TECHNICAL MEMORANDUM REPORT RSI-0059

CASE HISTORY ROCK MECHANICS EXAMINATION OF THE JEFFERSON ISLAND
SALT MINE: III. EVALUATION OF LABORATORY SPECIMEN
DIMENSIONS ON THE UNIAXIAL STRENGTH AND
DEFORMATIONAL CHARACTERISTICS OF DOME SALT

Submitted To

Office of Waste Isolation
Oak Ridge, Tennessee

operated by

Union Carbide Corporation
Nuclear Division

for the
Department of Energy

By

Randall G. Stickney

MASTER

September 27, 1977

(Revised and Resubmitted January 5, 1979)

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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 the 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 an essential part of the overall Rock Mechanics Program.

This report presents the results of a laboratory effort to determine the unconfined strength and elastic properties of dome salt from the Diamond Crystal Mine, Jefferson Island, LA. The effects of sample size and geometry on the compressive properties of this salt were investigated, and relationships for compressive strength and deformational modulus as a function of specimen diameter and length to diameter ratio were developed.

The results of a finite-element analysis of the stress state in a specimen loaded between steel platens are also presented.

The cooperation and assistance provided by the Diamond Crystal Salt Company, and in particular Mr. Theodore J. Nilssen, in securing and transporting the salt core is gratefully acknowledged. The author is indebted to the management and staff of RE/SPEC Inc. for their technical assistance, laboratory assistance, and assistance with the preparation of this report. The author is grateful to the South Dakota School of Mines and Technology and the University of Utah for the use of their testing machines.

The technical contents of this report have been reviewed by Dr. Paul F. Gnirk, Mr. Gary D. Callahan, and Mr. Francis D. Hansen of RE/SPEC Inc, and has been typed by Ms. Julie S. Annicchiarico.

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September 27, 1977

TECHNICAL MEMORANDUM REPORT RSI-0059

TO: Office of Waste Isolation
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Oak Ridge, TN 37830
Attn.: Dr. William C. McClain

FROM: Mr. Randall G. Stickney
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SUBJECT: Case History Rock Mechanics Examination of the Jefferson Island Salt Mine: III. Evaluation of Laboratory Specimen Dimensions on the Uniaxial Strength and Deformational Characteristics of Dome Salt (Union Carbide Corporation, Nuclear Division Subcontract No. 89Y-22303; RSI/001000/FY77).

1. INTRODUCTION

1.1. Statement of the Problem

This experimental program was undertaken in order to determine the quasi-static uniaxial behavior of dome salt from the Jefferson Island Mine. Cylindrical specimens having diameters ranging from 2 to 12 inches and length to diameter ratios from 0.5:1 to 2:1 were tested in unconfined compression at room temperature. A wide range of specimen sizes was used in the testing in order to determine the effect of specimen size on the compressive properties of this salt and to evaluate the uniaxial compressive strength. Specifically, the properties under investigation include the modulus of deformation, principal strain ratio, tensile strength and compressive strength. The tests were also modeled using the finite-element method in order to assess the stress distribution in the specimens during testing. A study has also been conducted by Hansen [1] to evaluate the strength and creep deformation characteristics of Jefferson Island salt at room temperature and elevated confining pressure.

[1] References listed in numerical order at the back of the text.

1.2. Review of Related Work

The standard test used in determining the mechanical properties of mine rock is the compression of a right circular cylinder of the rock. The cylinder is generally placed between steel loading platens and loaded with a uniform compressive stress. The specimen size and shape used for this test procedure have long been a matter of debate among engineers. Experimenters [2-8] have tested prismatic, cubical, and cylindrical specimens of various degrees of slenderness and overall sizes in attempts to evaluate the true mechanical properties of rock and other materials. In general, an increase in compressive strength is noticed for decreasing specimen slenderness (length to diameter ratio). In some cases, the specimen strength is empirically related to the strength of a specimen of the same material having a length to diameter ratio of 1:1.

For tests on marble, limestone, granite and sandstone, Obert, et. al. [3] found that the following equation described the changing strength phenomenon within a few percent of accuracy:

$$C_P/C_C = 0.778 + 0.222 D/h$$

where:

C_C = compressive strength of a cubical specimen ($D/h = 1.0$)

C_P = compressive strength of a specimen having a height different from the diameter or lateral dimension ($D/h \neq 1.0$)

D = diameter or lateral dimension of the specimen

h = height (or length) of the specimen.

From a study of coal, Hustrulid and Swanson [4] found that the following equation accurately described the strength behavior of the coal specimens:

$$C_P/C_C = 0.58 + 0.42 D/h$$

The strength of the coal was also found to have a dependence on specimen diameter for specimens having a length to diameter ratio of 1:1. The following formulation was derived for specimens having diameters ranging from 1 to 12 inches:

$$C_C = \frac{6,399}{\sqrt{D}}$$

Kessler and Murdock [5,6] from tests on concrete also observed increasing strength with decreasing length to diameter ratios. A variance in the strength of concrete of the order of 100 percent was observed between length to diameter ratios of 2:1 and 0.5:1.

Dreyer [7] has conducted extensive testing of rock salt and has observed a specimen strength formula of the following form:

$$C_0 = C_1 (L/D)^{-K} + C_2$$

where:

C_0 = compressive strength of the specimen (psi)

L = length (in.)

D = diameter (in.)

K = constant

C_1 = constant (psi)

C_2 = constant (psi)

One particular rock salt tested by Dreyer yielded the following specimen strength formula:

$$C_0 \text{ (psi)} = 3776 (L/D)^{-0.823} + 1394$$

From tests on potash, Beckman [8] derived the following strength formula:

$$C_0 \text{ (psi)} = 1200 (L/D)^{-1.8} + 3700$$

The curves obtained by Dreyer and Beckman are plotted in Figure 1.1.

The phenomenon of increasing strength with decreasing slenderness is generally attributed to the frictional restraint of the specimen ends by the loading platens. An approximate solution to a uniaxial loading on a cylinder with constrained ends was presented by Filon [9] in 1902. In his solution, no radial displacement along the perimeter of the specimen ends was permitted. However, the solution did not satisfy all of the boundary conditions due to its approximate nature. Pickett [10] presented a solution which allowed no radial displacement at any point on the contact surface, but this condition was not uniquely satisfied by the solution. Balla [11] attempted to improve Filon's solution by permitting variable radial displacement along the ends of the cylinder.

However, his solution gives finite values of shear and radial stresses along the perimeter of the cylinder at the contact surface. Brady [12] has presented an exact solution which satisfies the boundary conditions allowing limited radial expansion of the cylinder ends. Stress concentration ratios obtained from the results of Filon, Pickett, and Balla are plotted in Figure 1.2 for a circular cylinder with $L:D = 1:1$ and a Poisson's ratio of 0.50. Numerical solutions to this problem have also been investigated using the lattice analogy method [13] and finite element analysis [14-16]. The investigation by Pariseau [14] includes an analysis of a diameter mismatch between the cylinder and loading platens. This diameter mismatch is generally the configuration encountered in the uniaxial compression test.

Figure 1.1. Uniaxial Compressive Strength as a Function of L:D Ratio for Potash (Beckman) and White Rock Salt (Dreyer).

Figure 1.2. Stress Concentration Ratios Along the Interface of a Cylinder Loaded Between Rigid End Plates After Filon, Pickett, and Balla. σ_a is Applied Stress on a Cylinder Having $L:D = 1:1$, and Radius = a .

2. TEST PROGRAM

2.1. Test Matrix

The quasi-static testing of Jefferson Island domal salt cores consisted of 128 unconfined compressive strength tests at room temperature. The test specimens were right circular cylinders having nominal diameters of 2, 4, 6, 8 and 12 inches and length-to-diameter (L:D) ratios of 0.5:1, 1:1, 1.5:1, and 2:1. The distribution of tests among each of the diameter and length combinations is shown in Table 1.1. On the average, six specimens were tested for each combination of length and diameter. However, no specimens having an L:D ratio of 0.5:1 and a diameter of 12 inches were tested to failure as a testing machine of adequate capacity (> 600,000 lb.) was not readily available. Approximately 80 percent of the specimens were tested with the use of strain gauges to determine their mechanical properties. Also included in the testing program were indirect tensile strength tests on 52 specimens with approximate L:D ratios of 0.5:1. The number of tests conducted for each sample diameter is also shown in Table 1.1.

TABLE 1.1

TEST MATRIX

DIAM. (IN.) L:D	2	4	6 VERT.*	6 HORIZ.*	8	12
0.5	6	5	4	3	4	1
1	6	7	7	5	6	6
1.5	6	6	6	5	5	6
2	6	5	8	4	5	6
INDIRECT TENSION	17	11	10	1	7	6

* Vertical and Horizontal refer to coring direction; perpendicular and parallel, respectively to the mine floor.

2.2. Sample Collection

All of the samples to be tested were collected during the months of April and May, 1976, by RE/SPEC Inc. personnel on the 1,500 foot level of the Jefferson Island Mine near New Iberia, LA. Core drilling was undertaken at the site selected for in situ stress measurements (entry 3, crosscut J as shown in Figure 2.1). The samples were all obtained from a relatively small area; however, the rock salt in the mine is generally of consistent quality. The salt generally exhibits very little change in appearance or crystal size and the RE/SPEC Inc. field crew judged the salt at the drilling site to be representative of the entire section.

In order that tests could be made to determine whether this particular rock salt exhibits isotropic behavior, 6-inch core specimens were cut both perpendicular to the mine floor and horizontally from the solid rib. Cores were cut from the mine floor using a Truco air-powered masonry drill with a manual rack and pinion advance. With this advance mechanism, optimum drilling pressure could be maintained at all times by the driller. Standard masonry diamond coring bits were used for the coring and no major drilling problems were encountered. Since the use of water as a drilling fluid presents a saturation problem, compressed air was used to remove the drill cuttings from the core hole. Thus, it was possible to obtain a dry and relatively undisturbed core specimen. Upon recovery of the core specimens, they were wrapped in polyethylene and sealed to protect against moisture absorption.

Horizontal specimens were obtained from the site of the in situ stress measurements. Since the borehole deformation gauge requires a 1.5-inch diameter emplacement hole and a 6-inch diameter overcore, it was relatively easy to obtain core of six inches in diameter directly from the test holes. All of the horizontal specimens were cut using a column mounted, air-driven Sullivan diamond drill. The drill has a gear driven advance, powered by the air motor. This advance mechanism, while not as controllable as a hand-feed, proved to work fairly well for coring salt. The horizontal specimens were also cut dry, again using compressed air to remove the drill cuttings.

To insure that no damage occurred to the core as a result of shipment, the core specimens were packed in Styrofoam and shipped by truck to the RE/SPEC Inc. laboratory facilities in Rapid City, South Dakota.

Figure 2.1. 1500 Foot Level of the Jefferson Island Salt Mine Showing the Approximate Sample Collection Site.

2.3. Specimen Preparation

To initiate the specimen preparation procedure, each core was assigned a number and where applicable, the letter V or H to designate core orientation (vertical or horizontal). The core was then cut to obtain specimens with approximate length to diameter ratios of 0.5:1, 1:1, 1.5:1, and 2:1. When more than one specimen was cut from the same core, the resulting specimens were alphabetically classified in the order of cutting. A spring-tensioned drop-arm band saw was used to cut the core. The saw was equipped with a special vise to hold the specimens perpendicular to the saw blade so that parallelism of the specimen ends could be maintained to within one or two degrees.

Specimens having nominal diameters of 2, 4, 6, and 8 inches were finished by hand in an attempt to make the ends of the sample parallel and perpendicular to the sides. An 8-inch mill file was used for this and with judicious use, the specimen ends could be finished to within ± 0.005 inches. While this method was effective, it was a tedious procedure at best.

