is somewhat variable but averages about 0.25 inch diameter, which is relatively fine for rock salt.

Weeks Island (Domal) Salt: Obtained from four sites at the 735 ft. level of the Morton Salt Mine. The crystal size, coloration due to dispersed inclusions, and general condition are quite variable among the salt samples from each site. Crystal size ranges from 0.25 in. to 1.0 inch and greater in diameter, but generally averages 0.3 inches. Salt is generally free of concentrations of impurities as seen in the Lyons salt; however, coloration does vary from white and clean to various darknesses of gray, indicative of impurities scattered throughout. Cementation of crystal grains is highly variable in the Weeks Island salt; some specimens are competent (like JI salt), while other specimens are loosely cemented and can be crumbled by hand pressure.

Cote Blanche (Domal) Salt: Obtained from the Domtar Salt Mine at the 1000 ft. level. The physical appearance of Cote Blanche salt is similar to Weeks Island salt with the exception that Cote Blanche salt is consistently tightly cemented. The crystal grain sizes range from small (0.1 in.) to over 1.0 inch in diameter and coloration from white to very dark gray.

Avery Island (Domal) Salt: Obtained from the International Salt Mine at the 575 ft. level. Appears similar to the salt from Weeks Island and Cote Blanche domes. Crystal size is uniformly 0.5 in. in diameter and coloration is consistently light gray. Overall appearance, including tight cementation of crystal grains, is similar to Cote Blanche salt.

Figure 4. Representative Specimens of Domal Salt.

Figure 5. Representative Specimens of Bedded Salt.

Figure 6. Representative Specimens of Bedded Salt From Southeastern New Mexico after Creep Deformation.

2.5. Thermal Expansion

During the course of this experimental effort, the coefficient of thermal expansion was measured on strain gauged specimens of Lyons salt prior to unconfined compression tests at elevated temperature. The initial purpose of the experiment was to evaluate the bonding integrity of the strain gauge epoxy. Upon being satisfied with the bonding, the strain gauge response as a function of temperature was used to calculate a coefficient of expansion. For the temperature range of 82 to 208°F, the average coefficient for four Lyons' experiments was determined to be 21×10^{-6} in./in./°F which agrees very well with published data ⁽¹⁾.

2.6. Decrepitation Tests

Reference 1 contains results of thermal stability studies on salt from several sites in the U.S. and Europe. Specimens were heated as high as 400°C and monitored to determine fracturing temperatures. Not all of the salt specimens fractured. In this investigation, salt specimens from six sites in the U. S. were heated unconfined from room temperature to 240°C in the first hour of testing and subsequently from 240°C to 325°C in the second hour of testing. The results of these experiments are summarized in Table 4. The fracturing temperature of the Jefferson Island salt is comparatively low, however, the results were consistently low for all decrepitation tests.

TABLE 4
THERMAL STABILITY OF SALT

Location	Number of Specimens Tested	Fracturing Temperature (°C)	Salt Type
Lyons, KS	4	260-320	Bedded
SE New Mexico	3	*	Bedded
Jefferson Island, LA	3	200-225	Dome
Avery Island, LA	3	*	Dome
Weeks Island, LA	3	(1 of 3) 325	Dome
Cote Blanche, LA	2	*	Dome

*Indicates the specimens did not fracture up to 325°C.

Measurements of moisture content made using an Fhaus triple beam scale (accuracy to within $\pm 0.05\text{g}$). Sample weighings were made before and after the decrepitation tests, but generally the resolution of the scale was not sufficient to accurately determine the small percentage of moisture. The Lyons salt contained the greatest percentage of moisture by weight, approximately 0.15%, and the other salts contained of the order of 0.05% by weight.

As shown in Table 4, salt from only two sites, Lyons and Jefferson Island, consistently fractured when subjected to elevated temperature. Lyons salt specimens exploded violently. Jefferson Island salt decrepitated with an audible pop. One of three specimens of Weeks Island salt fractured. The other specimens did not fracture at temperatures to 325°C .

3. RESULTS OF TENSILE STRENGTH TESTS

The tensile strength of Lyons salt was determined by means of the Brazilian test procedure⁽¹⁶⁾. This is an indirect test method in which a diametrical line load is applied over the length of a rock cylinder ($L:D \leq 1:1$) and the tensile strength is computed according to:

$$\text{Tensile Strength: } T_o = 2P/\pi DL \quad (3)$$

where:

P is the line load (lbs.) required to initiate fracture along the diameter;

D is the specimen diameter (in.);

L is the specimen length (in.).

Preparation of the specimens involved sawing cores to length; machine milling of the specimen ends was not necessary. Narrow strips of cardboard were placed between the cylindrical surface of the specimen and the metal platens. Load-deflection curves were obtained for each test to facilitate observation of the peak load prior to crack initiation. Generally, indirect tensile crack development was along crystal boundaries, rather than through crystals which gives rise to a zig-zag break line. A combination of measurement techniques provided an accurate determination of the breaking strength.

A total of nineteen specimens were tested on a Tinius Olsen machine, which has a load resolution of ± 5 lbs. The results are listed in Table 5 and photographs of these indirect tensile test specimens are included in Appendix A. The indirect tensile strength of Lyons salt is consistent with the indirect tensile strength of salt from other sites in the U.S. These comparisons are listed in Table 6. From these collective data, it appears that the interspersed clay inclusions in the Lyons salt did not influence its tensile strength.

TABLE 5INDIRECT TENSILE STRENGTH OF LYONS, KANSAS BEDDED SALT AT ROOM TEMPERATURE

SPECIMEN I.D.	LENGTH (IN.)	LOAD (LBS.)	L:D	σ_T (PSI)
LSMF-1/1T	0.68	390	0.36:1	195
LSMF-1/2T	0.70	290	0.37:1	140
LSMF-1/3T	0.73	350	0.39:1	160
LSMF-1/4T	0.66	370	0.35:1	190
LSMF-1/5T	0.86	480	0.46:1	190
LSMF-1/6T	1.05	580	0.55:1	185
LSMF-1/7T	1.17	675	0.62:1	195
LSMF-1/8T	1.18	555	0.62:1	160
LSMF-1/9T	1.28	1,085	0.67:1	285
LSMF-1/10T	1.46	1,230	0.77:1	285
LSMF-1/11T	1.45	1,145	0.77:1	265
LSMF-1/12T	1.65	615*	0.87:1	--
LSMF-1/13T	1.75	1,390	0.93:1	265
LSMF-1/14T	1.72	1,590	0.91:1	310
LSMF-1/15T	2.00	1,720	1.06:1	290
LSMF-1/16T	1.82	1,390	0.96:1	260
LSMF-1/17T	2.01	1,210	1.06:1	200
LSMF-1/18T	2.06	1,675	1.09:1	275
LSMF-1/19T	2.18	1,395	1.15:1	215

* Crack developed on only one end of the specimen due to uneven specimen edge.

