TECHNICAL MEMORANDUM REPORT RSI-0063

PETROFABRIC ANALYSIS OF THE DEFORMATIONAL BEHAVIOR
OF LYONS, KS AND JEFFERSON ISLAND, LA ROCK SALT

Submitted To

*Office of Waste Isolation
Oak Ridge, Tennessee*

operated by

*Union Carbide Corporation
Nuclear Division*

for the

Department of Energy

By

*Neville L. Carter
Staff Consultant*

December 15, 1977

(Revised and Resubmitted on August 28, 1978)

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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 an essential part of the overall Rock Mechanics Program.

This report summarizes the results obtained from a series of petrofabric analyses of deformed and undeformed salt specimens. The specimens were originally obtained from a bedded salt mine near Lyons, Kansas where Project Salt Vault was conducted and from an operating salt mine in a domal salt formation at Jefferson Island, LA. Specimens from each site were tested in quasi-static triaxial compression and triaxial creep at RE/SPEC Inc. Subsequently, specimens which exhibited representative macroscopic deformational characteristics were selected for these fabric studies. The purpose of the petrofabric studies is to assist in developing a fundamental physical understanding of the mechanical results. Undeformed specimens were examined by optical techniques to determine preferred crystal orientations. Deformed specimens were studied by petrofabric techniques in order to characterize the deformational mechanisms. Finally, the results of the petrofabrics are compared to the mechanical data.

The technical contents of this report have been reviewed by Dr. Paul F. Gnirk and Mr. Francis D. Hansen, and the manuscript was typed by Ms. Julie S. Annicchiarico.

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August 28, 1978

TECHNICAL MEMORANDUM REPORT RSI-0063

TO: Office of Waste Isolation
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Oak Ridge, TN 37830

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

FROM: Dr. Neville L. Carter
Staff Consultant
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Rapid City, SD 57701

SUBJECT: Petrofabric Analysis of the Deformational Behavior of Lyons, KS
and Jefferson Island, LA Rock Salt (Union Carbide Corporation,
Nuclear Division Subcontract NO. 89Y-22303; RSI/001000/FY78).

1. INTRODUCTION

In order to obtain a fundamental physical understanding of mechanical results of tests on any material, it is necessary first to determine the nature of the deformational processes. To this end, the author has analyzed selected specimens from Lyons, KS bedded salt and Jefferson Island, LA domal salt deformed experimentally in various modes under the direction of F. D. Hansen of RE/SPEC Inc.. Undeformed, as-cored material was first examined carefully by optical techniques, and preferred crystal orientations (fabrics) were determined using universal stage techniques. A similar procedure was used for the most highly deformed specimens to assess changes in fabric induced by deformation, and petrographic techniques were used to determine the nature of the deformation. All specimens deformed to intermediate axial strains were analyzed carefully by petrographic techniques alone which are sufficient to characterize the deformation mechanisms, as will be detailed below. Finally, the results of these analyses have been correlated with the mechanical data of Hansen and have

thus provided a sound physical basis for interpretation of these data. The correlation so obtained should contribute in an important way to attempts at finite-element code modeling of the time-dependent behavior of excavations in rock salt as related to the disposal of radioactive waste.

2. EXPERIMENTS ON LYONS AND JEFFERSON ISLAND ROCK SALT

Tests of various sorts, to be summarized below, were performed by Hansen on two-inch diameter by four-inch long cores of Jefferson Island Louisiana (J.I.) domal salt and on Lyons, Kansas (LSMF)* bedded salt. J.I. salt is very clean in appearance, although small needles of anhydrite are scattered throughout but generally occur along halite grain boundaries. The grain size is somewhat variable but averages about 0.25 inch diameter, a relatively fine grainsize for rock salt. The fabric of undeformed J.I. salt, as determined for 100 crystals in two thin sections is shown in Figure 1A. Crystal orientations were determined by measuring normals to cleavage planes induced during the thin-sectioning process. This new procedure, developed in the course of the present study, involves creating straight, sharp cleavages, such as those shown in Figure 2A, during mechanical grinding; internal deformations of crystals are not normally produced by this method. It is then a simple though tedious matter, using universal stage techniques, to measure two sets of cleavages for each crystal and then construct graphically the third a-axis, thereby obtaining the complete orientation of the crystal.