The specimen preparation procedure was enhanced by the acquisition of a Lagun Model FDV-1 vertical milling machine in the latter stages of the testing program. This machine was used to finish the ends of the remaining specimens and was capable of holding parallelism to less than 0.001 inches across a two foot travel. Both a diamond wheel and a shell mill were used to finish the specimens. The shell mill proved to be the better of the two as the diamond wheel tended to fracture the specimen surface as a result of frictional heat build-up. A rotary speed of 300 RPM produced the best results. No finishing was necessary on the specimen sides.

Strain gauges were applied to most of the specimens tested in unconfined compression. The surfaces of the gauged specimens were prepared using 100-grit sandpaper to smooth the surface in the areas where strain gauges were applied. Sanding worked quite well on the rock salt; however, as small imperfections and voids remained on the specimen surface, a base coat of AE-15 epoxy from Micro-Measurements was used on the first few specimens to smooth the surface. This proved to be ineffective for two reasons. First, this epoxy required at least two days curing time and extensive surface sanding once the base coat had dried. Second, no apparent differences in strain gauge data were observed between specimens prepared with a base coat and those without.

Each specimen was gauged at mid-height with two diametrically opposed axial gauges and two lateral gauges, also diametrically opposed. Three different brands of strain gauges having gauge lengths of 1, 2 and 4 inches were used. These gauges included units from Micro-Measurements, BLH and special high elongation gauges from Magnaflux. From the strain gauge data, it was determined that the gauges from BLH performed with the greatest consistency and thus were used on the majority of the specimens. Three different epoxys were also tried on the first few specimens; AE-15 from Micro-Measurements, EPY-150 from BLH, and RTC from W. T. Bean Inc. The RTC proved to be the best of the three and was used extensively.

The surface of each specimen was marked with alignment marks and cleaned with freon. Four strain gauges were then taped to the surface of the specimen using the alignment marks. The gauges were peeled back one at a time and a liberal coat of epoxy was applied to both the gauge and the specimens surface. The gauges were then applied to the specimen surface and clamped using strips of silicone gum to evenly distribute clamping pressure which was applied using ordinary rubber bands. The epoxy was allowed to cure at least 24 hours before the clamping pressure was removed. At this time, a sealing coat of M-Coat C from Micro-Measurements was applied and the gauges were wired separately in a quarter bridge configuration using equal length lead wires.

Several of the specimens having the smoothest sides were selected for indirect tension tests. These specimens were cut to an approximate length to diameter ratio of 0.5:1 using the band saw. No further preparation of the specimen ends was done since the load is applied along the length of the cylinder in the indirect tension test.

2.4. Testing Equipment and Procedure

2.4.1. Tinius Olsen Machine and Procedure

Quasi-static testing on core specimens having nominal diameters of 2, 4, and 6 inches was accomplished using the 400,000 pound capacity Tinius Olsen testing machine shown in Figure 2.2. The machine is located in the Rock Mechanics Laboratory of the South Dakota School of Mines and Technology. Some of the 8-inch diameter specimens were also tested using this machine.

A Vishay-Ellis VE-20 digital strain indicator and a BLH 10 channel switch and balance unit were used to read the strain gauge data. Also, the Tinius Olsen testing machine has a built-in load cell and deflector-meter connected to an X-Y recorder from which a load-deflection plot was obtained for each test.

The 6-inch and 4-inch specimens were placed in the testing machine between two hardened steel platens which were approximately 7 inches in diameter and 2 inches thick. In order to distribute the load evenly and compensate for any non-parallelism, a 6-inch diameter hemispherical seat was placed between the upper platen and the loading surface of the testing machine. This testing arrangement is depicted in Figure 2.3. Since the Tinius Olsen is not a "stiff" machine, the deflectometer probe was positioned at the steel-salt interface on the upper loading platen to minimize the inherent combined softness of the testing machine and the hemispherical seat. When specimen length was less than four inches, the size of the deflectometer made it necessary to position the probe at the upper loading surface of the machine. This positioning had negligible effect on the load-deflection plots which were obtained for these tests. The 2-inch diameter specimens were placed in the machine in a similar manner to the 6- and 4-inch diameter specimens, using loading platens of 3 inches in diameter and 1-inch thickness in conjunction with a 2-inch diameter hemispherical seat. Special platens having a diameter of 8.25 inches were fabricated for the 8-inch diameter specimens. These platens were used in conjunction with the 6-inch hemispherical seat, using the same load frame configuration that was used for the 6-inch diameter specimens.

In order to accurately read the strain gauge data, a temperature compensating block was prepared for each different type of gauge by applying a gauge of each type to small salt blocks and wiring them in a 1/4 bridge configuration. The compensating blocks were wired in common with all four gauges on each specimen to form four half-bridge, single active-arm strain circuits which were wired to their respective channels on the BLH switch and balance unit. The switch-balance unit was wired to the 1/2 bridge input of the Vishay Ellis strain indicator, which was easily calibrated as it uses internal shunt resistors coupled with the digital display of the strain readout. The error in all strain readings was ± 10 micro-inches/inch, which proved to be adequate for data reduction purposes.

Figure 2.2. Tinius Olsen Testing Machine.

Figure 2.3. Typical Load Frame Configuration.

Initial strain gauge readings were taken and the loading valve of the Tinius Olsen machine was opened to approximately one-eighth of its fully open position. This setting yielded an initial loading rate of about 30 psi/min. It was attempted to hold this rate constant throughout each test with the use of the loading valve. While this does not appear to be excessively difficult, the valve did require constant adjustment throughout the loading range and the machine response became erratic at the higher stress levels. This behavior can in part be explained by the changing strain rate experienced by the specimen in the plastic region; however, the machine operator determined that the Tinius Olsen machine has an inherent tendency to overheat. Therefore, the pump cover was removed and a cooling fan was set in its place. This procedure held the required load rate adjustment to a minimum and thus it was possible to maintain a load rate of 25 to 30 psi/min. Loading the specimen at this rate approximates quasi-static conditions, while at the same time, keeping the duration of each test within reasonable lengths of time.

Dreyer [7] has conducted a series of tests to investigate the effects of loading rate on the compressive behavior of rock salt. Resulting stress-strain curves from this study are shown in Figure 2.4. In general, as the load rate increases, the stress-strain curve becomes more linear and the ultimate strength of the rock salt increases. Based on Dreyer's results, a load rate of 30 psi/min. predicts the quasi-static behavior of rock salt to a fair degree without requiring unreasonable testing times.

Strain gauge data were taken at approximately 75 psi intervals during the test until the gauges failed to operate. Loading, time and strain readings were recorded at all data points. Due to the ease of reading the digital indicator, no modifications of loading rate were made at these 75 psi intervals. The gauges could be read and recorded with such speed that the load varied only about 5 psi during the total reading time. Each specimen was loaded at a constant rate to a stress of approximately 50% of the expected unconfined strength of the specimen. At this point, the load was removed at a slightly higher rate, then reapplied at the original constant load rate to specimen failure. This cycling was done in order to obtain a work-hardened elastic modulus for the salt.

Figure 2.4. Fracture Curve of Halitic Rock Salt under Uniaxial Loading (From Dreyer [7])

2.4.2. 600,000 Pound Testing Machine and Procedure

A 600,000 pound capacity testing machine located in the Mines Building of the University of Utah was used to test the 12-inch diameter specimens and some of the 8-inch diameter specimens. This machine is servo-controlled through a system manufactured by Terra Tek, Inc. of Salt Lake City. The load frame of the machine consists of four columns, a base plate, an upper plate and a hydraulic actuator. The upper testing platen is connected to the upper plate of the load frame and the lower platen is connected to the actuator. Each of the four columns of the machine consists of a center column 3 inches in diameter and a series of hollow outer columns which act as spacers between the two end plates. The outer columns consist of three sections, the middle of which is a load cell. The columns of the machine were pre-loaded in order to increase the stiffness of the machine.

For testing of the 12-inch diameter specimens, a 12-inch square by 2 inch thick platen was placed on the lower platen of the machine. The specimen was centered on the square platen and a matching platen was centered on the top of the specimen. Two DCDT transducers were used to measure the axial deformation of the specimen. These transducers were attached across the two 12-inch platens on opposing sides. Using this arrangement, a small amount of platen deformation was measured in conjunction with specimen deformation; however, comparison of the DCDT data with strain gauge data showed the amount of platen deformation to be negligible as compared with the specimen deformation. Strain gauges were applied to three specimens of each L:D ratio (See Table 1.1) of the 12-inch diameter specimens in order to obtain the principal strain ratio and a comparison of DCDT data to strain gauge data.

Once the specimen was in place in the machine, the strain gauges (if used) were connected in four quarter bridge circuits to the BLH switch and balance unit and the Vishay-Ellis strain indicator. The DCDT transducers were connected in series through a linear amplifier to the horizontal input of an Esterline Angus X-Y recorder. Also, the four load cells were connected in series through a similar amplifier to the vertical input of the X-Y recorder. Calibrations for the load cells and DCDT's were supplied by the University of Utah.

Servo control of the machine could be supplied by feedback from one of the following sources; a large displacement transducer on the actuator, or the DCDT's across the sample, or the column load cells. The DCDT's used for specimen displacement did not have sufficient travel to justify their use as feedback control, and the load cells often caused an unstable feedback signal. Thus, the large displacement transducer on the actuator was used for control.

At the start of the test, the scales of the X-Y recorder and the strain indicator were balanced to read zero load, displacement and strain. The potentiometer which controls machine displacement was then turned to obtain closure of the loading platens which imposed a load on the specimen. The load resulting from platen closure was monitored carefully on the X-Y recorder and the closure rate of the loading platens was adjusted in order to obtain a load rate comparable to that used in earlier tests. This procedure worked well in the early stages of loading where the stress-strain curve is roughly linear. When the test reached a point where axial strain became large in relation to stress (the "knee" in the stress-strain curve), the loading procedure was altered in order to obtain a near quasi-static loading condition by the following procedure. A small amount of displacement was imposed on the machine, which imposed a corresponding load on the specimen. The machine was held at this amount of closure and the load was allowed to relax until stability was established. The specimens were loaded to failure in steps using this relaxation procedure which yielded an average load rate of roughly 15 psi/min. As before, when the specimen was at a load of approximately 50% of its compressive strength, it was unloaded to zero and subsequently reloaded at a slightly faster rate.

Strain gauge readings were taken at approximately 100 psi intervals throughout the test or until the gauges failed to operate. The maximum recordable axial strain was of the order of 1.5 percent.

Using the displacement control, much of the stress-strain curve for the salt was obtained in the post-failure region. Photographs were taken of the specimens at various stages of failure and the load-displacement plots were marked and numbered at the points where each photograph was taken. Appendix B contains the numbered stress-strain curves for most of these tests along with corresponding photographs.

The testing procedure used for the 8-inch specimens was similar to that used for the 12-inch specimens with the following exceptions: 8-inch diameter circular loading platens were used rather than the 12-inch square platens and the 6-inch hemispherical seat was placed between the upper loading platen and the upper plate of the load frame.

3. TEST RESULTS

3.1. Tensile Strength

Tensile strength of the Jefferson Island salt was determined by the Brazilian test procedure which is an indirect test where a line load is applied along the length of a cylinder [2]. The recommended L:D ratio for indirect tension specimens is not less than 0.5:1 and not greater than 1:1; the specimens tested in this program had nominal L:D ratios of 0.5:1.

Tensile tests were performed on the Tinius Olsen machine. The cylinders were placed in the machine with small strips of pasteboard between the salt cylinders and the loading platens of the machine in order to evenly distribute the line load along the cylinders. A load vs. diametral displacement plot was obtained for each test using the Tinius Olsen deflectometer.