TABLE 6

INDIRECT TENSILE STRENGTH OF SALT FROM THE U.S.A.
(TWO INCH DIAMETER SPECIMENS AT ROOM TEMPERATURE)

<i>SITE</i>	<i>TYPE OF SALT FORMATION</i>	<i>DEPTH (FT.)</i>	<i>TENSILE STRENGTH (PSI)</i>
<i>Lyons, Kansas</i>	<i>Bedded</i>	<i>1,000</i>	<i>225 ± 55</i>
<i>SE New Mexico</i>	<i>Bedded</i>	<i>1,900</i>	<i>200 ± 45</i>
<i>SE New Mexico</i>	<i>Bedded</i>	<i>2,700</i>	<i>240 ± 25</i>
<i>Jefferson Island, LA</i>	<i>Dome</i>	<i>1,500</i>	<i>225 ± 45</i>
<i>Avery Island, LA*</i>	<i>Dome</i>	<i>575</i>	<i>170 ± 25</i>
<i>Cote Blanche, LA</i>	<i>Dome</i>	<i>1,000</i>	<i>280 ± 40</i>
<i>Weeks Island, LA</i>	<i>Dome</i>	<i>735</i>	<i>155 ± 50</i>

* Experimental effort in progress.

4. RESULTS OF QUASI-STATIC COMPRESSION TESTS

A total of 19 compressive strength tests were completed on salt from Lyons, Kansas. Five of these tests were unconfined compression ($\sigma_2 = \sigma_3 = 0$ psi) and fourteen were triaxial compression ($\sigma_2 = \sigma_3 > 0$ psi). Particular test parameters were given in the test matrix (Table 3). Estimates of moduli of deformation were calculated for all of these tests. Ultimate strength and principal strain ratio were determined for about half of the tests. These data will be presented in the following subsections. Each of the following sections will contain comparisons of the Lyons results to results obtained for salt from other localities.

4.1. Unconfined Compressive Strength

Five unconfined (uniaxial) compressive strength tests were conducted, with three at ambient temperature and two at elevated temperature. Of the three ambient unconfined compression tests, two were conducted on a Tinius Olsen machine at the South Dakota School of Mines and Technology and the third was conducted on Machine No. 3. Four electrical resistance strain gauges were epoxied to each specimen at midheight. Two gauges were axially aligned and two were aligned circumferentially; both pairs were diametrically opposed. The testing procedure for the first two tests (LSMF-1/1 and LSMF-1/2) involved cycling the specimen through two load/unload cycles at relatively low stress levels and then applying a constantly increasing load to failure on the third cycle. The third unconfined test at ambient temperature (LSMF-2/1) was not cycled, but continuously loaded to failure. The load application rate for these tests was between 100 and 200 psi/min.

The strain gauges on these specimens operated well at lower stress levels (and consequently, lower strain) but ultimately failed to operate at axial strains approaching 1.0 percent. In order to evaluate the stress-strain response to ultimate strength, the third unconfined test was equipped with LVDT gauges to record axial displacement. The relative difference in the strain magnitude between measurements with strain gauges and LVDT gauges was significant at low stresses, but gradually became insignificant as the stresses and strains increased. Approaching the strain gauge limit on the third test, the strain gauges indicated an axial strain of 0.87 percent and the LVDT gauges indicated a strain of 0.85 percent.

Two Lyons salt specimens were tested in unconfined compression at a temperature of 95°C. The specimens were strain gauged in the same manner as the ambient temperature unconfined tests. The strain gauges and the epoxy adhesive operated quite successfully at this temperature. One of the tests was cycled to 750 psi, unloaded, then reloaded to failure. The other was loaded slowly at a rate of 30 psi/min. without cycling. In this manner, the effect of temperature, load rate, and hardening were evaluated.

A summation of the properties is presented in Table 7, including test identification, unconfined compressive strength, temperature and approximate moduli of deformation. Two data points from Reference 1 are also listed from tests conducted on 2 inch cubes. Plots of the stress-strain curves are superimposed in Figure 7. Tests utilizing LVDT gauges have stress-strain curves to ultimate strength, while tests with strain gauges alone are extrapolated (dashed lines) to ultimate strength.

The ultimate strength values determined for two inch cubes versus values for 2 x 4 in. cylinders show some effects of differences of L:D ratios: i.e. 1:1 versus 2:1, with 1:1 ratio yielding greater strength due to end friction. The geometry effect is not as great as might be expected for rock salt based on previously reported work ⁽⁸⁾, where a difference of 25% was found by increasing the L:D from 1:1 to 2:1 using right circular cylinders. In addition to apparent geometrical effects, it is not known if the cubes and cylinders were obtained from the same location, therefore, some sampling variability is probably inherent in these comparisons.

Values of deformational moduli show the effect of hardening induced by cyclic loading. The hardening effect is apparent both at room temperature and 95°C. This observation has been substantiated by several other experimental programs ^(5,6,8). The conclusion drawn is that natural rock salt tends to unload and reload on a hardened stress-strain path due to the history of previous loading. In all cases, the unload/reload stress-strain response is nearly linear and two to five times steeper than the initial loading stress-strain curve. The net result is a higher value for modulus of deformation for the cycled tests as shown in Table 7. These moduli were calculated as a secant or average slope of the stress-strain curve over the stress interval of 500 to 1500 psi in the load cycle to failure.

Other quantitative evaluations show that moduli of deformation as well as ultimate strengths are significantly reduced at elevated temperature. The modulus has been demonstrated to be insensitive to geometric changes ⁽⁸⁾. An indication that this conclusion also applies to these tests is demonstrated by comparing the modulus for test LSMF-2/1 and the modulus of the unirradiated cube, which are 0.39×10^6 and 0.35×10^6 psi, respectively.

Poisson's ratio was also monitored for these experiments by virtue of the laterally bonded strain gauges. However, after much consideration, the values determined were not acceptable due to high variability. The variability is obviously attributable to dilation cracking, which initiates in a principally vertical orientation relative to the core axis and perpendicular to the lateral gauges. As a consequence, Poisson's ratio is definable only for very low stress (strain) levels.

Table 2.3 of Reference 1 contains a summary of physical properties of rock salt exposed to various doses of radiation. The compressive strength of cubes delineate some of the variances between rock salt of bedded and domal formations. It is, therefore, of interest to encapsulate in this section a similar list of strengths of various salt formations as determined by testing cylindrical specimens at room temperature. A bar graph of unconfined compressive strengths of salt from eight locations is shown in Figure 8 . It should be noted that this salt is unirradiated and orientation of the test specimens was vertical; i.e. force was applied perpendicular to bedding. Notedly, the strength of salt is lower for the 2:1 right circular specimens than for the 2 inch cubes. Also, no definitive difference in strength exists between dome and bedded salt solely on the basis of deposition. Strength is a site specific property.

TABLE 7

MECHANICAL PROPERTIES OF LYONS, KANSAS SALT FROM
UNCONFINED COMPRESSIVE STRENGTH TEST DATA

TEST I.D.	TEMP. (°C)	UNCONFINED COMPRESSIVE STRENGTH (psi)	MODULUS OF DEFORMATION ^d 10 ⁶ psi
ORNL 4555 ^a	AMBIENT	4200 ± 500	0.35 ^b
ORNL 4555 ^a	200	3900 ± 200	0.09 ^b
LSMF-1/1	24	3785	1.23 ^c
LSMF-1/2	24	3460	1.17 ^c
LSMF-2/1	24	3720	0.39
LSMF-2/3	95	2750 (EST.)	0.18
LSMF-3/2	95	3060	0.29 ^c

a = Tests conducted on 2 inch cubes.

b = Elastic modulus from 0 to 0.2% axial strain (approximately 1000 psi).

c = Stress application was cycled to stress levels of approximately 1/3 failure strength before loading to failure.

d = Elastic modulus calculated as secant from 500 to 1500 psi.