The fabric pattern of Figure 1A indicates a very weak preferred crystal orientation in undeformed J.I. dome salt. This is in marked contrast to the very strong orientations commonly found for domal salts analyzed to date (Muehlberger and Clabaugh, 1968; Schwerdtner, 1968). This result is also contrary to that found in a similar manner for undeformed LSMF bedded salt (Figure 1B). In that specimen, there is a very strong concentration of a-axes parallel to the core axis (vertical) with a girdle of a-axes in a plane normal to it. It should be expected that these very different fabrics for J.I. and LSMF salt might have a profound effect on the mechanical properties of these materials. However, LSMF salt also differs from J.I. salt in that it is appreciably coarser-grained (0.4 inch average diameter) and is considerably more impure (apparent concentrations of clays in layers) which could also affect the mechanical results.

* The Kansas salt was obtained from the Lyons Salt Mine Floor and is hereinafter referred to as LSMF salt.

Figure 1. Fabrics of Halite Specimens. Contours in Intervals of One Percent per One Percent Area. Lower Hemisphere, Equal-Area Projections. Core Axes are Vertical.

A. J.I. 16/10 - Undeformed. 300 a-axes in 100 Grains.

B. LSMF 2/15 - Undeformed. 162 a-axes in 54 Grains.

C. J.I. 16/9. Deformed at 25°C, 500 psi Confining Pressure at a Stress Rate of 450-500 psi/min. to a Maximum Stress of 7500 psi and a Strain of 24.3%. 75 a-axes in 25 Grains.

D. LSMF 3/1. Deformed in Creep at 25°C and 500 psi Confining Pressure at a Stress Difference of 4500 psi to 27.5% Strain. 75 a-axes in 25 Grains.

A Undeformed J.I. Cleaved During Sectioning Process.

0.25 mm

B

0.5 mm

LSMF 3/1. Intense Shear Zone Associated with Photoelastic Lamellae (ENE-Trending).

C

1.0 mm

LSMF 1/7. Intense Photoelastic Effects at Early-Formed Cleavages and Faint Photoelastic Lamellae (N-S).

Figure 2. Photomicrographs of Halite Specimens Under Crossed Polarizers.

The materials described above have been deformed by Hansen in quasi-static compression and in creep modes at various confining pressures to variable axial strains, mainly at 25°C although a few tests have been carried out to 100°C on LSMF salt. For J.I. salt, confining pressures have ranged from 14.5 to 2000 psi with axial stress differences, in compressive creep tests of 5 to 10 days duration at 1500 psi confining pressure, ranging from 1500 to 6000 psi (Hansen, 1977a). Most of the tests on LSMF salt were carried out in uniaxial or triaxial compression at confining pressures ranging from 14.5 to 5000 psi (Hansen, 1977b). In addition, indirect tensile strength tests were conducted on many specimens of both materials yielding an average tensile strength of 225 psi for J.I. salt (Hansen, 1977a) and of 115 psi for LSMF salt (Hansen, 1977b).

All of the specimens tested in triaxial compression and in creep for both materials deformed in the transient creep regime; steady state flow was not achieved even in the few experiments at elevated temperature. Most of the specimens deformed homogeneously, and those selected for the present analysis are shown in Figure 3. The cores have been sawed into half-cylinders and are arranged, from left to right, in order of increasing strain; undeformed cores are not shown. Segregated impurities in the LSMF salt (top) are evident as is the coarser grain size. Specimens shown on the left of the photograph have been shortened by about 13 percent and those shown at the extreme right, by about 26 percent. The highly deformed LSMF specimen 3/1 has a uniform barrel shape, but the center of the specimen has a milky, broken, cataclastic appearance. The shape of the highly strained J.I. specimen 16/9 is less uniform and a diagonal through-going fault (upper left to lower right) is evident in the specimen.