The specimens were loaded at a rate of approximately 200 psi/min. Once the ultimate load was reached, the large specimens (4, 6, 8, and 12-inch diameter) broke suddenly and in a fairly straight line across the diameter. However, the 2-inch diameter specimens tended to crush rather than break cleanly. This may be attributed to the large crystal size in relation to the diameter of the 2-inch specimens as tensile separation tended to occur along crystal boundaries. Since failure was not always visible in the 2-inch specimens, the load-displacement curve was monitored as the test progressed. The ultimate load was easily ascertained from this curve as the first significant drop in load. As the diameter of the specimens became large in relation to crystal size, a more linear separation was observed. There was, however, no significant difference in the data obtained from the 2-inch specimens as compared to that obtained from the larger specimens since the mean tensile strength for the 2-inch specimens was within the standard deviation of the other data. Photographs of three representative post-failure tension specimens are shown in Figure 3.1. The irregular breakline of the 2-inch specimen may be compared to the relatively smoother breakline of the larger specimens. A typical load vs. diametral displacement curve is shown in Figure 3.2.

A summary of the results of the indirect tension tests are presented in Table 3.1 and the data are plotted in Figure 3.3. Tensile strength for the Brazilian test procedure is calculated using the following formulation:

Figure 3.1. Three Representative Post-Failure Indirect Tension Specimens.

Figure 3.2. Typical Load vs. Diametral Displacement
Curve for 6" Diameter Jefferson Island Salt.

TABLE 3.1

TENSILE STRENGTH OBTAINED FROM INDIRECT TENSION

TESTS ON JEFFERSON ISLAND DOME SALT

SAMPLE I.D.	L _O (IN.)	D _O (IN.)	F _O (LBS.)	T _O (PSI)	MEAN T _O AND STD. DEV. (PSI)
8/1	1.180	1.970	1025	280.7	224.8* (46)
8/2	0.975	1.950	827	276.9	
8/3	0.795	1.965	513	208.9	
8/7	1.185	1.980	1025	278.1	
8/9A	0.985	1.975	789	258.2	
8/9B	1.250	1.920	907	240.6	
8/10	0.900	1.970	513	184.2	
8/11	1.325	1.980	1143	277.4	
8/12	1.135	1.980	552	156.4	
8/13	1.045	1.940	631	198.1	
8/14	1.150	1.980	986	275.7	
8/16	1.260	1.965	986	253.5	
2/1	1.370	2.140	749	162.6	
2/2	1.290	2.140	867	199.9	
2/3	1.250	2.140	907	215.9	
2/4	1.385	2.140	947	203.4	
2/5	1.550	2.140	789	151.4	
4/1	2.480	4.010	2930	187.6	258.8 (44)
4/2	1.970	4.010	3130	256.1	
4/3	1.970	4.010	3130	252.2	
4/4	2.115	4.020	3620	271.1	
4/5	1.840	4.010	2510	216.6	
4/6	2.100	4.010	3550	268.4	
4/7	2.820	4.010	3300	199.9	
4/8	2.175	4.005	3940	287.9	
4/9	2.075	4.010	4290	328.2	
4/10	2.180	4.015	3630	264.0	
4/11	2.105	4.010	4180	315.3	
1/6V	3.050	5.719	4900	178.8	200.7 (20)
2/6V	2.810	5.719	4300	170.3	
3/6V	2.930	5.719	6300	239.3	
4/6V	2.995	5.719	5840	217.1	
5/6V	2.855	5.719	5000	195.0	
6/6V	2.910	5.719	5300	202.7	
7/6V	2.995	5.719	5630	209.3	
8/6V	3.165	5.719	5590	196.6	
9/6V	3.095	5.719	5590	201.1	
10/6V	3.105	5.719	5000	179.3	
1/6H	3.050	5.719	5970	217.9	

* From Hansen [1]

TABLE 3.1. (CONT'D)

SAMPLE I.D.	L _o (IN.)	D _o (IN.)	F _o (LBS.)	T _o (PSI)	MEAN T _o AND STD. DEV. (PSI)
24/8	2.719	7.594	6,800	209.7	194.5 (34)
10B/8	3.938	7.594	9,650	205.4	
7B/8	3.938	7.594	8,050	171.4	
1/8	2.938	7.594	5,400	154.1	
2/8	3.375	7.594	6,900	171.4	
3/8	3.906	7.594	7,000	150.2	
17/8	4.000	7.594	9,200	192.8	
18/12	5.750	11.625	19,200	182.9	179.3 (24)
30/12	4.934	11.625	17,100	189.8	
8/12	5.125	11.625	17,650	188.6	
5A/12	5.750	11.625	15,700	149.5	
20A/12	5.750	11.625	21,100	201.0	
10/12	6.250	11.625	29,100	254.9	
MEAN TENSILE STRENGTH FOR ALL TESTS					217.3 (45)

Figure 3.3. Indirect Tensile Strengths of Jefferson Island Salt Specimens.

$$T_o = 2F_o / (\pi DL)$$

where T_o is indirect tensile strength, F_o is the ultimate line load, D is the original specimen diameter, and L is the original specimen length. The mean tensile strength for Jefferson Island salt is 217 psi with a standard deviation of 45 psi.

3.2. Axial Compression Properties

3.2.1. Discussion of Stress-Strain Curves

The stress-strain curves obtained in the laboratory are presented in Appendix B. These curves were derived from the load-displacement curves and from the strain gauge data. The stress-strain curves for samples tested with strain gauges were obtained by plotting the incremental stress-strain data for each load step of the test. Axial stress at each increment was obtained by dividing machine load by the area as corrected for change in the cross-sectional area of the specimen due to lateral strain. The following approximate correction was used, which assumes that the salt deforms incompressibly, and strain magnitudes are small:

for a deformed specimen:

$$A = \text{AREA} = \frac{\pi D^2}{4}$$

where $D = D_o + \epsilon_2 D_o$

$$A = \pi/4 (D_o^2 + 2\epsilon_2 D_o^2 + \epsilon_2^2 D_o^2)$$

assume $\epsilon_2 = -.5 \epsilon_1$

$$A = \pi/4 (D_o^2 - \epsilon_1 D_o^2 + .25 \epsilon_1^2 D_o^2)$$

assume $.25 \epsilon_1^2$ negligible

$$A = \pi/4 D_o^2 (1 - \epsilon_1)$$

$$\pi/4 D_o^2 = A_o$$

$$A = A_o (1 - \epsilon_1)$$

$$\sigma_c = P/A$$

$$\sigma = P/A_o$$

$$\sigma_c = P/A_o (1 - \epsilon_1)$$

$$P = \sigma A_o$$

$$\sigma_c = \sigma / (1 - \epsilon_1)$$

where σ_c = corrected axial stress (psi)
 σ = engineering axial stress (psi)
 ϵ_1 = axial strain
 ϵ_2 = lateral strain

Axial and lateral strains were calculated at each load step from both gauge readings. In some instances, the strain gauges malfunctioned and an approximate value for strain was calculated using indirect methods. Stress-strain curves for 12-inch diameter specimens were obtained from the load-displacement plots. The load scale of the plot was divided by the original cross-sectional area of the specimen to obtain stress and the displacement scale was divided by the original specimen length to obtain axial strain. Due to the relatively low states of stress and strain encountered in the uniaxial test, the differences between these curves and the corrected stress-strain curves obtained from the strain gauged specimens were determined to be negligible.

In general, the curves are concave downward exhibiting a plastic-strain hardening behavior with no well-defined initial yield point. Strain hardening behavior is characterized by an increasing stress at each increment of permanent strain. The stress increases in this manner with each load increment until an ultimate load is reached where the salt loses intercrystalline cohesion resulting in a decrease in load bearing capacity.

Some of the curves obtained for the hand-finished specimens (2,4,6, and 8-inch diameter) show large strain increments in relation to the corresponding stress in the initial stages of loading. This early effect is caused by the reaction of the specimen to any nonparallelism or roughness between the specimen ends and the loading platens. Once the platens were sufficiently seated on the specimen ends, the stress-strain response was generally consistent between tests.

The curves obtained for the specimens finished with the vertical mill (12-inch diameter) show a linear relationship between stress and strain in the early stages of loading. A representative stress-strain curve for a 12-inch diameter specimen is shown in Figure 3.4. The initial secant modulus of these curves from 0 to approximately 700 psi was roughly equivalent to the modulus obtained from the unload-reload cycle at 50 percent strength. Initial yield was generally of the order of 700 psi.

When the specimens were unloaded at approximately 50 percent strength, the stress-strain response was roughly linear. Upon subsequent reloading, linear stress-strain response was also observed with a small amount of hysteresis being present. Linear response continued on the reload curve to a stress level roughly equivalent to that attained before unloading. When the specimen was loaded beyond this point, permanent deformation again occurred and the stress-strain response was nearly the same as it was before the specimen was unloaded.

Failure generally occurred at about 3 percent axial strain. As the specimens approached failure, midplane lateral strain became predominant as a pronounced barreling of the specimen was observed. Barreling was accompanied by audible cracking; however, no visible cracking generally appeared until the specimen reached its ultimate load. At this point, multiple vertical cracks developed at the specimen surface followed by a sloughing of the specimen sides. Some of the specimens were taken to total failure which was characterized by continued sloughing of the specimen sides. The sloughing was predominant at the center of the specimen leaving cones of material at the loading platens which gave the failed specimen an "hourglass" shape. Photographs of specimens at various stages of failure are shown in Figure 3.5 as well as in Appendix B.

Much of the post-failure stress-strain curve was obtained for the 12-inch specimens in the following manner. At the first significant drop in load, the failure was arrested by unloading the specimen to a stable load and then reloading the specimen until failure continued. The failure was stabilized in this manner at each significant drop in load. Post-failure curves obtained by this procedure for the 12-inch specimens are presented in Appendix B.

3.2.2. Deformational Modulus and Principal Strain

3.2.2.1. Methods of Calculation

A listing of the properties obtained from the laboratory testing program is contained in Appendix A. The properties listed include measurements of the modulus of deformation, principal strain ratio, and compressive strength.

For a perfectly elastic material, the modulus of elasticity is clearly defined as the proportional ratio of stress to strain. However, for a material which exhibits a nonlinear stress-strain response such as rock salt, the modulus is clearly a nonlinear function of stress. Secant, tangent, and offset are methods commonly used to calculate the modulus of deformation for such nonlinear materials. The secant

Figure 3.4. Representative Stress-Strain Curve for a 12-Inch Diameter Jefferson Island Specimen.

Figure 3.5. Jefferson Island Salt Specimens at Various Stages of Failure.

modulus is defined as the slope of the secant to the stress-strain curve at a corresponding stress or simply σ/ϵ . The tangent modulus is defined as the tangent ($d\sigma/d\epsilon$) to the stress-strain curve at an instantaneous stress. Offset modulus is defined as the secant to the stress-strain curve at some amount of strain (e.g. 0.2 percent is commonly used for metals). The offset procedure was not used to calculate the deformational modulus in this investigation due to the variable strains encountered in the initial portion of the stress-strain curves. An approximate integral modulus can be computed on the basis of mechanical work done per unit volume of the specimen, which is the area under the stress-strain curve [17]:

$$W = \int \sigma_a d\epsilon_1$$

where W is the mechanical work done, σ_a is applied stress and ϵ_1 is axial strain. If linear elasticity is assumed between load steps ($\sigma = E\epsilon$), the integral may be approximated by:

$$\int \sigma_a d\epsilon_1 = E \int \epsilon_1 d\epsilon_1 = \frac{1}{2} E \epsilon_1^2$$

where E is the modulus of deformation. Solving the above equation for E yields:

$$E = \frac{2}{\epsilon_1^2} \int \sigma_a d\epsilon_1$$

For each load increment of the strain gauge tests, the tangent modulus was computed using a central difference method and the integral modulus was computed using the trapezoidal rule for integration as follows:

TANGENT MODULUS:

$$E(i) = \frac{\sigma_a(i+1) - \sigma_a(i-1)}{\epsilon_1(i+1) - \epsilon_1(i-1)}$$

INTEGRAL MODULUS:

$$E(i) \approx \frac{\sum_{J=1}^i [\sigma_a(J) + \sigma_a(J-1)] [\epsilon_1(J) - \epsilon_1(J-1)]}{[\epsilon_1(i)]^2}$$

As discussed in Section 3.2.1, the hand-finished specimens exhibited erratic reactions to platen seating in the initial stages of loading. These effects generally damped out at a stress of approximately 700 psi and the stress-strain curves became roughly linear to approximately 1500 psi where accentuated non-linearity of the stress-strain response was commonly observed. The secant modulus from 700 psi to 1500 psi was computed for the hand-finished specimens in order to obtain an estimation of the initial loading modulus which was independent of the platen seating phenomenon. For the machine-finished specimens (12 in. diam.), the initial loading modulus was computed by fitting a "best fit" line to the load-deflection curve approximately between 700 to 1500 psi. The load and deflection scales were divided by original specimen area and original specimen length, respectively to obtain the stress and strain scales.