Figure 7 . Unconfined Compressive Strength Test Results for Lyons, Kansas Bedded Salt (Force Applied Perpendicular to Planes of Stratification).

FIGURE 8. UNCONFINED COMPRESSIVE STRENGTH OF BEDDED AND DOME SALT.

4.2. Triaxial Compressive Strength

Fourteen triaxial compressive strength tests were completed on Lyons salt at ambient and elevated temperatures. Ultimate strength, modulus of deformation and principal strain ratio have been determined. A preponderance of data collected was applied load (stress) as a function of axial displacement (strain). These data were interpreted to determine a modulus of deformation of the specimens. During eight of the fourteen tests, lateral strain was measured which makes possible calculation of principal strain ratio, $-\epsilon_2/\epsilon_1$. Data pertaining to lateral strain and principal strain ratio were necessary for proper evaluation of ultimate strength data, because salt is ductile under confinement pressures and often exhibits axial strain, ϵ_1 , up to 25 percent without structural failure. Large strains in the salt specimens during testing changed the original geometry. The differential axial stress applied to the specimen was calculated on the basis of the instantaneous area corrected for strain distortion.

Parameter variation for triaxial compression tests includes confining pressure, temperature, load rate, and maximum strain. The combination of test conditions and machine capability precluded obtaining ultimate compressive strength on several of the specimens. In order to facilitate the ensuing discussion of experimental results, Table 8 has been prepared which lists the mechanical properties of the Lyons salt.

4.2.1. Modulus of Deformation

Axial, as well as lateral strain, is a nonlinear function of the applied differential stress. Natural rock salt exhibits near zero yield strength and continuous strain hardening. Triaxial compressive strength data for Lyons salt exhibit concave stress-strain responses, which are characteristic of compression of natural rock salt. Appendix B contains plots of the reduced test data such that each test may be examined by the reader on an individual basis.

Several factors influence determination of moduli of deformation. For example, temperature and pressure are test variables which have considerable influence, the former to a greater extent than the latter. Other variables, such as load rate and load history, affect the stress-strain

TABLE 8

MECHANICAL PROPERTIES OF LYONS, KANSAS SALT TESTED IN TRIAXIAL COMPRESSION

TEST I.D.	CONFINING PRESSURE (PSI)	TEMP. (°C)	LOAD RATE (PSI/MIN.)	MODULI OF DEFORMATION (10 ⁶ PSI)		PRINCIPAL STRAIN RATIO (-ε ₂ /ε ₁)
				INTEGRATED 0-2500 PSI	SECANT 500-2500 PSI	
LSMF - 1/6	500	25	45	0.56	0.44	0.38
LSMF - 1/5	500	25	86	0.89	1.23	--
LSMF - 1/7	500- 1000	25	610	1.80	1.22	--
LSMF - 1/3	1000	25	95	1.18	0.70	0.33
LSMF - 1/4	2000	25	95	1.10	0.65	0.40
LSMF - 1/9	3000	25	120	0.44	0.75	--
LSMF - 2/5	5000	25	125	0.52	1.09	--
<hr/>						
LSMF - 2/9	500	100	33	0.13	0.07	0.51
LSMF - 2/2	1000	100	70	0.41	0.22	0.46
LSMF - 2/4	2000	100	41	0.39	0.21	0.46
LSMF - 3/4	2000	100	17	0.35	0.19	0.51
LSMF - 3/7	1500	100	80	0.13	0.07	0.47

relationship. Therefore, in order to resolve the individual test results into a quantity which can be compared between tests, evaluations of moduli must be made in a consistent fashion.

A "linear" modulus of elasticity does not exist for rock salt. However, an approximation of a modulus of deformation is of interest for purposes of large-scale structural analysis. In this report, approximations of moduli of deformation were calculated by numerical integration of the stress-strain curve over a differential stress range of 0 to 2500 psi. These values were compared to secant calculations which were made by approximating a straight line through data points between 500 and 2500 psi. For a more detailed discussion and representative computations of the various moduli, see Reference 8.

Figure 9 is a plot of six representative triaxial compressive tests conducted at confining pressures of 500, 1000 and 2000 psi and at temperatures of 24 and 100°C. Elevated temperature obviously gives rise to a much higher strain rate and corresponding lower ultimate strength. As a consequence, the deformational modulus at 100°C is approximately one-fourth of the modulus at room temperature. For example, the average secant modulus at room temperature is 0.87×10^6 psi and at 100°C is 0.15×10^6 psi. Average moduli calculated using numerical integration is 0.93×10^6 psi and 0.28×10^6 psi for room temperature and 100°C, respectively.

Table 9 lists values of moduli of deformation determined for salt from five different locations in the U.S. For comparative purposes, the secant values have been used. Lyons salt is on the average the stiffest of the salts from five sites. From the standard deviations listed in Table 9, it is apparent that dome salt is consistent in quality between these three sites and data are reproducible experimentally. The variation in experimental data is reflected by the standard deviation which is greater for SE New Mexico bedded salt than for the dome salt, while Lyons bedded salt data are the most variable. This result is consistent with the physical characterization of the salt (see Section 2.4). Dome salt is normally free of impurities and consists of uniform grains, while salt from these bedded sites contains considerable amounts of impurities and has larger and more variable crystal sizes.

Figure 9 . Differential Axial Stress as a Function of Axial Strain for Triaxial Compression Tests on Lyons Salt at 24°C and 100°C.

TABLE 9

AVERAGE MODULI OF DEFORMATION FOR SALT
FROM VARIOUS LOCATIONS IN THE U.S.

SITE	SALT TYPE	SECANT MODULUS ^a (10 ⁶ psi)
Lyons, KS	Bedded	0.87 ± 0.31
SE New Mexico	Bedded	0.57 ± 0.20 (4,7) ^b
Jefferson Island, LA	Dome	0.42 ± 0.09 (3) ^b
Weeks Island, LA	Dome	0.38 ± 0.11 (5) ^b
Cote Blanche, LA	Dome	0.46 ± 0.05 (6) ^b

- a. Values of modulus were calculated from triaxial compression test data by taking a straight line measurement over an approximately linear portion of the stress-strain curve, usually between differential stress levels of 500 and 2000 psi. All calculations utilized data from the initial stress application, not from cyclic stress applications.
- b. Number in parentheses refer to references given at the end of this report.