Figure 3. Photograph of Half-Cylinders of Deformed Lyons and Jefferson Island Halite. Shortening increases to Right from about 13% to about 26%. Note Through-going Fault in J.I. 16/9.

JEFFERSON ISLAND DOME SALT

LYONS, KANSAS BEDDED SALT

3. DEFORMATION MECHANISMS

Thin sections were cut from the centers of all specimens shown in Figure 3 and the details of careful petrographic analyses of these sections are given in the appendix; only the main results will be summarized here. A summary of data pertaining to the specimens as reported herein is given in Table 1. Table 1 itemizes for each specimen the type of test conducted, the stress rates or differential stresses applied, temperature, confinement pressure and comments on petrofabrics. The two most highly strained specimens, LSMF 3/1 and J.I. 16/9 were selected for fabric analysis as, if crystal rotations are appreciable during deformation, they should be most marked in these specimens. Two thin sections were prepared from the central, most highly strained areas of both specimens but were of rather poor quality because of the fractured nature of the material. Accordingly, it was possible to measure far fewer crystals than for the undeformed specimens. Nonetheless, the fabric for J.I. 16/9 is presented in Figure 1C and that for LSMF 3/1 in Figure 1D. The fabric for J.I. 16/9 is still essentially random, the 5 percent maximum shown having little statistical significance for so few crystals. The fabric of LSMF 3/1 is appreciably weaker than the starting material (Figure 1B) and this is ascribed mainly to mechanical rotations along fractures. Thus, apart from such mechanical rotations, which are reasonably minor in both materials, there appears to be no major crystal reorientation due to plastic flow. Actually, such major reorientations would not be predicted for strains lower than about 60 percent for ductile behavior (Schwerdtner, 1968).

Petrographic examination of LSMF 3/1, deformed in creep at 4500 psi stress difference, reveals that the dominant mode of deformation has been cataclasis. Fracturing is prominent and shear zones, such as that shown in Figure 2B, associated with intense photoelastic effects (light areas) are common, especially along grain boundaries. The thin, nearly E-W lamellae in that photomicrograph are photoelastic lamellae caused by long range stresses from trapped dislocation arrays in the (110) slip planes, the primary translation-gliding mechanism in halite (Carter and Heard, 1970). Photoelastic lamellae internal to the crystals are few, however, indicating that plastic deformation has not played a major role during straining of the specimen.

LSMF specimen 1/7, deformed at 500 to 1000 psi confining pressure at a stress rate of 610 psi/min. to a maximum stress level near 9,000 psi,

TABLE 1
SPECIMENS ANALYZED PETROGRAPHICALLY

SPECIMEN IDENTIFICATION	TEST MODE	$\Delta\sigma$ (psi/min) or $\Delta\sigma$ (psi)	TEMP. ($^{\circ}\text{C}$)	$\sigma_2 = \sigma_3$ (psi)	MAX. ϵ_1 (%)	COMMENTS ON PETROFABRICS
J1-16/10	UNDEFORMED				Zero	Weak preferred crystal orientations.
J1-16/9	QUASI-STATIC	450 to 500	25	500	24.3	Cataclastic with little appreciable reorientation.
J1-8/4	CREEP	4500/6000*	25	1500	11.2/13.4	Uniform deformation with homogeneous translation and intense plastic flow.
J1-8/9	QUASI-STATIC	20	25	2000	17.7	Dominantly plastic strain along (110) slip planes.
J1-16/3	QUASI-STATIC	20	25	2000	13.4	Behavior similar to J1-8/9.
LSMF-2/15	UNDEFORMED				Zero	Marked concentration of <u>a</u> -axes parallel to the core axis.
LSMF-3/1	CREEP	4500	25	500	27.5	Scattered <u>a</u> -axes around periphery suggesting some rotation with dominant fracturing.
LSMF-1/7	QUASI-STATIC	675	25	500 to 1000	13.0	Dominantly ductile deformation with some sheaving along grain boundaries.
LSMF-3/4	QUASI-STATIC	18	100	2000	14.0	Deformed by homogeneous plastic flow.