Since the salt work hardens (increasing load and elastic limit with each increment of plastic strain), an evaluation of the elastic properties can be obtained by unloading the specimen to zero load and subsequently reloading it. The Jefferson Island specimens were unloaded at approximately 50 percent of their breaking strength and reloaded at a load rate of approximately 30 psi. A tangent to the unloading curve and the reloading curve was computed at each load increment (approximately every 75 psi). With the exception of the extreme end points of the cycle, the tangent to the stress-strain curve was fairly constant, indicating elastic behavior. The tangent moduli were averaged over the unload-reload cycle (excluding the end points of the cycle) to obtain the values presented in Appendix A.

For the specimens tested with strain gauges, the integral modulus based on mechanical work done on the specimen was computed for each load increment. The values reported in Appendix A include an initial modulus and a modulus for the reload cycle. A range of 0 to 1,500 psi was used for these values in order to obtain a comparison with the initial loading secant.

The principal strain ratio was calculated for the unload-reload cycle using the ratio of lateral to axial strain on an incremental basis at each load increment. These incremental values were averaged to obtain the values reported in Appendix A. In order to obtain a comparison of the principal strain ratio, the integral modulus based on area under the stress-

strain curve was computed at each load increment using lateral strain as follows:

$$E_2(i) = \frac{\sum_{J=1}^i (\sigma_a(J) + \sigma_a(J-1)) (\epsilon_2(J) - \epsilon_2(J-1))}{\epsilon_2(i)^2}$$

where σ_a is applied axial stress and ϵ_2 is lateral strain. The principal strain ratio was defined as:

$$\nu \text{ (Integral Basis)} = E_1/E_2$$

since: $E_1 \approx \sigma_1/\epsilon_1$ $E_2 \approx \sigma_2/\epsilon_2$ and $\sigma_2 = \sigma_1$

$$\nu = (\sigma_1/\epsilon_1) / (\sigma_2/\epsilon_2) = \epsilon_2/\epsilon_1$$

where:

E_1 is axial modulus on integral basis

E_2 is lateral modulus on integral basis

The values for the principal strain ratio on an area basis for the 0 to 1500 psi range on the initial and reload cycles are also presented in Appendix A.

3.2.2.2. Results

The mean and standard deviation of the properties obtained are presented in Table 3.2 in order of increasing diameter and decreasing length to diameter ratio. The mean and standard deviation of all the data are also presented. In general, a decrease in elastic modulus was observed with an increase in length to diameter ratio. This behavior was exhibited in the modulus data for all methods of calculations. A "Student t" comparison, which tests the difference in the means of the two sets of data, was performed on the reloading modulus data for the 2:1 specimens. The comparison showed that at an average confidence level of 90% there is no significant change in modulus with varying specimen diameter. A statistically significant change (of the order of 99% confidence) was observed in modulus with changing length to diameter ratio. A least-squares regression of the data is shown in Figure 3.6. The different calculations of modulus show generally the same trend of decreasing modulus with increasing length to diameter ratio. Since the material was similar in all tests, the deformational modulus

TABLE 3.2

MEAN ELASTIC PROPERTIES OF JEFFERSON ISLAND DOME SALT

DIAM. (IN.)	L/D RATIO	MODULUS OF DEFORMATION (MEAN AND STANDARD DEVIATION) (10^6 PSI)				PRINCIPAL STRAIN RATIO (MEAN AND STANDARD DEVIATION) RELOAD CYCLE	
		INITIAL LOADING SECANT 700-1,500 PSI	AVG. TANGENT TO UNLOAD RELOAD CURVE	INTEGRAL MODULUS 0-1,500 PSI		$-\epsilon_2/\epsilon_1$ 0-1,500 PSI	E_1/E_2 (INTEGRAL) 0-1,500 PSI
				INITIAL	RELOAD		
2	2:1	0.403 (0.040)	3.04 (0.48)	0.276 (0.060)	0.864 (0.203)	0.351 (0.032)	0.193 (0.040)
	1.5:1	0.422 (0.092)	3.13 (0.18)	0.204 (0.061)	1.120 (0.310)	0.344 (0.057)	0.269 (0.063)
	1:1	0.958 (0.324)	3.34 (0.45)	0.741 (0.269)	1.260 (0.180)	0.416 (0.123)	0.348 (0.228)
	0.5:1	---	---	---	---	---	---
4	2:1	0.447 (0.057)	3.32 (0.15)	0.651 (0.196)	2.730 (0.340)	0.344 (0.021)	0.299 (0.039)
	1.5:1	0.621 (0.089)	3.45 (0.24)	0.596 (0.152)	2.470 (0.350)	0.346 (0.031)	0.313 (0.048)
	1:1	0.683 (0.145)	3.48 (0.44)	0.981 (0.410)	2.450 (0.670)	0.319 (0.043)	0.288 (0.074)
	0.5:1	0.795 (0.176)	3.88 (0.21)	0.849 (0.262)	2.480 (0.420)	0.247 (0.035)	0.205 (0.045)
6	2:1	0.659 (0.303)	3.25 (0.22)	1.200 (0.611)	2.810 (0.540)	0.334 (0.067)	0.317 (0.079)
	1.5:1	0.629 (0.144)	3.32 (0.34)	1.320 (0.537)	2.710 (0.520)	0.356 (0.098)	0.350 (0.080)
	1:1	0.912 (0.448)	3.64 (0.79)	1.620 (0.675)	3.270 (0.960)	0.343 (0.068)	0.351 (0.071)
	0.5:1	1.270 (0.360)	4.15 (0.47)	2.780 (0.950)	3.680 (0.950)	0.310 (0.910)	0.337 (0.095)
8	2:1	0.485 (0.034)	3.51 (0.10)	0.927 (0.049)	2.430 (0.175)	0.296 (0.007)	0.250 (0.006)
	1.5:1	0.600 (0.174)	3.63 (0.26)	1.080 (0.405)	2.980 (0.679)	0.317 (0.052)	0.308 (0.059)
	1:1	0.815 (0.378)	3.84 (0.16)	1.770 (0.758)	3.160 (0.438)	0.312 (0.036)	0.283 (0.067)
	0.5:1	0.722 (0.019)	3.18 (0.88)	---	---	---	---
12	2:1	2.570 (0.470)	3.15 (0.24)	1.180 (0.190)	2.920 (0.420)	0.403 (0.064)	0.347 (0.038)
	1.5:1	2.770 (0.380)	3.40 (0.36)	1.190 (0.390)	2.620 (0.420)	0.313 (0.014)	0.318 (0.084)
	1:1	2.260 (0.530)	3.78 (0.79)	1.170 (0.740)	2.700 (0.570)	0.329 (0.039)	0.334 (0.196)
	0.5:1	1.650	2.72	1.210	1.740	0.365	0.164
ALL DIAM.	2:1	0.518 (0.161)	3.24 (0.29)	0.830 (0.386)	2.390 (0.830)	0.339 (0.054)	0.285 (0.071)
	1.5:1	0.590 (0.145)	3.34 (0.36)	0.963 (0.559)	2.450 (0.740)	0.341 (0.068)	0.315 (0.073)
	1:1	1.090 (0.670)	3.63 (0.61)	1.340 (0.690)	2.700 (0.970)	0.344 (0.075)	0.322 (0.117)
	0.5:1	1.210 (0.730)	3.86 (0.62)	1.860 (1.260)	3.240 (0.980)	0.293 (0.079)	0.278 (0.104)

Figure 3.6. Dependence of the Modulus of Deformation on the Length to Diameter Ratio for Jefferson Island Dome Salt (Data Points Shown are Average Values for 128 Tests).

should not vary greatly with sample size. However, the decrease in deformational modulus with an increase in length to diameter ratio reflects the fact that due to an elastic mismatch between the sample and the steel loading platens, a triaxial stress state exists in the sample rather than a truly uniaxial state. Based on the tangent to the reload curve, the work-hardened elastic modulus of this salt appears to be of the order of 3.3×10^6 psi. For the 0 to 1500 psi range of the reload cycle, the principal strain ratio for this salt is of the order of 0.33. The principal strain ratio was calculated using $-\epsilon_2/\epsilon_1$. Fairly good agreement of data was obtained for calculations of the principal strain ratio on an integral basis and for the equivalent calculations on the reload cycle.

3.2.3. Unconfined Compressive Strength

A summary of the compressive strengths for the specimens tested are presented in Appendix A. The mean and standard deviations of the data for each diameter and length combination are listed in Table 3.3 in order of increasing diameter and decreasing length to diameter ratio. In all cases, the compressive strength was calculated by dividing the ultimate applied stress by the original specimen area.

Dreyer [7] suggests that the cubical compressive strength of a pure rock salt specimen is dependent on the edge length of the specimen as related to the crystal size. For any unique salt, there is a critical edge length below which the compressive strength falls off sharply. This is due to the fact that below the critical edge length, the number of crystals across the specimen is small such that the specimen finishing process leaves very few undisturbed crystals resulting in a loss in specimen integrity and cohesion. Also, with the crystal size being large in relation to sample diameter, specimens having a uniform distribution of crystal boundaries throughout are not readily obtained.

Figure 3.7. shows Dreyer's results for cubical compressive strength as a function of edge length for a rock salt having a grain density of approximately 25 grains/in.². The mean data for Jefferson Island specimens having a length to diameter ratio of 1:1 are superimposed on Figure 3.7. From a visual inspection, the grain density of the Jefferson Island specimens were estimated to be of the order of 25 grains/in.². Dreyer's results show a critical edge length of approximately 4 inches. The Jefferson Island data are in general agreement with Dreyer's results. The strength of the 2-inch, 1:1 Jefferson Island specimens is of the order of 15 percent

TABLE 3.3

MEAN UNCONFINED COMPRESSIVE STRENGTH
OF JEFFERSON ISLAND DOME SALT

DIAMETER (IN.)	L:D RATIO	MEAN COMPRESSIVE STRENGTHS (PSI)	STANDARD DEVIATION
2	2:1	2,960	322
	1.5:1	3,311	246
	1:1	4,086	200
	0.5:1	6,261	392
4	2:1	3,768	219
	1.5:1	4,124	178
	1:1	4,826	175
	0.5:1	6,935	590
6 (VERT.)	2:1	4,003	210
	1.5:1	4,256	255
	1:1	5,195	326
	0.5:1	8,043	530
6 (HORIZ.)	2:1	4,170	119
	1.5:1	4,644	234
	1:1	5,198	123
	0.5:1	7,516	462
8	2:1	3,392	80
	1.5:1	3,809	176
	1:1	4,495	214
	0.5:1	6,895	483
12	2:1	3,589	364
	1.5:1	3,654	264
	1:1	4,562	314
	0.5:1	-	-
SUMMARY FOR ALL DIAMETERS	2:1	3,632	460
	1.5:1	3,951	483
	1:1	4,730	456
	0.5:1	7,025	775

Figure 3.7. Cubical Compressive Strength as a Function of Edge Length for Rock Salt having a Grain Density of Approximately 25 grains/in.².

lower than the average strength of the other 1:1 Jefferson Island specimens which indicates that a critical edge length of just under 4 inches is roughly correct for this salt.