Routine triaxial compressive strength tests were conducted by increasing the differential stress level incrementally until the specimen failed or until the test apparatus had stroked to its maximum. During these tests, the confining pressure was held constant. In order to evaluate the behavior of Lyons salt to unload situations as well as response to variable confining pressures, two special tests were conducted. These tests, LSMF-2/6 and LSMF-2/7, were conducted at room temperature. First, the specimens were subjected to a hydrostatic stress state of 500 psi, subsequently loaded to a differential stress level of 1750 psi, then unloaded to the original hydrostatic stress state. The hydrostatic stress state was then increased to 1000 psi, followed by differential stress application to 2250 psi, and unloaded to a 1000 psi hydrostatic stress state. Then, the hydrostatic stress was increased to 2000 psi, followed by differential stress application to 2750 psi and unloaded. The hydrostatic stress was then decreased to 500 psi and the specimen was once again loaded differentially.

Lateral strain was not monitored during these two cyclic load experiments. Axial displacement was monitored by means of an x-y plotter. The resultant stress-strain curve for test LSMF-2/6 is shown in Figure 10. Test LSMF-2/7 tracked these results almost identically. In addition to plotted information, data were periodically printed for key points during the test. As a result of the combined data, the initial secant modulus from a differential stress level of 500 to 2000 psi was 0.45×10^6 psi and 0.64×10^6 psi for LSMF-2/6 and LSMF-2/7, respectively. The unload secant modulus over this interval was 1.47×10^6 psi and 1.61×10^6 psi, respectively. The unload modulus appears to change very little for the subsequent load/unload cycles. The hardened modulus represented by the unload stress-strain response has been observed in previous investigations (5,6,8). Typical magnitudes of the hardened modulus range from 2 to 5 times the initial modulus.

4.2.2. Principal Strain Ratio

The ratio of principal strains, $-\epsilon_2/\epsilon_1$, is routinely measured by two methods. Strain gauges may be used for unconfined tests and volumetric methods for confined tests. However, due to strain gauge susceptibility to error when bonded to coarsely crystalline rock where the gauge length to crystal size ratio is minimal, the volumetric method is more reliable.

Figure 10. Differential Axial Stress as a Function of Axial Strain for Cyclic Triaxial Compression Test on Lyons, Kansas Salt.

For that matter, the unconfined compression experiments which were gauged were not to be used for evaluation of principal strain ratio.

Principal strain ratios for natural rock salt subjected to triaxial compression are nonlinear functions of applied stress and/or axial strain. Initially, at low stresses and strains of $\leq 1.0\%$, the principal strain ratio increases from 0.1 to 0.4, whereupon the ratio approaches 0.5 rather asymptotically. The two plots shown in Figures 11 and 12 depict the variation of principal strain ratio in two different ways. Figure 11 is a plot of the principal strain ratio variation with axial strain. Figure 12 is a plot of volumetric strain ($\Delta V = \epsilon_1 - 2\epsilon_2$) as a function of differential axial stress. These plots are counterparts to the stress-strain curves shown previously in Figure 9 in that they contain similar test conditions.

The effects of temperature and confinement pressure are not discernible from Figure 11. The ratio of principal strains varies in a consistent manner regardless of temperature and confinement within the test regime. Figure 12 shows that elevated temperature gives rise to dilatency ($-\epsilon_2/\epsilon_1 > 0.5$) at a more rapid rate and at notably less differential stress than room temperature. Also, it is apparent from these data, that dilatency at room temperature, occurs at relatively the same differential stress level at two different confining pressures. At elevated temperature, increases in confining pressure appear to retard dilatency.

The phenomenological behavior of lateral strain especially with regard to principal strain ratio variation has been consistent for other natural rock salts tested utilizing these types of apparatus (4,5,6,7,9,15).

4.3. Mohr Envelope of Failure

Of the nineteen compressive strength tests completed in this experimental effort, only seven attained ultimate compressive strength. Of these seven, five were unconfined compression tests; the other two were ambient triaxial compression tests at confining pressures of 500 and 1000 psi. Figure 13 is a Mohr envelope utilizing ultimate strengths determined by indirect tension, unconfined and confined compression at room temperature. The indirect tensile strength data are plotted to represent the stress state within a test specimen at failure.

The Mohr diagram can be fitted with either a linear or nonlinear envelope. A linear envelope fits well to a point of tangency to the stress circle at 500 psi confining pressure. At higher confining pressures, a linear envelope diverges from tangent to the Mohr's circles. Concave envelopes, such as parabolas, are typically derived for rock salt material. As a general comparison, these Mohr's circles in Figure 13 are nearly identical to others determined for various U.S. sites. For example, if a linear envelope is drawn tangent to the tension, unconfined compression and triaxial circle at 500 psi, the angle of internal friction is 55° . This value is nearly identical to values of ϕ determined for Weeks Island salt ⁽⁵⁾.

Figure 14 is a bar chart which depicts the ultimate differential stress at failure for triaxial compression tests at 500 psi confining pressure for rock salt from four locations in the U.S., including Lyons, Kansas. As clearly illustrated, under confinement pressure the strengths are very similar regardless of the original character differences.

Figure 11. Variation of Principal Strain Ratio With Axial Strain During Quasi-static Triaxial Compression Tests on Two-Inch Diameter Specimens of Lyons, Kansas Salt.

Figure 12. Volumetric Strain as a Function of Differential Stress During Quasi-static Triaxial Compression Tests on Two-Inch Diameter Specimens of Lyons, Kansas Salt.

Figure 13. Mohr's Envelope for Lyons Kansas Salt.

FIGURE 14. TRIAXIAL COMPRESSIVE STRENGTH OF BEDDED AND DOMAL SALT ($\sigma_2 = \sigma_3 = 500$ PSI AND ROOM TEMPERATURE).

5. RESULTS OF TRIAXIAL CREEP EXPERIMENTS

A total of fourteen triaxial creep experiments was completed on Lyons salt. Test procedures were described in Section 2.2.4 and a matrix of the creep experiment was listed in Table 3. The creep test procedure involved subjecting the salt specimen to a hydrostatic stress state prior to application of differential axial stress. After the hydrostatic stresses equilibrated, the creep experiment was initiated by quasi-static application of a differential stress to the desired level for creep, whereupon the differential stress was held constant. The stress on the specimen was usually not corrected to account for specimen deformation; tests periodically corrected for strain will be indicated later.

Data were collected by means of printed output in engineering units. The millivolt signals from transducers were amplified, conditioned and calibrated to engineering units. During initial portions of a test, data were collected at a rate of one set of readings per minute. Dependent on the rate of deformation, the time increments between scans were gradually increased. Assembly of data into punched cards was accomplished by hand coding. The card decks were processed on a CDC 3400 computer, which reduced displacement measurements to strains, plotted raw data, and numerically fit the experimental data with power law functions.

This section will discuss the results of the creep experiments from the viewpoint of stress application, axial strain behavior, lateral strain behavior, and comparison to other salt creep results.

5.1. Differential Stress Application to Creep Initiation

During differential stress application, measurements of axial and, when possible, lateral displacements were made. As these data represent limited quasi-static compression tests, the resulting mechanical properties and behavior of the salt are of interest. Table 10 has been compiled to summarize the results obtained during stress application. Table 10 lists the differential axial stress, confining pressure, temperature, and load rates, as well as magnitudes of axial and lateral strain obtained. An estimate of a modulus of deformation is included

for each experiment. This modulus was calculated by numerical integration of the stress strain curve over a differential stress range of 0 to 1500 psi. This bracket of differential stress was selected because a differential stress of 1500 psi is common to all tests. Calculation of moduli of deformation by integration results in values approximately equal to the secant calculation over the same interval.