* Two stage creep experiment

has deformed dominantly by ductile deformation, although a few limited shear zones associated with plastic deformation are evident. Many grains, such as that shown in Figure 2C, contain faint photoelastic lamellae (N-S trending) along (110) but in general only clumps of dislocation are observed in this lightly strained specimen. Some sliding has taken place along pre-existing or earlier formed cleavage planes as is indicated in Figure 2C by intense photoelastic effects in their vicinity; this feature is common to most of the specimens analyzed. LSMF specimen 3/4, deformed at 100°C at 2000 psi confining pressure at a stress rate of 18 psi/min. to a maximum stress of 4724 psi, has been shortened by about the same amount as 1/7 and shows very similar deformation effects. There has been very little sliding along grain boundaries, and cleavages and intense photoelastic effects are few. All indications are that this specimen has deformed dominantly by homogeneous plastic deformation, a feature doubtlessly aided by the elevated temperature.

J.I. specimen 16/9, deformed at a confining pressure of 500 psi and a stress rate of 450-500 psi/min. to a maximum stress of 7500 psi, has many features similar to its counterpart LSMF 3/1. Deformation has been dominantly cataclastic, and cleavages are commonly curved with intense photoelastic effects along them as well as along grain boundaries and irregular fractures, many of which contain accumulations of anhydrite crystals. Photoelastic lamellae are not common, and where present, they are fine, closely-spaced and strongly curved at grain boundaries, such as those shown in Figure 4A. Most are parallel to (110) but, in one instance, lamellae were observed to be parallel to (100), a secondary slip system in halite (Carter and Heard, 1970).

J.I. specimen 8/4 was deformed in creep for 10 days at 4500 psi and then for 5 days at 6000 psi for a total strain of 25 percent. Macroscopically, this specimen appears to have deformed much more homogeneously than 16/9 and microscopic examination confirms this impression. Cleavages are much straighter and sharper than in 16/9 and there are far fewer fractures. Fine slip bands parallel to (110), such as those in Figure 4B, are present in many grains, and intense photoelastic effects along pre-existing or early formed cleavages (Figure 4B) and long fractures and grain boundaries indicate some sliding along them. The specimen has thus deformed by uniform flow accommodated in part by sliding and by homogeneous translation gliding within grains.

A

0.1 mm

J.I. 16/9. Bent Photoelastic Lamellae Near Cleavage Cracks and Grain Boundary.

B

1.0 mm

J.I. 8/4. Strong Photoelastic Effects at Cleavages and Grain Boundaries and Faint, Intersecting Sets of Photoelastic Lamellae.

C

1.0 mm

J.I. 8/9. Broad Photoelastic Bands Parallel to (110), the Primary Slip System.

D

0.1 mm

J.I. 16/3. Orthogonal Slip Bands and Intense Photoelastic Effects at Cleavage Boundaries.

Figure 4. Photomicrographs of Deformational Features in Deformed Halite Specimens.

J.I. specimen 8/9, deformed at 2000 psi confining pressure at a stress rate of 20 psi/min. to 8025 psi and 18 percent strain, has also shortened dominantly by plastic flow within the crystals. Broad photoelastic lamellae parallel to (110) (Figure 4C) are present in a few crystals although most of the slip lamellae are faint and fine. There is some sliding along cleavages and grain boundaries, but deformation has been dominated by plastic flow. A similar observation holds for J.I. specimen 16/3, also deformed at 2000 psi confining pressure at a stress rate of 20 psi/min. but to a maximum stress level of 6800 psi and an axial strain of 13 percent. Fine intersecting photoelastic lamellae (Figure 4D) are also characteristic of this specimen, indicating flow by plastic deformation. However, intense photoelastic effects along cleavages, associated with (110) flow, are observed, but the author believes that these could be related to the thin-sectioning process; a second section will be made for confirmation at a later date.