In other materials, such as coal [4], a decrease in strength is observed with increasing specimen diameter or edge length. This effect is not strongly present in rock salt; however, a slight decrease in the strength data was noticed for the 8 and 12-inch diameter specimens. The strength of these specimens was roughly of the order of 5 to 10 percent lower than the average strength of the 4 and 6 inch specimens for each L:D ratio.

The Jefferson Island salt can be considered largely isotropic as the data for the 6-inch horizontal specimens were consistent with the data for the vertical specimens. Again using a "Student t" comparison at a confidence level of 99%, no difference was detected between the mean strength values for horizontal and vertical 6-inch specimens.

A strong dependence of apparent ultimate strength in relation to the L:D ratio is exhibited by this salt. The experimental strength data are plotted in Figure 3.8. The effect of increasing crushing strength with decreasing L:D ratio is largely due to an elastic mismatch between the steel loading platens and the specimen ends. The theoretical radial expansion of the salt is of the order of 10 times greater than that for steel with the modulus of steel being 30×10^6 psi, the modulus of rock salt about 3×10^6 psi, and the principal strain ratio being roughly equivalent for the two materials. Physically, if no slip is occurring at the salt-steel interface, the radial expansion of the salt is fixed to that of the steel during loading. This phenomenon creates radial stresses in the specimen which act as an "effective" confining pressure. These radial stresses tend to damp out as the distance along the specimen from the loading platens increases. For specimens with a L:D ratio of less than 2:1, the radial stresses exist throughout the specimen and thus a uniaxial stress state is never achieved. It would be expected that as the L:D ratio of the specimen increases, the crushing strength would approach a value which is representative of the true uniaxial compressive strength. This is in general true; however, as specimens become long and slender, buckling tends to occur during loading thus lowering the apparent compressive strength of the specimen.

Figure 3.8. Unconfined Compressive Strength of Jefferson Island Rock Salt.

The following expression was fit to the mean of the experimental data for each L:D ratio using a combination of the least squares method and a graphical approach:

$$C_o = 1318(L:D)^{-1.63} + 3380$$

$$r = 0.998$$

where C_o is compressive strength in psi and r is the correlation coefficient. The data for the 2-inch specimens were excluded from this analyses on the hypothesis that 2 inches is below the critical edge length for a test specimen of Jefferson Island salt. The equation above is plotted in Figure 3.9, which also shows the range and mean of the experimental data.

It should be noted here that the non-uniaxial stress state present in the specimens is not totally a function of the confining effect of the loading platens. Since the loading platens used in this testing effort were not of the same diameter as the test specimens, some stress concentration in the specimens was caused by platen overhang much in the manner that stress concentration in a mine pillar is created by the overburden and the mine opening.

Figure 3.9. Compressive Strength as a Function of L:D Ratio for Jefferson Island Rock Salt.

4. FINITE ELEMENT ANALYSIS

4.1. Input Parameters

A finite element analysis was conducted in order to assess the stress distribution in a cylindrical test specimen loaded between steel loading platens of a larger diameter than the specimen. An analysis was also conducted to determine the effect of the platen-specimen diameter mismatch without elastic mismatch effects. An elastic analysis was conducted for both cases. An existing RE/SPEC axisymmetric finite element program employing eight-noded quadrilateral elements was used for the analysis.

The finite-element model used is shown in Figure 4.1. The model is axially symmetric and also symmetric about a horizontal plane at the mid-height of the specimen. A diameter of six inches was used for the model. L:D ratios of 0.5:1, 1:1, 1.5:1 and 2:1 were obtained by adding or removing elements at the center of the specimen. The model shown in Figure 4.1 is of a specimen having a L:D ratio of 1.5:1. Platen dimensions of two inches thickness and seven inches in diameter were used for all cases. Mesh convergence studies were not made to determine how adequately this mesh represents the stress concentration.

Elastic properties used in the analysis were determined from average test values from the unload-reload cycle for six-inch diameter specimens as $E = 3.28 \times 10^6$ psi and $\nu = 0.333$; where E and ν are Young's modulus of elasticity and Poisson's ratio, respectively. Properties of the steel were assumed to be $E = 30 \times 10^6$ psi and $\nu = 0.290$.

4.2. Properties Mismatch Analysis

For the case of the test specimen loaded between steel platens, an evenly distributed load of 1,000 psi compression was applied along the upper surface of the model. The nodes along the horizontal mid-plane of the specimen were fixed at zero displacement in the z direction and unlimited displacement in the r direction. The node representing the center of the specimen was fixed to zero displacement in both r and z direction. Nodes along the axis were allowed to displace in the z direction only.

At the specimen-platen interface, the assumption is made that no slip occurs between the salt and the steel platens. The radial expansion of the specimen ends is therefore limited to the radial expansion of the loading platens. In order to assess the validity of this assumption, the ratio of shearing stress to axial stress was calculated along the interface.

Figure 4.1. Finite Element Model used for Analysis of Elastic Stress Distribution in a Cylindrical Test Specimen of $L:D = 1.5:1$.

If slip is occurring, this is the definition of the coefficient of sliding friction. Values obtained ranged from 0.01 near the center of the specimen to 0.27 near the perimeter of the specimen. Reported values for the coefficient of sliding friction for metals on stone lie between 0.30 and 0.70 [18]. Assuming that these values are valid for rock salt on steel, the no-slip assumption is essentially correct.

Physically, the perimeter of the specimen end compresses about 15 percent more than the center resulting in a convex appearance of the specimen ends. This phenomenon is largely due to the diameter mismatch between the specimen and the loading platen as the free perimeter of the platen displaces more than the platen center which is compressed by the salt specimen. High stress concentrations at the perimeter of the specimen are the result of the diameter mismatch. The stress conditions along the ends of the specimen are presented in Figure 4.2. In this figure, all stresses are normalized to the applied stress. If evenly distributed, a specimen stress of 1,361 psi corresponds to a stress of 1,000 psi at the platens; therefore, 1,361 psi was used as the applied stress in all calculations. The stress condition at the specimen ends was found to be independent of the L:D ratio of the specimen.

Figure 4.3 shows the stress conditions throughout the specimen for L:D ratios of 2:1, 1.5:1, 1:1, and 0.5:1. The stress concentration presented here is the ratio of "equivalent" stress to the applied stress of 1,361 psi. In this analysis, the assumption was made that the stress state at any point in the specimen is characterized by the octahedral shearing stress [19]:

$$\tau_{\text{oct}} = \frac{1}{3} [(\sigma_z - \sigma_r)^2 + (\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + 6(\sigma_{rz}^2 + \sigma_{r\theta}^2 + \sigma_{\theta z}^2)]^{1/2}$$

where:

- τ_{oct} = octahedral shearing stress
- σ_z = axial stress
- σ_r = radial stress
- σ_θ = tangential stress
- $\sigma_{rz}, \sigma_{r\theta}, \sigma_{\theta z}$ = shearing stresses

a useful expression for equivalent stress is often used and is defined as follows:

Figure 4.2. Stress Concentrations at the Face of a Specimen Compressed Between Platens of Mismatching Diameters (σ_a is Applied Stress, σ_z is Axial Stress, σ_r is radial stress, σ_θ is Tangential Stress, and σ_{rz} is Shearing Stress).

$$\sigma_e = \frac{3}{\sqrt{2}} \tau_{oct}$$

where σ_e is equivalent stress. In the case of a uniaxial stress state where; $\sigma_z = \sigma_1$, $\sigma_r = \sigma_\theta = 0$, the equivalent stress is equal to σ_z .

The confining effect of the steel platens can be viewed in Figure 4.3 for the various L:D ratios. While the region of the specimen which is confined by the loading platens ($\sigma_e/\sigma_a < 1$) is of the same general size for all L:D ratios, the effect of platen confinement becomes pronounced as the L:D ratio of the specimen decreases. Of interest is the fact that the σ_e/σ_a ratio for the 0.5:1 sample is less than one in all regions, except for the periphery of the specimen ends.

4.3. Diameter Mismatch with Matching Properties Analysis

In order to analyze the elastic mismatch effect from the testing configuration, an analysis was made in which the loading platens were given the same properties as the specimen ($E = 3.28 \times 10^6$, $\nu = 0.333$). This configuration roughly corresponds to the room and pillar configuration in a salt mine. Other input parameters were the same as those used in the elastic mismatch analysis. A comparison of the stress conditions at the specimen-platen interface can be viewed in Figure 4.2. While the concentration of vertical stress is nearly equivalent for the two cases, the concentration of radial, tangential and shearing stresses is smaller for the matching properties case. However, the trend of increasing stress with increasing radius for all directional stresses at the ends of the specimen is common to both cases.

Equivalent stress was calculated as before and the stress contours presented in Figure 4.4 for the four L:D ratios. The concentration of stress at the perimeter of the sample ends is nearly the same for both cases; however, the confined region ($\sigma_e/\sigma_a < 1$) is numerically larger for the elastic mismatch case. Also of interest is the area of low stress concentration at the perimeter of the specimens loaded between steel platens. This phenomenon is not present for the case of matching elastic properties. A combination of the above factors indicate that the natural fracturing of the specimen is impeded by the confining effect of steel loading platens. However, due to stress concentration at the perimeter of the specimen ends, the true uniaxial compressive strength of the salt appears to be approximately 1.2 times higher than the crushing strength obtained for laboratory samples having an L:D ratio of 2:1.

(A) $L:D = 2:1$

(B) $L:D = 1.5:1$

(C) $L:D = 1:1$

(D) $L:D = 0.5:1$

Figure 4.3. Distribution of Equivalent Stress Ratio (σ_e / σ_a) in Specimens Loaded Between Steel Platens (Specimen Length is $2b$ (0 at horizontal midplane) and Specimen Diameter is $2a$).

(A) $L:D = 2:1$

(B) $L:D = 1.5:1$

(D) $L:D = 0.5:1$

(C) $L:D = 1:1$

Figure 4.4. Distribution of Equivalent Stress Ratio (σ_e/σ_a) in Specimens Loaded Between Platens of the Same Material as the Specimen with Diameter Mismatch (Specimen Height is $2b$ (0 at horizontal midplane) and Specimen Diameter is $2a$).

4.4. Comparison of Finite Element Results with Actual Tests

In order to check the validity of the finite-element results, a comparison was made to laboratory results from the testing of six-inch diameter specimens. While there is no practical method by which the stress distribution in a laboratory test specimen can be measured, extensive measurements of specimen deformation are made which can be used as a basis of comparison.

The 1,000 psi compressive load on the finite-element model corresponds to a nominal specimen stress of 1361 psi. From the finite-element results for a sample of L:D = 2:1 loaded between steel platens, a total axial strain at the perimeter of the specimen of 405 μ in./in. was indicated. The average axial strain from the test results for 2:1 six-inch specimens was 429 μ in./in. for the reload portion of the unload-reload cycle from 0 to approximately 1,360 psi. The total axial strain from the finite element results for a sample of L:D = 1.5:1 was 397 μ in./in. and the average of the test results for six-inch 1.5:1 specimens was 440 μ in./in. For 1:1 specimens, finite element results gave an axial strain of 394 μ in./in. For 0.5:1 specimens, finite-element results gave an axial strain of 374 μ in./in. with average test results being 370 μ in./in.

Figure 4.5 shows the total radial displacement along test specimens of length = 2b (b is a variable) from the finite-element mismatched properties analysis. Again the increasing confining effect of the steel platens with decreasing L:D ratio is evident. From the test results on the reload cycle from 0 to approximately 1,360 psi for six-inch specimens, the average mid-plane radial displacement of the 0.5:1 specimens was 2.5×10^{-4} in. Average mid-plane radial displacement for L:D ratios of 1:1, 1.5:1, and 2:1 was 4.5×10^{-4} in.

Since fairly good agreement exists between actual test data and the finite-element results, it is felt that the comparative analysis provided realistic information.

4.5. Derivation of an Approximate Pillar Formula

While the laboratory testing arrangement is similar to the pillar arrangement in a mine, the expression for compressive strength as a function of L:D ratio which was derived for laboratory specimens (section 3.2.3.) does not accurately describe pillar behavior. This is because the confining effect of the steel loading platens is magnified as the L:D ratio of the specimen decreases.