Five of the experiments were multistage creep tests. Calculation of the moduli for these experiments only encompasses the first stress application.

In general, data listed in Table 10 compare well with data obtained similarly for quasi-static compression tests. A definite trend exists between load rate and modulus of deformation. For instance, room temperature creep experiments which were loaded to creep stress at rates of 200-250 psi/min. resulted in moduli of deformation greater than 1.0×10^6 psi. This compares favorably to quasi-static data (Table 8) where increased load rates increased the calculated modulus. Another trend typical of natural salt illustrated by these applications is a variation in principal strain ratio; initially values are low, 0.2, and increase in a nonlinear fashion approaching 0.5 at axial strains of the order of 2.0 percent. Test LSMF-3/1 is particularly illustrative of this point. At an axial strain of 1.92 percent, the principal strain ratio is 0.41. The other stress applications resulted in axial strains less than 1.0 percent and the corresponding principal strain ratios are 0.3 and less.

TABLE 10

SUMMARY OF TEST RESULTS FOR TRIAXIAL
COMPRESSION TO INITIATE CREEP ON LYONS, KANSAS SALT

TEST I.D.	CONFINING PRESSURE (PSI)	TEST TEMP. (°C)	LOAD RATE (PSI/MIN.)	DIFF. AXIAL STRESS (PSI)	TOTAL AXIAL STRAIN (%)	TOTAL LATERAL STRAIN (%)	AXIAL STRAIN @ 1500 PSI (%)	INTEGRATED MODULUS FROM 0 TO 1500 PSI (10 ⁶ PSI)
LSMF-1/8	500	24	200	1500/3000/4500	0.135	0.021	0.135	1.40
LSMF-2/8	500	100	75	1500/3000	0.488	0.172	0.488	0.50
LSMF-3/1	500	24	250	4500	1.917	0.788	0.187	1.11
LSMF-4/1	500	24	230	3000	0.510	0.166	0.123	1.58
LSMF-3/6	1800/1500/1500	24	---	1700/3000/4500	---	---	---	---
LSMF-3/5	500	70	125	1500	0.251	0.073	0.251	0.82
LSMF-3/8	500	24	95	1500/3000	0.295	---	0.295	0.58

5.2. Axial Strain as a Function of Time

Axial strain data were plotted in terms of strain as a function of time. Axial strain was calculated as engineering strain, i.e. axial displacement divided by original length, L_0 . For multistage tests, L_0 for each stage was taken as specimen length upon initiation of that stage which accounted for previous deformation of the specimen.

Creep data collected were mostly in the transient regime; strain rates decreased with time. These data were accurately fit to an equation of the form:

$$\epsilon_1 = Kt^n \quad (4)$$

where: ϵ_1 = axial strain
 t = time (sec.) ($t \geq 1$ hour)
 K = experimental constant

Evaluation of Equation 4 was accomplished by the method of least squares fitted through plots of $\log_{10}$ axial strain as a function of $\log_{10}$ time. The resultant equation was then used to describe the transient creep response for subsequent calculations of strain magnitudes and rates. An illustrative example of a typical result is shown in Figure 15-A and 15-B. Figure 15-A illustrates $\log_{10}$ strain as a function of $\log_{10}$ time, including the fit of a least squares line. Figure 15-B is a comparison of the axial strain as a function of time calculated from the resultant equation and the raw experimental data.

Table 11 contains a summary of resultant creep data for Lyons salt. A power law of the form of Equation 4 is listed for the transient portions of each test. The individual power laws were used to compute axial creep strains at various times which are listed in Table 12. Two important items should be noted when examining the Tables: (1) only four tests were conducted at elevated temperatures, and (2) differential stresses were adjusted on some of the tests to account for deformation of the specimen.

Figure 15. Typical Results of Curve Fitting Experimental Data.

TABLE 11

SUMMARY OF EXPERIMENTAL AXIAL STRAIN RESULTS FOR LYONS, KANSAS SALT

TEST I.D.	TEST MACH.	TEST TEMP. (°C)	σ_2 (PSI)	$\Delta\sigma$ (PSI)	STAGE OF TEST	DURATION	ϵ_1^* (%)	ϵ_2^* (%)	LEAST SQUARES FIT TO CREEP DATA IN TRANSIENT REGIME	COMMENTS
LSNF-1/8 STG. 1	2	28	500	1500	APP	8 MINS.	0.135	0.021	$\epsilon_1 = 1.176(10^{-5})t^{0.3233}$ $\epsilon_1 = 1.913(10^{-4})t^{0.2863}$ $\epsilon_1 = 2.618(10^{-4})t^{0.3931}$	
LSNF-1/8 STG. 2	2	28	500	3000	CREEP	232 HRS.	0.101	--		
LSNF-1/8 STG. 3	2	28	500	4500	APP	7 MINS.	0.407	0.207		
					CREEP	14 HRS.	1.251	0.500		
LSNF-2/8 STG. 1	1	100	500	1500	APP	7 MINS.	0.844	0.438	$\epsilon_1 = 5.132(10^{-5})t^{0.4881}$ $\epsilon_1 = 2.084(10^{-3})t^{0.3541}$	
					CREEP	114 HRS.	4.433	2.432		
LSNF-2/8 STG. 2	1	100	500	3000	APP	7 MINS.	2.076	0.856		
					CREEP	16 HRS.	16.293	7.938		
LSNF-3/1	1	26	500	4500	APP	18 MINS.	1.917	0.788	$\epsilon_1 = 1.621(10^{-4})t^{0.4687}$	CORRECTED FOR STRAIN
					CREEP	417 HRS.	27.500	19.665		
LSNF-4/1	2	26	500	3000	APP	13 MINS.	0.510	0.166	$\epsilon_1 = 2.773(10^{-5})t^{0.4318}$	
					CREEP	865 HRS.	1.720	0.770		
LSNF-3/6 STG. 1	3	28	1800	1700	APP	190 HRS.	0.103	--	$\epsilon_1 = 6.875(10^{-7})t^{0.5510}$ $\epsilon_1 = 2.030(10^{-4})t^{0.3223}$ $\epsilon_1 = 3.311(10^{-4})t^{0.3818}$	
LSNF-3/6 STG. 2	3	28	1500	3000	CREEP		1.367	--		
LSNF-3/6 STG. 3	3	28	1500	4500	APP		8.059	--		
LSNF-3/5 STG. 1	1	70	500	1500	APP	12 MINS.	0.251	0.073	$\epsilon_1 = 1.401(10^{-5})t^{0.5147}$ $\epsilon_1 = 6.271(10^{-4})t^{0.4188}$	CORRECTED FOR STRAIN
LSNF-3/5 STG. 2	1	70	500	3000	CREEP	96 HRS.	1.017	0.556		
					APP	15 MINS.	1.371	0.669		
					CREEP	105 HRS.	12.498	7.656		
LSNF-3/8 STG. 1	3	24	500	1500	APP	14 MINS.	0.273	--	$\epsilon_1 = 2.064(10^{-4})t^{0.1509}$ $\epsilon_1 = 1.630(10^{-4})t^{0.3806}$	CORRECTED FOR STRAIN
LSNF-3/8 STG. 2	3	24	500	3000	CREEP	143 HRS.	0.146	--		
					APP	13 MINS.	0.773	--		
					CREEP	2800 HRS.	7.720	--		

*Strains in these columns are total strains at test termination.