In summary, the specimens examined have deformed by a combination of cataclasis and plastic flow along (110) within grains. The dominant mechanism appears to depend mainly on the total strain and loading histories of the specimens.

4. CORRELATION WITH MECHANICAL RESULTS

Stress-strain and strain-time curves (Hansen, 1977a and b) are plotted in Figure 5 for the seven LSMF and J.I. specimens analyzed. Referring first to the stress-strain curves for triaxial compression at constant loading rate, it is seen that all specimens except LSMF 3/4, deformed at 100°C, show very strong work-hardening. J.I. specimen 16/9, loaded at 500 psi/min., strongest of the J.I. specimens, has deformed by cataclastic flow, and eventually failed by faulting as indicated by the drop in stress. The two other J.I. specimens, 8/9 and 16/3, loaded at a rate of 20 psi/min. are somewhat weaker and show similar, almost reproducible, behavior. These specimens are more ductile, having deformed by a combination of plastic flow (dominant) and sliding along cleavages and grain boundaries. Inasmuch as confining pressure above 500 psi does not significantly influence the mechanical behavior, differences in loading rates probably account for both differences in flow stress (Hansen, 1977a) and in the nature of the deformational processes.

LSMF 1/7, deformed at a loading rate comparable to J.I. 16/9, is clearly stronger than the J.I. specimen. On the basis of the rather small difference in flow stress between J.I. specimens deformed at 20 and 500 psi/min., the small difference in loading rates of LSMF 1/7 and J.I. 16/9 cannot account for the large difference in flow stress. Rather, differences in the physical nature of the starting material are likely to provide the explanation. On the basis of the fabrics (Figure 1), the LSMF 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, this LSMF specimen deformed dominantly by plastic deformation as compared to predominant cataclastic flow for J.I. 16/9. The only reasonable conclusion remaining, tenable at least to the author, lies in the coarser grain size and more heterogeneous nature (including segregated impurities) of the LSMF bedded salt. Finally, notice the large drop in strength and nearly steady state behavior of LSMF 3/4, which deformed mainly by plastic flow, a behavior attributable to the elevated temperature of this experiment.

Figure 5. Stress-Strain (A) and Strain-Time (B) Curves for Deformed Halite Specimens Analyzed. (See Text for Discussion).

Only two of the specimens analyzed were deformed in creep and the resulting strain-time curves are given in Figure 5B. LSMF 3/1 appears to show a large range of secondary (steady state) creep, leading to accelerating creep but the dominantly cataclastic deformation of this specimen indicates that this creep is not of the usual thermally-activated, diffusion-controlled type. J.I. 8/4, deformed at the same stress level of 4500 psi in the first stage, shows appreciably more strain for a given time, in accord with the conclusions drawn from the quasi-static compression tests (Figure 5A). An increase in flow stress to 6000 psi for J.I. 8/4 increases the strain for any given time greatly, as expected. Thus, the results from the creep tests are entirely compatible with those from the triaxial compression tests.

5. CONCLUDING REMARKS

From the foregoing observations, it is concluded that the mechanical behavior and flow processes for both bedded salt from Lyons, KS and domal salt from Jefferson Island, LA are entirely correlative and compatible. Specimens loaded at high stress rates to high strains deform predominantly by cataclastic flow, whereas plastic flow dominates at the lower rates and strains. An exception to this observation is LSMF 1/7 which has flowed plastically although loaded at a high rate to a high stress level. This behavior is attributed to the initial fabric which is strong and is such that very large numbers of primary slip planes are oriented in planes of high shearing stress. Normally, such a fabric would be expected to ensure that LSMF salt should be weaker than the randomly oriented J.I. material; however, the coarser grain size and heterogeneity of LSMF salt seems to overrule the effect of fabric. Finally, as expected, increasing the temperature to 100°C decreases the flow stress greatly and nearly leads to steady state creep; this is because more thermally-activated processes contribute to the creep strain.