Figure 4.5. Total Radial Specimen Displacement for Specimens of Variable Height (h) from Finite Element Data.

An approximate pillar formula can be obtained by modifying the exponential portion of the specimen strength formula $[C_o = 3,380 + 1,318(L/D)^{-1.63}]$. The pillar formula would be of the following form:

$$C_p = 3,380 + (K) 1,318(H/W)^{-1.63}$$

where

C_p = pillar compressive strength in psi

H = pillar height

W = pillar width

K = specimen confinement factor

Exact evaluation of the factor K cannot be determined from this analysis. However, judging from the finite element results, K would be less than 1, say of the order of 0.75. Better estimates of the factor K can be made from the actual testing of model room and pillar arrangements in bench scale experiments. Extensive testing of this type has been conducted by Dreyer [7].

5. SUMMARY AND CONCLUSIONS

The results of an extensive laboratory testing program have been presented in this report. The testing program was undertaken in order to evaluate the uniaxial compressive properties of Jefferson Island dome salt and to investigate the effects of specimen size and geometry on those properties. Jefferson Island salt exhibits a plastic stress-strain response to loading with continuous work hardening in all load ranges. A linear, elastic stress-strain response was observed from a cyclic unloading at 50 percent approximate strength. The following properties were observed from this unloading cycle. The modulus of deformation (average tangent) is of the order of 3×10^6 psi. The principal strain ratio (ϵ_2/ϵ_1) is of the order of 0.3.

The compressive strength of the specimens is described by the following formula:

$$C_o = 3,380 + 1,318(L/D)^{-1.63}$$

The phenomenon of increasing strength with a decreasing L:D ratio is due in part to an elastic mismatch between the salt specimen and the steel loading platens and also in part due to a mismatch between specimen and platen diameters.

The strength of the specimens having a diameter of two inches was approximately 15 percent lower than the average strength of the larger specimens. The lowered strength of the two-inch specimens indicates that for Jefferson Island salt specimens there is a critical diameter below which the test data may not be truly representative. This critical diameter appears to be of the order of four inches.

A finite element analysis was undertaken to assess the stress distribution in specimens loaded between steel platens. The results of this analysis compared well with laboratory data.

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APPENDIX A

COMPRESSIVE PROPERTIES OBTAINED FROM UNIAXIAL
QUASI-STATIC TESTS ON JEFFERSON ISLAND DOME SALT

NOTE: Explanation of the methods of calculations are on pages 30, 31 and 32. In particular, the values listed herein for principal strain ratio were calculated from unload/reload data.

SAMPLE I.D.	LENGTH (IN.)	DIAMETER (IN.)	COMPRESSIVE STRENGTH (PSI)	MODULUS OF DEFORMATION $E \times 10^6$ PSI				PRINCIPAL STRAIN RATIO	
				INITIAL LOADING SECANT (700-1500 PSI)	AVG. TANGENT TO UNLOAD- RELOAD CURVE AT 50% STRENGTH	INTEGRAL MODULUS		RELOAD CYCLE 0-1500 PSI	
						INITIAL LOAD CYCLE 0-1500 PSI	RELOAD CYCLE 0-1500 PSI	$-\epsilon_2/\epsilon_1$	INTEGRAL E_1/E_2
26	4.163	2.139	2950	.332	3.71	.274	.938	-	-
21A	4.148	2.138	3259	.434	3.26	.281	.765	.390	.182
25	4.255	2.138	2813	.406	3.16	.181	.559	.365	.248
22B	4.236	2.141	3167	.436	3.09	.322	1.05	.328	.190
21B	4.272	2.138	2395	-	-	-	-	-	-
22A	4.217	2.139	3172	.409	2.65	.323	1.01	.322	.153
38C	3.230	2.130	3534	.483	3.00	.515	1.36	.339	.265
33C	3.237	2.141	3611	.425	3.00	.390	1.08	.336	.173
30C	3.213	2.141	3250	.287	2.94	.294	.715	.287	.274
27	3.176	2.141	3361	.493	3.07	.193	1.05	.327	.195
28A	3.032	2.141	3167	.463	3.37	.163	1.28	.372	.258
28B	3.220	2.141	2944	.446	3.13	.166	1.44	.388	.349
20B	2.156	2.141	4333	.782	2.68	.727	1.41	.229	.230
23A	2.161	2.141	4333	1.49	3.66	.935	1.09	.353	.197
34A	2.262	2.141	3944	.648	3.78	.337	1.07	.500	.126
38B	2.205	2.139	3868	.869	3.13	.676	1.27	.500	.599
33B	2.197	2.140	4004	.756	2.92	.533	1.02	.437	.551
30B	2.175	2.139	4031	1.00	3.47	1.03	1.47	.500	.590
38A	1.151	2.138	5571	-	-	-	-	-	-
33A	1.102	2.140	6117	-	-	-	-	-	-
30A	1.135	2.140	6561	-	-	-	-	-	-
20A	1.106	2.139	6317	-	-	-	-	-	-
23B	1.180	2.139	6678	-	-	-	-	-	-
34B	1.104	2.138	6323	-	-	-	-	-	-

SAMPLE I.D.	LENGTH (IN.)	DIAMETER (IN.)	COMPRESSIVE STRENGTH (PSI)	MODULUS OF DEFORMATION $E \times 10^6$ PSI				PRINCIPAL STRAIN RATIO	
				INITIAL LOADING SECANT (700-1500 PSI)	AVG. TANGENT TO UNLOAD- RELOAD CURVE AT 50% STRENGTH	INTEGRAL MODULUS		RELOAD CYCLE 0-1500 PSI	
						INITIAL LOAD CYCLE 0-1500 PSI	RELOAD CYCLE 0-1500 PSI	$-\epsilon_2/\epsilon_1$	INTEGRAL E_1/E_2
21	8.000	4.000	3907	.502	3.49	.888	3.20	.336	.353
12	7.934	4.000	3796	.442	3.30	.546	2.39	.370	.276
1	8.000	4.020	3987	.415	3.43	.536	2.73	.330	.288
2A	8.063	4.000	3732	.372	3.28	.453	2.90	.363	.324
15A	7.969	4.020	3419	.505	3.10	.834	2.42	.324	.256
8A	6.000	4.020	4239	.716	3.68	.400	2.92	.381	.385
23B	5.969	4.020	4231	.573	3.42	.520	2.17	.308	.271
19B	6.000	4.015	3942	.608	3.30	.791	2.47	.370	.336
13B	6.000	4.020	3853	.498	3.09	.489	2.12	.324	.299
7B	5.969	4.000	4218	.594	3.73	.632	2.25	.346	.274
24B	5.970	4.020	4262	.735	3.47	.741	2.86	-	-
8B	4.000	4.020	4696	.499	2.90	.630	1.78	.328	.269
19A	3.970	4.020	4743	.693	3.17	.968	2.60	.272	.239
13A	4.000	4.000	4751	.601	3.49	.365	1.84	.291	.266
4B	4.010	4.005	5033	.661	3.46	1.12	3.11	.284	.295
9B	4.050	4.005	5080	.935	4.18	1.46	3.54	.371	.414
4A	4.030	4.005	4612	.702	3.65	.854	2.25	.366	.352
4D	4.010	4.005	4866	1.32	3.45	1.47	2.01	.308	.193
20A	2.075	4.020	6421	.722	3.76	.588	2.20	.228	.162
7A	1.915	4.000	6923	1.03	4.19	1.13	2.86	.287	.237
23A	1.995	4.025	7820	.997	4.11	1.24	2.13	.340	.279
24A	2.015	4.020	6382	.810	3.86	.669	2.03	.262	.171
9A	2.020	4.020	7130	.617	3.72	1.01	2.81	.209	.249

(RSI-0059)

A-3

SAMPLE I.D.	LENGTH (IN.)	DIAMETER (IN.)	COMPRESSIVE STRENGTH (PSI)	MODULUS OF DEFORMATION $E \times 10^6$ PSI				PRINCIPAL STRAIN RATIO	
				INITIAL LOADING SECANT (700-1500 PSI)	AVG. TANGENT TO UNLOAD- RELOAD CURVE AT 50% STRENGTH	INTEGRAL MODULUS		RELOAD CYCLE 0-1500 PSI	
						INITIAL LOAD CYCLE 0-1500 PSI	RELOAD CYCLE 0-1500 PSI	$-\epsilon_2/\epsilon_1$	INTEGRAL E_1/E_2
18VA	11.875	5.750	4024	.669	3.41	1.32	3.22	.298	.275
16VA	12.125	5.719	3621	.682	3.08	1.21	2.82	.421	.418
14VA	12.000	5.750	3847	.464	3.44	.893	2.76	.336	.315
19VB	12.000	5.719	3874	.401	3.48	.581	2.47	.341	.266
17VA	12.063	5.750	4255	.603	3.25	1.03	2.93	.419	.423
20VA	11.938	5.719	4185	.579	3.13	1.88	1.63	.244	.177
11VB	12.063	5.750	4146	.751	3.02	.878	2.47	.403	.379
21VA	12.063	5.719	4070	1.08	2.82	-	-	.230	-
16VB	9.000	5.719	4300	.581	2.79	1.92	1.81	.188	.233
13VA	9.000	5.719	4166	.891	3.31	1.44	2.70	.373	.332
13VB	8.938	5.719	4419	.645	3.63	.882	2.77	.373	.282
20VB	8.938	5.719	4652	.645	3.09	2.37	2.35	.215	.294
11VA	9.000	5.719	3991	.555	3.56	.823	2.57	.312	.303
21VB	8.938	5.719	4010	.579	3.34	.799	2.56	.318	.288
15VB	6.063	5.750	4929	.749	3.33	1.99	2.09	-	-
19VA	5.938	5.719	4594	.656	3.66	.989	2.86	.337	.396
12VB	6.063	5.719	5335	.660	2.17	.409	.409	.284	.245
17VB	5.938	5.719	5508	.708	2.95	2.16	1.95	.338	.432
22VA	6.000	5.719	5353	1.00	4.29	1.94	4.34	.345	.348
22VB	5.938	5.750	5199	1.90	4.54	2.11	4.82	.466	.475
22VC	6.063	5.719	5450	1.512	3.86	2.84	4.01	.288	.344
14VC	3.000	5.750	7510	.813	4.76	1.89	2.64	.411	.345
19VC	2.969	5.689	8427	1.28	3.43	.460	2.64	.162	.210
17VC	2.969	5.719	7670	1.02	4.14	1.74	4.19	.220	.230
22VD	2.906	5.719	8565	3.46	4.56	3.67	5.06	.345	.464