TABLE 12
AXIAL CREEP STRAIN AT VARIOUS TIMES

TEST I.D.	(PSI)	TEMP. (°C)	LEAST SQUARES EQUATION	AXIAL STRAIN AT VARIOUS TIMES*						
				4 HRS.	12 HRS.	1 DAY	2 DAYS	5 DAYS	10 DAYS	40 DAYS
LSMF-1/8(1)	1500	24	$\epsilon_1 = 1.176(10^{-5})t^{0.3233}$	$2.60(10^{-4})$	$3.71(10^{-4})$	$4.64(10^{-4})$	$5.80(10^{-4})$	$7.80(10^{-4})$	$9.76(10^{-4})$	$(1.53(10^{-3}))$
LSMF-1/8(2)	3000	24	$\epsilon_1 = 1.913(10^{-4})t^{0.2863}$	$2.97(10^{-3})$	$4.06(10^{-3})$	$4.95(10^{-3})$	$6.04(10^{-3})$	$7.86(10^{-3})$	$(9.58(10^{-3}))$	--
LSMF-1/8(3)	4500	24	$\epsilon_1 = 2.618(10^{-4})t^{0.3931}$	0.01116	0.01753	0.02331	0.03100	0.04518	(0.06008)	--
LSMF-2/8(1)	1500	100	$\epsilon_1 = 5.132(10^{-5})t^{0.4881}$	$5.50(10^{-3})$	$9.39(10^{-3})$	0.01318	0.01848	0.02890	(0.04054)	--
LSMF-2/8(2)	3000	100	$\epsilon_1 = 2.084(10^{-3})t^{0.3541}$	0.0618	0.09127	0.11666	0.14911	(0.20626)	--	--
LSMF-3/1(1)	4500	24	$\epsilon_1 = 1.621(10^{-4})t^{0.4687}$	0.01441	0.02412	0.03383	0.04620	0.07098	0.09823	0.18811
LSMF-4/1(1)	3000	24	$\epsilon_1 = 2.773(10^{-5})t^{0.4318}$	$1.73(10^{-3})$	$2.78(10^{-3})$	$3.75(10^{-3})$	$5.06(10^{-3})$	$7.52(10^{-3})$	0.01015	(0.01846)
LSMF-3/6(1)	1700	24	$\epsilon_1 = 6.875(10^{-7})t^{0.5510}$	$1.34(10^{-4})$	$2.46(10^{-4})$	$3.61(10^{-4})$	$5.29(10^{-4})$	$8.76(10^{-4})$	$(1.28(10^{-3}))$	--
LSMF-3/6(2)	3000	24	$\epsilon_1 = 2.030(10^{-4})t^{0.3223}$	$4.44(10^{-3})$	$6.33(10^{-3})$	$7.92(10^{-3})$	$9.90(10^{-3})$	0.01330	(0.01663)	--
LSMF-3/6(3)	4500	24	$\epsilon_1 = 3.311(10^{-4})t^{0.3818}$	0.01281	0.01949	0.02539	0.03309	0.04694	0.06117	(0.10385)
LSMF-3/5(1)	1500	70	$\epsilon_1 = 1.401(10^{-5})t^{0.5147}$	$1.94(10^{-3})$	$3.41(10^{-3})$	$4.87(10^{-3})$	$6.95(10^{-3})$	0.01114	(0.01592)	--
LSMF-3/5(2)	3000	70	$\epsilon_1 = 6.271(10^{-4})t^{0.4188}$	0.03458	0.05479	0.07324	0.09791	(0.14371)	--	--
LSMF-3/8(1)	1500	24	$\epsilon_1 = 2.064(10^{-4})t^{0.1509}$	$8.75(10^{-4})$	$1.03(10^{-3})$	$1.15(10^{-3})$	$1.27(10^{-3})$	$1.46(10^{-3})$	$(1.62(10^{-3}))$	--
LSMF-3/8(2)	3000	24	$\epsilon_1 = 1.630(10^{-4})t^{0.3806}$	$6.23(10^{-3})$	$9.47(10^{-3})$	0.01233	0.01605	0.02275	0.02962	0.05021

* Numbers appearing in parentheses denote data calculated for times beyond termination of the test.

As a consequence of the formerly mentioned experimental variations coupled with a small population of test data, a certain amount of judgement must be exercised in the process of finalizing a creep law to be used in finite element simulations. The following discussion will present results of other experimental efforts in addition to Lyons as well as results on Lyons salt determined by Lomenick (1). Lomenick's tests were conducted on model pillars, while tests in this program were conducted on right circular cylinders. The model pillar specimens were cylindrical with a portion of the center ground out to represent the pillar and surrounding room. Transient test results have been represented by power laws of the form:

$$\epsilon_1 = K t^n \sigma^m T^p \quad (5)$$

where: σ = differential stress (psi)

t = time (seconds)

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

K = empirical constant

Table 13 lists five power laws for salt from sites in the U.S.A. Of these, two have been derived independently for Lyons Salt, two were derived for bedded salt from Southeastern New Mexico, and one for domal salt from Jefferson Island, LA. The empirical power law used by Ratigan and Callahan (17) in finite element simulation of Project Salt Vault has not strictly been a result of experimental work reported herein. In this report, a minimal number of elevated temperature tests were completed which precluded evaluation of a power on temperature. Therefore, the power of 9.5 on temperature as determined by Lomenick (1) was used. This power, 9.5, compares favorably with powers determined for salt from southeastern New Mexico. The power on stress determined for this experimental effort was approximately 3.7 which was considered somewhat high based on results of Lomenick and other experimental efforts listed in Table 13. Therefore, the power on stress was taken as 3.0. The greatest difference between the two empirical laws for Lyons salt as given in Table 13 is the power on time which is 0.4 and 0.3, respectively. For simulation purposes, a power of 0.4 was used as it was comparable to other results listed in Table 13. Finally, the coefficient, K , was chosen to give values for creep strain between the results of Lomenick and the limited experimental results contained in this report.

TABLE 13

EMPIRICAL POWER LAWS FOR TRANSIENT SALT CREEP

SITE	REFERENCE	POWER LAW *	COMMENTS
Lyons, Kansas	1	$\epsilon_1 = 1.1(10^{-38})t^{0.3}\sigma^{3.0}T^{9.5}$	Converted time to seconds
Lyons, Kansas	18	$\epsilon_1 = 5.1(10^{-39})t^{0.4}\sigma^{3.0}T^{9.5}$	Converted time to seconds and Temp. to $^{\circ}K$
SE N. Mexico	4	$\epsilon_1 = 1.7(10^{-39})t^{0.48}\sigma^{2.7}T^{10.2}$	Differential stress not corrected for strain
SE N. Mexico	7	$\epsilon_1 = 1.1(10^{-35})t^{.47}\sigma^{2.5}T^{9.0}$	Differential stress corrected for strain
Jefferson Island, LA	3	$\epsilon_1 = 3.4(10^{-13})t^{.38}\sigma^{2.5}$	Ambient temperature tests

* t = time (sec.)