The generalizations drawn above are based only on detailed studies of seven samples of LSMF and J.I. salt. However, the samples were selected to cover most of the physical range of tests on these materials. Examination of the much more extensive mechanical results of Hansen (1977a and b) on these materials suggests that these generalizations are likely to hold for all conditions tested to date. Therefore, it should be possible in the future to spotcheck extreme tests, and a few of those under intermediate conditions, using the tedious procedures employed in this analysis, to evaluate deformational behavior over the entire spectrum of test conditions.

The creep strain in any material is given by

$$\epsilon = \epsilon_e + \epsilon_p + \epsilon_t + \epsilon_{ss} + \epsilon_a \quad (1)$$

where ϵ_e is the instantaneous elastic strain upon loading, ϵ_p the instantaneous plastic strain produced during loading, ϵ_t the transient creep strain, ϵ_{ss} the steady state creep strain and ϵ_a the accelerating creep strain. Inasmuch as we are interested primarily in fairly large creep strains, ϵ_e and ϵ_p (< 1%) may generally be neglected. Accelerating

creep, ϵ_a , while potentially important locally, is poorly understood, relatively rarely observed, and will be ignored here. It is expected that transient, ϵ_t , and steady state, ϵ_s , creep will dominate deformations with which we are concerned.

It is observed that transient creep strain of materials is well represented by the relation

$$\epsilon_t = \alpha \log(1 - \nu t) + \beta t^m \quad (2)$$

where α , ν and β are material constants, t is time and m , the time exponent. In general, especially for crystalline rocks, the first term dominates in the low temperature transient regime whereas the second term overwhelms the first in the high temperature regime (Carter, 1978). Apparently because of the soft, ductile nature of halite, Hansen (1977a) has found experimentally that, even at the low temperatures employed, a good fit to the second term alone is obtained. Expanding this term we have

$$\epsilon_t = \beta t^m = \beta_0 \sigma^n t^m \exp(-E/RT) \quad (3)$$

where β_0 is a material constant, σ the differential stress and n the stress exponent, E the creep activation energy, and the remaining parameters have been defined previously or have their usual significance. Hansen (1977a) has found for room temperature creep tests on J.I. rock salt that $n = 2.52$ and $m = 0.38$, values that are most reasonable on the basis of extensive studies on other materials (Carter, 1978). However, the temperature dependence of the creep strain, given by the exponential function, has not yet been determined and this information is crucial to a complete transient creep equation describing the behavior of the material at other than room temperature. A few triaxial compression experiments to 100°C have been conducted on LSMF salt (Hansen, 1977b), but analyses of these and room temperature data are not yet sufficiently complete to allow estimates of n , m and E .

The most complete data for transient creep of halite are those of Le Compte (1965), obtained for fine-grained, artificially-prepared rock salt. A reanalysis of his data at 1 kb confining pressure in the temperature interval 175° to 200°C gives

$$\epsilon_t = 200 \sigma^{1.4} t^{0.55} \exp\left(-\frac{19.7}{RT \cdot 10^{-3}}\right) \quad (4)$$

for σ in bars, t in seconds and E in Kcal/mole. The best data available for steady state creep for rock salt, also artificially-prepared, are those of Heard (1972). For steady state creep of all important rock-forming materials, for which information is available, the data are best fit by the relation (Carter, 1976)

$$\dot{\epsilon}_{ss} = A \exp(-Q/RT) \sigma^n \quad (5)$$

where $\dot{\epsilon}$ is the strain rate, A a nearly temperature-insensitive material constant, Q the activation energy for creep, σ the stress difference, and n the stress exponent. Over a wide range of temperatures (to 400°C), strain rates, 10^{-1} to 10^{-8} /sec. and stresses at 2 kb confining pressure, Heard's steady state data for halite are best fit by

$$\dot{\epsilon}_{ss} = 2.5 \times 10^{-6} \exp\left(-\frac{23.5}{RT \cdot 10^{-3}}\right) \sigma^{5.5} \quad (6)$$