SAMPLE I.D.	LENGTH (IN.)	DIAMETER (IN.)	COMPRESSIVE STRENGTH (PSI)	MODULUS OF DEFORMATION $E \times 10^6$ PSI				PRINCIPAL STRAIN RATIO	
				INITIAL LOADING SECANT (700-1500 PSI)	AVG. TANGENT TO UNLOAD- RELOAD CURVE AT 50% STRENGTH	INTEGRAL MODULUS		RELOAD CYCLE 0-1500 PSI	
						INITIAL LOAD CYCLE 0-1500 PSI	RELOAD CYCLE 0-1500 PSI	$-\epsilon_2/\epsilon_1$	INTEGRAL E_1/E_2
2HA	12.063	5.689	4271	1.38	3.32	2.71	3.62	.303	.291
4HB	12.125	5.750	4275	.559	3.28	.955	3.12	.345	.305
32HA	12.063	5.719	4049	.452	4.76	1.00	7.65	-	-
33HD	12.000	5.719	4088	.288	3.53	.689	3.06	-	-
1H	9.000	5.689	4349	.518	2.95	1.10	2.10	.500	.394
6HB	8.938	5.719	4808	.430	3.08	.897	2.92	.456	.451
5HB	9.000	5.719	4535	.876	3.91	1.97	3.98	.318	.350
6HA	9.000	5.750	4583	.681	3.16	1.24	2.91	.433	.467
33HC	9.000	5.719	4944	.519	2.39	1.11	2.27	.426	.454
6HE	6.000	5.719	5295	.698	3.05	1.38	2.36	.350	.326
5HC	6.000	5.719	5022	.821	3.74	1.45	3.61	.318	.345
32HB	6.000	5.719	5334	.456	4.96	1.04	3.71	-	-
5HA	5.750	5.719	5159	1.12	3.77	2.04	3.72	.266	.253
33HB	6.000	5.750	5180	.460	2.72	1.08	2.53	.440	.353
6HD	2.938	5.689	7715	1.59	3.79	3.71	3.60	.364	.400
6HC	3.000	5.719	7845	1.16	3.91	2.12	3.13	.381	.406
4HA	3.000	5.719	6988	1.77	4.49	3.52	4.53	.286	.303
22	15.313	7.563	3440	.519	3.58	.943	2.65	.293	.251
1	15.188	7.563	3250	.486	3.41	.939	2.49	.288	.256
11	15.125	7.563	3440	.517	3.42	.995	2.21	.304	.243
4	15.188	7.563	3384	.439	3.64	.869	2.30	.293	.256
14	15.313	7.563	3362	.466	3.51	.891	2.51	.303	.246
20	15.250	7.563	3473	.400	2.97	.901	2.05	.333	.336

SAMPLE I.D.	LENGTH (IN.)	DIAMETER (IN.)	COMPRESSIVE STRENGTH (PSI)	MODULUS OF DEFORMATION $E \times 10^6$ PSI				PRINCIPAL STRAIN RATIO	
				INITIAL LOADING SECANT (700-1500 PSI)	AVG. TANGENT TO UNLOAD- RELOAD CURVE AT 50% STRENGTH	INTEGRAL MODULUS		RELOAD CYCLE 0-1500 PSI	
						INITIAL LOAD CYCLE 0-1500 PSI	RELOAD CYCLE 0-1500 PSI	$-\epsilon_2/\epsilon_1$	INTEGRAL E_1/E_2
6	12.000	7.563	3696	.495	3.42	.688	2.50	.321	.328
16	12.031	7.563	3907	.862	3.86	1.70	3.86	.278	.297
24	11.938	7.563	3673	.633	3.71	1.06	2.49	.405	.388
8	11.438	7.563	4074	.611	3.87	1.21	3.58	.291	.306
23	11.375	7.563	3696	.401	3.29	.762	2.49	.289	.223
7A	8.000	7.563	4508	.733	3.97	1.46	2.77	.303	.230
17A	7.938	7.563	4731	.754	3.95	1.44	3.61	.305	.275
26B	8.000	7.563	4608	.443	3.87	1.74	3.05	.319	.265
9	7.563	7.563	4408	1.05	3.66	2.75	3.34	.378	.380
25B	7.563	7.563	4597	1.44	3.95	2.54	3.62	.296	.343
2	7.750	7.563	4119	.469	3.62	.716	2.57	.271	.205
17B	3.915	7.563	7046	.707	3.09	-	-	-	-
21	3.688	7.563	7212	.744	2.35	-	-	-	-
10A	3.688	7.563	6178	.666	5.11	-	-	-	-
25A	3.875	7.563	7143	.715	4.11	-	-	-	-
17	21.781	11.636	4057	3.00	3.13	-	-	-	-
1	22.438	11.622	3540	2.31	3.00	1.03	2.91	.400	.374
3	22.938	11.614	3628	3.00	2.86	1.39	2.51	.341	.303
2	22.000	11.627	3015	2.88	3.53	1.12	3.35	.468	.364
15	22.188	11.658	3846	2.40	3.30	-	-	-	-
27	20.531	11.633	3394	1.84	3.07	-	-	-	-

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SAMPLE I.D.	LENGTH (IN.)	DIAMETER (IN.)	COMPRESSIVE STRENGTH (PSI)	MODULUS OF DEFORMATION $E \times 10^6$ PSI				PRINCIPAL STRAIN RATIO	
				INITIAL LOADING SECANT (700-1500 PSI)	AVG. TANGENT TO UNLOAD- RELOAD CURVE AT 50% STRENGTH	INTEGRAL MODULUS		RELOAD CYCLE 0-1500 PSI	
						INITIAL LOAD CYCLE 0-1500 PSI	RELOAD CYCLE 0-1500 PSI	$-\epsilon_2/\epsilon_1$	INTEGRAL E_1/E_2
32	17.500	11.635	3404	2.85	3.64	1.30	2.48	.297	.253
4	17.656	11.612	3641	2.26	2.81	.761	2.28	.320	.412
25	17.625	11.635	3932	2.59	3.33	1.51	3.09	.322	.288
23	17.531	11.634	3751	3.10	3.70	-	-	-	-
21	17.344	11.633	3910	3.28	5.66	-	-	-	-
6	17.656	11.625	3287	2.53	3.52	-	-	-	-
31B	11.622	11.640	4214	2.54	4.54	-	-	-	-
16B	11.925	11.627	4364	1.56	4.39	-	-	-	-
10	11.920	11.649	4565	2.03	4.26	-	-	-	-
24	11.689	11.640	4934	1.82	2.43	1.03	2.07	.302	.155
20B	11.507	11.631	4347	2.78	3.43	1.98	2.85	.357	.302
5B	11.703	11.638	4947	2.81	3.64	.513	3.18	-	.544
31A	5.691	11.649	-	1.65	2.72	1.21	1.74	.365	.164

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APPENDIX B

UNIAXIAL STRESS-STRAIN CURVES AND
PHOTOGRAPHS FOR JEFFERSON ISLAND SALT SPECIMENS

NOTE: AXIAL STRAIN (NEGATIVE) AND LATERAL
STRAIN (POSITIVE) ARE BOTH DEPICTED
AS POSITIVE STRAIN IN FIGURES B-1
THROUGH B-129.

Figure B-1. Jefferson Island Salt Sample
No. 15, 12-Inch Diameter,
in Various Stages of Failure.

Figure B-2. Jefferson Island Salt Sample No. 15, 12-Inch Diameter, in Various Stages of Failure.

Figure B-3. Stress-Strain Curve for Jefferson Island Salt Sample No. 15, 12-Inch Diameter, L:D = 2:1.

Figure B-4. Jefferson Island Salt Sample No. 27, 12-Inch Diameter, in Various Stages of Failure.

Figure B-5. Jefferson Island Salt Sample No. 27, 12-Inch Diameter, in Various Stages of Failure.

Figure B-6. Stress-Strain Curve for Jefferson Island Salt Sample No. 27, 12-Inch Diameter, L:D = 2:1.

Figure B-7. Jefferson Island Salt Sample No. 25, 12-Inch Diameter, in Various Stages of Failure.

Figure B-8. Jefferson Island Salt Sample No. 25, 12-Inch Diameter, in Various Stages of Failure.

Figure B-9. Stress-Strain Curve for Jefferson Island Salt Sample No. 25, 12-Inch Diameter, L:D = 1.5:1.

Figure B-10. Jefferson Island Salt Sample No. 32, 12-Inch Diameter, in Various Stages of Failure.

Figure B-12. Stress-Strain Curve for Jefferson Island Salt Sample No. 32, 12-Inch Diameter, L:D = 1.5:1.

Figure B-13. Jefferson Island Salt Sample No. 4, 12-Inch Diameter, in Various Stages of Failure.

Figure B-14. Jefferson Island Salt Sample No. 4, 12-Inch Diameter, in Various Stages of Failure.

Figure B-15. Stress-Strain Curve for Jefferson Island Salt Sample No. 4, 12-Inch Diameter, L:D = 1.5:1.

Figure B-16. Jefferson Island Salt Sample No. 23, 12-Inch Diameter, in Various Stages of Failure.

Figure B-17. Jefferson Island Salt Sample No. 23, 12-Inch Diameter, in Various Stages of Failure.

Figure B-18. Stress-Strain Curve for Jefferson Island Salt Sample No. 23, 12-Inch Diameter, L:D = 1.5:1.

Figure B-19. Jefferson Island Salt Sample No. 21, 12-Inch Diameter, in Various Stages of Failure.

Figure B-20. Jefferson Island Salt Sample No. 21, 12-Inch Diameter, in Various Stages of Failure.

Figure B-21. Stress-Strain Curve for Jefferson Island Salt Sample No. 21, 12-Inch Diameter, L:D = 1.5:1.

Figure B-22. Jefferson Island Salt Sample No. 6, 12-Inch Diameter, in Various Stages of Failure.

Figure B-23. Jefferson Island Salt
Sample No. 6, 12-Inch
Diameter, in Various
Stages of Failure.

Figure B-24. Stress-Strain Curve for Jefferson Island Salt Sample No. 6, 12-Inch Diameter, L:D = 1.5:1.

Figure B-25. Jefferson Island Salt Sample No. 24, 12-Inch Diameter, in Various Stages of Failure.

Figure B-26. Jefferson Island Salt
Sample No. 24, 12-Inch
Diameter, in Various
Stages of Failure.

Figure B-27. Stress-Strain Curve for Jefferson Island Salt Sample No. 24, 12-Inch Diameter, L:D = 1:1.

Figure B-28. Jefferson Island Salt Sample No. 20B, 12-Inch Diameter, in Various Stages of Failure.

Figure B-29. Jefferson Island Salt Sample No. 20B, 12-Inch Diameter, in Various Stages of Failure.

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Figure B-30. Stress-Strain Curve for Jefferson Island Salt Sample No. 20B, 12-Inch Diameter, L:D = 1:1.

Figure B-31. Stress-Strain Curve for Jefferson Island Salt Sample No. 22, 8-Inch Diameter, L:D = 2:1.

Figure B-32. Stress-Strain Curve for Jefferson Island Salt Sample No. 1, 8-Inch Diameter, L:D = 2:1.

Figure B-33. Stress-Strain Curve for Jefferson Island Salt Sample No. 11, 8-Inch Diameter, $L:D = 2:1$.

Figure B-34. Stress-Strain Curve for Jefferson Island Salt Sample No. 4, 8-Inch Diameter, $L:D = 2:1$.

Figure B-35. Stress-Strain Curve for Jefferson Island Salt Sample No. 14, 8-Inch Diameter, L:D = 2:1.

Figure B-36. Stress-Strain Curve for Jefferson Island Salt Sample No. 20, 8-Inch Diameter L:D = 2:1.

Figure B-37. Stress-Strain Curve for Jefferson Island Salt Sample No. 6, 8-Inch Diameter, $L:D = 1.5:1$.

Figure B-38. Stress-Strain Curve for Jefferson Island Salt Sample No. 16, 8-Inch Diameter, $L:D = 1.5:1$.

Figure B-39. Stress-Strain Curve for Jefferson Island Salt Sample No. 24, 8-Inch Diameter, $L:D = 1.5:1$.

Figure B-40. Stress-Strain Curve for Jefferson Island Salt Sample No. 8, 8-Inch Diameter, $L:D = 1.5:1$.

Figure B-41. Stress-Strain Curve for Jefferson Island Salt Sample No. 23, 8-Inch Diameter, $L:D = 1.5:1$.

Figure B-42. Stress-Strain Curve for Jefferson Island Salt Sample No. 7A, 8-Inch Diameter, $L:D = 1:1$.

Figure B-43. Stress-Strain Curve for Jefferson Island Salt Sample No. 17A, 8-Inch Diameter, $L:D = 1:1$.

Figure B-44. Stress-Strain Curve for Jefferson Island Salt Sample No. 26B, 8-Inch Diameter, $L:D = 1:1$.

Figure B-45. Stress-Strain Curve for Jefferson Island Salt Sample No. 9, 8-Inch Diameter, L:D = 1:1.

Figure B-46. Stress-Strain Curve for Jefferson Island Salt Sample No. 25B, 8-Inch Diameter, L:D = 1:1.