 σ = differential axial stress (psi)T = temperature ($^{\circ}K$)

Note: Formulation of the transient creep law for Jefferson Island salt does not contain a temperature term since all of the tests were conducted at ambient temperature.

It is felt that tempering the creep law in this fashion provides a reasonable estimate for purposes of simulation by finite element methods. One important consideration which has an influence on the creep behavior during experimental deformation is the effect of sample size. As stated in Reference 1, Section 12.3.5.:

"The width-to-length ratio of salt pillars is an important consideration in predicting mine closure. ... it is seen that pillar shortening proceeds at a faster rate with models having smaller diameter-to-height ratios. Thus pillar strength increases with increasing width-to-height (W/H) ratios. For instance, after 800 hours of testing, it is observed that a W/H = 3 sample deformed . . . approximately 43% more than the W/H = 4 specimen ... The W/H = 2 pillar showed even greater deformation ...; this is 73% more pillar shortening than the W/H = 4 sample after the same period of testing".

Therefore, a specimen, such as tested in this program with a width-to-height ratio of 1/2:1, would be expected to deform more than a specimen having a greater W/H ratio.

As alluded to earlier, formulation of creep strain into a power law for the fourteen tests encompassed in this report was not too successful due to a small population of tests and other factors. However, a reasonable estimate of a creep law—an evaluation of this author—has been used by Ratigan and Callahan ⁽¹⁷⁾ in their finite element simulations. In Figure 16, the simulation law is compared to both Lomenick's power law and a power law derived from the room temperature experiments of this report. The creep law used for simulation of Project Salt Vault ⁽¹⁷⁾ predicts strains between those experimentally determined by Lomenick and this author.

5.3. Lateral Strain as a Function of Time

Lateral strain response was measured during nine of the creep experiments; the remaining five tests were conducted on Machine 3 which does not have a lateral measurement system. Lateral strain was measured volumetrically by means of a servo-control system which also controlled lateral pressure. Lateral strain data were acquired by measuring the turns of a potentiometer in intimate contact with the cylinder of the servo-intensifier. Lateral data acquired were handled in the same manner as axial strain, i.e., first documented and plotted and then fit to equations by the method of least squares.

Figure 16. Comparison of Axial Strain as a Function of Time at Room Temperature for Lyons, Kansas Salt.

(Note: Ambient experiments performed on right circular cylinders while Lomenick's test were performed on model pillars)

Appendix D contains the individual plots of lateral strain as a function of time and $\log_{10}$ lateral strain as a function of $\log_{10}$ time. Collectively, the qualitative shape of the lateral strain curves correspond to the axial strain curves. Similarly, the experimental lateral data lend themselves well to a power law curve fit which expresses lateral strain as a function of time of the form of Equation 4. To summarize the results, Table 14 was prepared which lists test information, a power law equation which fits the transient experimental data, and calculations of principal strain ratios. Principal strain ratio is calculated by dividing the negative of lateral strain by axial strain. As lateral strain is measured on a volumetric basis, it is inherently necessary to maintain a leak-proof system. If a minor leak is discovered after initiation of a test, the lateral strain data will be erroneous. Such was the case in Test LSMF-1/8(1) listed in Table 14, where a high-pressure connection leaked between the vessel and the intensifier system.

Often times, the magnitude of lateral strain is small ($\epsilon_2 < 1.0\%$). This is equivalent to an almost imperceptible volume of confining oil. Apparent leaks in these situations are reflected by a gradual decrease in principal strain ratio, e.g. LSMF-1/8(2), where the leak discovered during the first stage was not completely sealed. However, seven of the nine tests were completely sealed and resulted in consistent and reliable data.

Overall, the amount of data generated in these tests is too small to arrive at definitive conclusions. The majority of the results appears to indicate constant volume deformation, i.e., $-\epsilon_2/\epsilon_1 = 0.5$. Response of lateral strain as a function of time was approximately one-half the magnitude of the magnitude of the axial strain, and the powers on time, t , in the least squares equations are nearly equal between equations for axial and lateral strain.

As noted in Section 5.1., as differential axial stresses were applied, principal strain ratios for the tests trended toward 0.5. As evidenced by the results listed in Table 14, the principal strain ratio is nearly constant for a particular test. In a few cases, principal strain ratio exceeds 0.5 in which case the specimen is undergoing dilatency.

TABLE 14

SUMMARY OF EXPERIMENTAL LATERAL STRAIN RESULTS FOR LYONS, KANSAS SALT

TEST I.D.	$\Delta\sigma$ (PSI)	TEMP. (C.)	LEAST SQUARES ** EQUATION (secs.)	LATERAL STRAINS AT VARIOUS TIMES*					
				4 HRS.	12 HRS.	1 DAY	2 DAYS	5 DAYS	10 DAYS
LSMF-1/8 (1)	1500	24	Not Calculated			(SYSTEM LEAKED)			
PRINCIPAL STRAIN RATIOS									
LSMF-1/8 (2)	3000	24	$\epsilon_2 = 2.210(10^{-4})t^{0.1741} (.96)$	$1.17(10^{-3})$	$1.42(10^{-3})$	$1.60(10^{-3})$	$1.80(10^{-3})$	$2.12(10^{-3})$	$(2.39(10^{-3}))$
PRINCIPAL STRAIN RATIOS				0.38*	0.34	0.31	0.29	0.26	0.24
LSMF-1/8 (3)	4500	24	$\epsilon_2 = 1.436(10^{-4})t^{0.3931} (.99)$	$6.19(10^{-3})$	$9.54(10^{-3})$	0.0125	0.0164	0.0236	(0.0310)
PRINCIPAL STRAIN RATIOS				0.55	0.54	0.54	0.53	0.52	0.52
LSMF-2/8 (1)	1500	100	$\epsilon_2 = 1.567(10^{-5})t^{0.5111} (.99)$	$2.09(10^{-3})$	$3.67(10^{-3})$	$5.23(10^{-3})$	$7.45(10^{-3})$	0.0119	(0.0170)
PRINCIPAL STRAIN RATIOS				0.38	0.39	0.40	0.40	0.41	0.42
LSMF-2/8 (2)	3000	100	$\epsilon_2 = 8.142(10^{-4})t^{0.3759} (.99)$	0.0298	0.0450	0.0584	0.0758	(0.1069)	--
PRINCIPAL STRAIN RATIOS				0.48	0.49	0.50	0.51	0.52	
LSMF-3/1 (1)	4500	24	$\epsilon_2 = 5.641(10^{-5})t^{0.5040} (.99)$	$7.03(10^{-3})$	0.0122	0.0174	0.0246	0.0391	0.0554
PRINCIPAL STRAIN RATIOS				0.49	0.51	0.51	0.53	0.55	0.56
LSMF-4/1 (1)	3000	24	$\epsilon_2 = 1.615(10^{-5})t^{0.4185} (.94)$	$8.88(10^{-4})$	$1.41(10^{-3})$	$1.88(10^{-3})$	$2.51(10^{-3})$	$3.69(10^{-3})$	$4.93(10^{-3})$
PRINCIPAL STRAIN RATIOS				0.51	0.52	0.50	0.50	0.49	0.49
LSMF-3/5 (1)	1500	70	$\epsilon_2 = 4.466(10^{-6})t^{0.5640} (.99)$	$9.89(10^{-4})$	$1.84(10^{-3})$	$2.72(10^{-3})$	$4.02(10^{-3})$	$6.73(10^{-3})$	$9.96(10^{-3})$
PRINCIPAL STRAIN RATIOS				0.51	0.54	0.56	0.57	0.60	0.62
LSMF-3/5 (2)	3000	70	$\epsilon_2 = 2.497(10^{-4})t^{0.4463} (.99)$	0.0179	0.0293	0.0399	0.0543	(0.0818)	--
PRINCIPAL STRAIN RATIOS				0.52	0.53	0.54	0.55	0.57	

* Principal strain ratios decrease which is evidence of a minor leak in the lateral system. This is probably a result of not completely sealing the leak discovered in stage 1 of this experiment.

** Correlation coefficient is denoted in parentheses.

5.4. Discussion

A comparison of the relative flow between two very different types of natural rock salt can be made by comparing results of nearly identical creep experiments. Two example creep experiments which were performed on Machine 2 at differential axial stress levels of 3000 psi on virgin specimens of salt at room temperature are LSMF-4/1 and JI-8/15 (Reference 3). The single difference between these two tests is that LSMF-4/1 and JI-8/15 were confined at pressures of 500 and 1500 psi, respectively. These two experiments have been fit with power laws as follows:

$$\text{LSMF-4/1: } \epsilon_1 = 2.773 (10^{-5}) t^{.4318} \quad (6)$$

$$\text{JI-8/15: } \epsilon_1 = 3.310 (10^{-4}) t^{.3479} \quad (7)$$

where t is in seconds.

Both of these equations fit the respective experimental data with correlation coefficients of 0.99, where 1.00 indicates a perfect linear fit on log-log plots. JI-8/15 was a ten day test which resulted in about 3.8 percent axial strain while LSMF-4/1 continued for 36 days and attained an axial strain of 1.7 percent. Figure 17 is a plot of these equations.

After 10 days subjected to differential stresses of 3,000 psi, the Jefferson Island salt deformed almost four times more than the Lyons salt. If axial strain calculations are extrapolated for one year, the relative difference is a factor of 2.8. It should be noted that the confining stress on the Jefferson Island salt (1500 psi) was greater than the confining stress on the Lyons salt (500 psi). Increased confinement pressure usually retards creep deformation.

Table 15 lists axial creep strains of salt from four different sites in the USA which could be plotted similar to Figure 16. The data are calculated using a power law which was evaluated for each series of tests by multiple regression techniques. Table 15 shows that the Lyons salt deformed considerably less than the other salts which include bedded salt from Southeastern New Mexico.

Figure 17.. Comparison of Similar Creep Experiments on Different Salt at Room Temperature.

TABLE 15

EMPIRICAL POWER LAWS FOR TRANSIENT CREEP OF NATURAL ROCK SALT

SITE	REGRESSION POWER LAW $\epsilon_1 = K t^n \sigma^m T^p$				$\sigma_1 - \sigma_3$ (psi)	TEMP. (°C)	AXIAL STRAINS AT VARIOUS TIMES				
	K	n	m	p			4 HRS.	12 HRS.	2 DAYS	5 DAYS	10 DAYS
ERDA #9	$1.1(10^{-35})$	0.47	2.5	8.97	3,000	22.5	$5.8(10^{-3})$	$9.6(10^{-3})$	0.0184	0.0281	0.0389
ERDA #9	$1.1(10^{-35})$	0.47	2.5	8.97	3,000	100.0	0.0445	0.0743	0.1417	0.2170	--
AEC #7	$1.7(10^{-39})$	0.48	2.7	10.20	3,000	22.5	$6.9(10^{-3})$	0.0116	0.0226	0.0351	0.0490
AEC #7	$1.7(10^{-39})$	0.48	2.7	10.20	3,000	100.0	0.0700	0.1189	0.2312	--	--
LYONS ^(a)	$5.1(10^{-39})$	0.40	3.0	9.50	3,000	22.5	$2.0(10^{-3})$	$3.1(10^{-3})$	$5.3(10^{-3})$	$7.7(10^{-3})$	0.0101
LYONS ^(a)	$5.1(10^{-39})$	0.40	3.0	9.50	3,000	100.0	$6.8(10^{-3})$	0.0266	0.0463	0.0668	0.0881
J.I.	$3.4(10^{-13})$	0.38	2.52	--	3,000	22.5	$7.5(10^{-3})$	0.0114	0.0193	0.0273	0.0355
LYONS ^(b)	$7.2(10^{-16})$	0.40	3.7	--	3,000	22.5	$2.4(10^{-3})$	$3.8(10^{-3})$	$6.6(10^{-3})$	$9.5(10^{-3})$	0.0126

(a) Power law used by Ratigan and Callahan ⁽¹⁷⁾ for simulation of Project Salt Vault using finite element methods.

(b) Ambient temperature power law derived explicitly from ambient temperature experimental results discussed in this report.

Additional examples of the relative strength and deformational behavior of Jefferson Island and Lyons salt are presented in Reference 14. While experimental results are consistent for both quasi-static compression and creep tests, this is not what would be inferred from petrofabric analyses by N. L. Carter (14). An excerpt of Carter's discussion follows:

"On the basis of the fabrics, the LSMF (Lyons) bedded salt would be expected to be the weaker since virtually all crystals have dodecahedral (110) primary slip planes in orientations of very high shearing stress. In fact, as noted above, the LSMF specimens (1/7) deformed dominately by plastic deformation as compared to predominate cataclastic flow for JI-16/9. The only reasonable conclusion remaining, tenable at least to the author, lies in the coarser grain size and more heterogeneous nature.... of the LSMF bedded salt."

Based on Carter's petrofabric work (14) it appears that salt may behave substantially different during experimental deformation than predicted from petrofabric analyses. These differences will most likely occur when salt specimens contain a significant amount of random mineralogical impurities. Experimentally, the behavior of two salts which are very different mineralogically and genetically have also been shown to be similar; e.g., refer to Table 15 and compare Jefferson Island domal salt to ERDA #9 bedded salt. On the basis of physical characterization (Section 2.4.), one would expect dissimilar results; however, as listed in Table 15, the magnitudes of axial strains at various times are comparable.

As evidenced by Carter (14), the deformational mechanisms are influenced by several experimental parameter variations in addition to original fabric. Of these, the most important is elevated temperature, which gives rise to a mechanism of homogeneous plastic deformation. Room temperature tests, on the other hand, reveal that the dominate mode of deformation has been cataclasis. In addition, load rate influences the deformation mechanisms; slower load rates generally allow more plastic flow; faster rates promote cataclastic flow. Further study of petrofabrics of salt from several of the sites mentioned in this report is in progress. This extended investigation will enhance the present knowledge of the deformation mechanisms operative during mechanical tests in order that the flow laws obtained have physical significance.

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APPENDIX APHOTOGRAPHS OF TESTED SPECIMENS

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