Figure B-47. Stress-Strain Curve for Jefferson Island Salt Sample No. 2, 8-Inch Diameter, L:D = 1:1.

Figure B-48. Stress-Strain Curve for Jefferson Island Salt Sample No. 10A, 8-Inch Diameter, L:D = 0.5:1.

Figure B-49. Stress-Strain Curve for Jefferson Island Salt Sample No. 2HA, 6-Inch Diameter, L:D = 2:1.

Figure B-50. Stress-Strain Curve for Jefferson Island Salt Sample No. 4HB, 6-Inch Diameter, L:D = 2:1.

Figure B-51. Stress-Strain Curve for Jefferson Island Salt Sample No. 32HA, 6-Inch Diameter, $L:D = 2:1$.

Figure B-52. Stress-Strain Curve for Jefferson Island Salt Sample No. 33HB, 6-Inch Diameter, $L:D = 2:1$.

Figure B-53. Stress-Strain Curve for Jefferson Island Salt Sample No. 1H, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-54. Stress-Strain Curve for Jefferson Island Salt Sample No. 6HB, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-55. Stress-Strain Curve for Jefferson Island Salt Sample No. 5HB, 6-Inch Diameter, L:D = 1.5:1.

Figure B-56. Stress-Strain Curve for Jefferson Island Salt Sample 6HA, 6-Inch Diameter, L:D = 1.5:1.

Figure B-57. Stress-Strain Curve for Jefferson Island Salt Sample No. 33HC, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-58. Stress-Strain Curve for Jefferson Island Salt Sample No. 6HE, 6-Inch Diameter, $L:D = 1:1$.

Figure B-59. Stress-Strain Curve for Jefferson Island Salt Sample No. 5HC, 6-Inch Diameter, $L:D = 1:1$.

Figure B-60. Stress-Strain Curve for Jefferson Island Salt Sample No. 32HB, 6-Inch Diameter, $L:D = 1:1$.

Figure B-61. Stress-Strain Curve for Jefferson Island Salt Sample No. 5HA, 6-Inch Diameter, L:D = 1:1.

Figure B-62. Stress-Strain Curve for Jefferson Island Salt Sample No. 33HB, 6-Inch Diameter, L:D = 1:1.

Figure B-63. Stress-Strain Curve for Jefferson Island Salt Sample No. 6HD, 6-Inch Diameter, L:D = 0.5:1.

Figure B-64. Stress-Strain Curve for Jefferson Island Salt Sample No. 6HC, 6-Inch Diameter, L:D = 0.5:1.

Figure B-65. Stress-Strain Curve for Jefferson Island Salt Sample No. 4HA, 6-Inch Diameter, L:D = 0.5:1.

Figure B-66. Stress-Strain Curve for Jefferson Island Salt Sample No. 18VA, 6-Inch Diameter, L:D = 2:1.

Figure B-67. Stress-Strain Curve for Jefferson Island Salt Sample No. 16VA, 6-Inch Diameter, L:D = 2:1.

Figure B-68. Stress-Strain Curve for Jefferson Island Salt Sample No. 14VA, 6-Inch Diameter, L:D = 2:1.

Figure B-69. Stress-Strain Curve for Jefferson Island Salt Sample No. 19VB, 6-Inch Diameter, $L:D = 2:1$.

Figure B-70. Stress-Strain Curve for Jefferson Island Salt Sample No. 17VA, 6-Inch Diameter, $L:D = 2:1$.

Figure B-71. Stress-Strain Curve for Jefferson Island Salt Sample No. 20VA, 6-Inch Diameter, L:D = 2:1.

Figure B-72. Stress-Strain Curve for Jefferson Island Salt Sample No. 11VB, 6-Inch Diameter, L:D = 2:1.

Figure B-73. Stress-Strain Curve for Jefferson Island Salt Sample No. 16VB, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-74. Stress-Strain Curve for Jefferson Island Salt Sample No. 13VA, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-75. Stress-Strain Curve for Jefferson Island Salt Sample No. 13VB, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-76. Stress-Strain Curve for Jefferson Island Salt Sample No. 20VB, 6-Inch Diameter, $L:D = 1.5:1$.

Figure B-77. Stress-Strain Curve for Jefferson Island Salt Sample No. 11VA, 6-Inch Diameter, L:D = 1.5:1.

Figure B-78. Stress-Strain Curve for Jefferson Island Salt Sample No. 21VD, 6-Inch Diameter, L:D = 1.5:1.

Figure B-79. Stress-Strain Curve for Jefferson Island Salt Sample No. 15VB, 6-Inch Diameter, $L:D = 1:1$.

Figure B-80. Stress-Strain Curve for Jefferson Island Salt Sample No. 19VA, 6-Inch Diameter, $L:D = 1:1$.

Figure B-81. Stress-Strain Curve for Jefferson Island Salt Sample No. 12VB, 6-Inch Diameter, $L:D = 1:1$.

Figure B-82. Stress-Strain Curve for Jefferson Island Salt Sample No. 17VB, 6-Inch Diameter, $L:D = 1:1$.

Figure B-83. Stress-Strain Curve for Jefferson Island Salt Sample No. 22VA, 6-Inch Diameter, L:D = 1:1.

Figure B-84. Stress-Strain Curve for Jefferson Island Salt Sample No. 22VB, 6-Inch Diameter, L:D = 1:1.

Figure B-85. Stress-Strain Curve for Jefferson Island Salt Sample No. 22VC, 6-Inch Diameter, $L:D = 1:1$.

Figure B-86. Stress-Strain Curve for Jefferson Island Salt Sample No. 14VC, 6-Inch Diameter, $L:D = 0.5:1$.

Figure B-87. Stress-Strain Curve for Jefferson Island Salt Sample No. 19VC, 6-Inch Diameter, L:D = 0.5:1.

Figure B-88. Stress-Strain Curve for Jefferson Island Salt Sample No. 17VC, 6-Inch Diameter, L:D = 0.5:1.

Figure B-89. Stress-Strain Curve for Jefferson Island Salt Sample No. 22VD, 6-Inch Diameter, $L:D = 0.5:1$.

Figure B-90. Stress-Strain Curve for Jefferson Island Salt Sample No. 21, 4-Inch Diameter, $L:D = 2:1$.

Figure B-91. Stress-Strain Curve for Jefferson Island Salt Sample No. 12, 4-Inch Diameter, L:D = 2:1.

Figure B-92. Stress-Strain Curve for Jefferson Island Salt Sample No. 1, 4-Inch Diameter, L:D = 2:1.

Figure B-93. Stress-Strain Curve for Jefferson Island Salt Sample No. 2A, 4-Inch Diameter, L:D = 2:1.

Figure B-94. Stress-Strain Curve for Jefferson Island Salt Sample No. 15A, 4-Inch Diameter, L:D = 2:1.

Figure B-95. Stress-Strain Curve for Jefferson Island Salt Sample No. 8A. 4-Inch Diameter, $L:D = 1.5:1$.

Figure B-96. Stress-Strain Curve for Jefferson Island Salt Sample No. 23B, 4-Inch Diameter, $L:D = 1.5:1$.

Figure B-97. Stress-Strain Curve for Jefferson Island Salt Sample No. 19B, 4-Inch Diameter, $L:D = 1.5:1$.

Figure B-98. Stress-Strain Curve for Jefferson Island Salt Sample No. 13B, 4-Inch Diameter, $L:D = 1.5:1$.

Figure B-99. Stress-Strain Curve for Jefferson Island Salt Sample No. 7B, 4-Inch Diameter, $L:D = 1.5:1$.

Figure B-100. Stress-Strain Curve for Jefferson Island Salt Sample No. 24B, 4-Inch Diameter, $L:D = 1.5:1$.

Figure B-101. Stress-Strain Curve for Jefferson Island Salt Sample No. 8B, 4-Inch Diameter, $L:D = 1:1$.

Figure B-102. Stress-Strain Curve for Jefferson Island Salt Sample No. 19A, 4-Inch Diameter, $L:D = 1:1$.

Figure B-103. Stress-Strain Curve for Jefferson Island Salt Sample No. 13A, 4-Inch Diameter, $L:D = 1:1$.

Figure B-104. Stress-Strain Curve for Jefferson Island Salt Sample No. 4B, 4-Inch Diameter, $L:D = 1:1$.

Figure B-105. Stress-Strain Curve for Jefferson Island Salt Sample No. 9B, 4-Inch Diameter, $L:D = 1:1$.

Figure B-106. Stress-Strain Curve for Jefferson Island Salt Sample No. 4A, 4-Inch Diameter, $L:D = 1:1$.

Figure B-107. Stress-Strain Curve for Jefferson Island Salt Sample No. 4D, 4-Inch Diameter, $L:D = 1:1$.

Figure B-108. Stress-Strain Curve for Jefferson Island Salt Sample No. 20A, 4-Inch Diameter, $L:D = 0.5:1$.

Figure B-109. Stress-Strain Curve for Jefferson Island Salt Sample 7A, 4-Inch Diameter, L:D = 0.5:1.

Figure B-110. Stress-Strain Curve for Jefferson Island Salt Sample No. 23A, 4-Inch Diameter, L:D = 0.5:1.

Figure B-111. Stress-Strain Curve for Jefferson Island Salt Sample No. 24A, 4-Inch Diameter, L:D = 0.5:1.

Figure B-112. Stress-Strain Curve for Jefferson Island Salt Sample No. 9A, 4-Inch Diameter, L:D = 0.5:1.

Figure B-113. Stress-Strain Curve for Jefferson Island Salt Sample No. 26, 2-Inch Diameter, $L:D = 2:1$.

Figure B-114. Stress-Strain Curve for Jefferson Island Salt Sample No. 21A, 2-Inch Diameter, $L:D = 2:1$.

Figure B-115. Stress-Strain Curve for Jefferson Island Salt Sample No. 25, 2-Inch Diameter, L:D = 2:1.

Figure B-116. Stress-Strain Curve for Jefferson Island Salt Sample No. 22B, 2-Inch Diameter, L:D = 2:1.

Figure B-117. Stress-Strain Curve for Jefferson Island Salt Sample No. 22A, 2-Inch Diameter, L:D = 2:1.

Figure B-118. Stress-Strain Curve for Jefferson Island Salt Sample No. 38C, 2-Inch Diameter, L:D = 1.5:1.

Figure B-119. Stress-Strain Curve for Jefferson Island Salt Sample No. 33C, 2-Inch Diameter, $L:D = 1.5:1$.

Figure B-120. Stress-Strain Curve for Jefferson Island Salt Sample No. 30C, 2-Inch Diameter, $L:D = 1.5:1$.

Figure B-121. Stress-Strain Curve for Jefferson Island Salt Sample No. 27, 2-Inch Diameter, $L:D = 1.5:1$.

Figure B-122. Stress-Strain Curve for Jefferson Island Salt Sample No. 28A, 2-Inch Diameter, $L:D = 1.5:1$.

Figure B-123. Stress-Strain Curve for Jefferson Island Salt Sample No. 28B, 2-Inch Diameter, $L:D = 1.5:1$.

Figure B-124. Stress-Strain Curve for Jefferson Island Salt Sample No. 20B, 2-Inch Diameter, $L:D = 1:1$.

Figure B-125. Stress-Strain Curve for Jefferson Island Salt Sample No. 23A, 2-Inch Diameter, L:D = 1:1.

Figure B-126. Stress-Strain Curve for Jefferson Island Salt Sample No. 34A, 2-Inch Diameter L:D = 1:1.

Figure B-127. Stress-Strain Curve for Jefferson Island Salt Sample No. 38B, 2-Inch Diameter, L:D = 1:1.

Figure B-128. Stress-Strain Curve for Jefferson Island Salt Sample No. 33B, 2-Inch Diameter, L:D = 1:1.

Figure B-129. Stress-Strain Curve for Jefferson Island Salt Sample No. 30B, 2-Inch Diameter, L:D = 1:1.