As an example of the utility of such complete creep equations, we may calculate times, as a function of stress, to achieve a creep strain of 10 percent at 200°C for transient (eqn. 4) and steady state (eqn. 6) creep. The results are presented in Figure 6 and the implications drawn therefrom could be of considerable interest to waste isolation in rock salt. At a stress difference of 10 bars, a transient creep strain of 0.1 at 200°C would be achieved in about 3 years; at 100 bars, in about 3 days; and at 200 bars, in one-half day. For similar stress levels, the same creep strain in the steady state would require about 290 years, 8 hours, and ten minutes. Thus, it is evident that complete creep data of the type illustrated by equations (4) and (6) are extremely important for estimates of the rates of closure of excavated openings in salt.

Clearly, the various physical constants given in equations (4) and (6) for fine-grained, artificially-prepared, pure rock salt would not be expected to hold for the much coarser-grained, impure, heterogeneous, natural rock salts having variable preferred crystal orientations. The example given above (Figure 6) does, however, emphasize the importance of obtaining complete flow laws for transient and steady state creep of all natural rock salts of potential repositories. It is recommended, therefore, that complete creep equations of the type of (4) and (6) be

TIME vs STRESS FOR $\epsilon = 0.1$, 200°C

Figure 6. Extrapolation of Equations (4) and (6) in Log Time - Log Stress Space for Transient and Steady State Creep for Halite. (See Text for Discussion).

generated for salt of all potential disposal sites; creep and constant strain rate tests are particularly suitable for this purpose. Under all circumstances, the deformation mechanisms operative during the tests must be evaluated in order that the flow laws obtained have physical significance. Finally, finite element codes attempting to model mine closure must make use of these data, perhaps through a piecemeal linearization of a complete creep-rate equation of the form

$$\dot{\epsilon} = m\beta/t^{1-m} + \dot{\epsilon}_{ss}, \quad (7)$$

where the meaning of these terms has been discussed above.

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APPENDIX AJEFFERSON ISLAND, LA DOMAL SALT (J.I.)

Specimen 16/10: Undeformed - very clean - grain size somewhat variable by averages ca. 0.25 in. Specimen cut $\perp$ to core axis and grains were cleaved during the grinding process. Fabric shows nearly random orientation. Each crystal is well cleaved into straight, sharp cleavages making the fabric determination possible. There are no photoelastic effects either associated with cleavages or internal to the grains indicating that the section preparation process did not induce appreciable plastic strain. Measurement of two sections was necessary for the complete fabric analysis.

Specimen 16/9: Specimen is markedly barrel-shaped and contains a diagonal through-going anastomosing fault. The specimen was deformed at a confining pressure of 500 psi, at a stress rate $\Delta\sigma$ of 450-500 psi/min. to max $\Delta\sigma = 7500$ psi to a maximum strain at 25°C of 24.34%. Approximately 10% of the total strain occurred at post-failure. Because of maximum bulging with highest concentration of strain in the central area, a fabric analysis was performed on this specimen rather than 8/4 as maximum grain rotation was expected. The central area of the split cylinder appears highly cataclastic in nature and proved to be very difficult for making coherent thin sections, several grains and areas plucking out in the process. It was possible in two sections to measure only 75 a -axes of 25 grains; it is difficult to say much from so few measurements. One would expect, from dominant slip on one of the (110) planes that a -axes concentrations would be removed from the core axis and periphery. There is some hint that this has happened but the tendency is not strong indicating little appreciable reorientation effect.

In this section, the salt has a very cataclastic appearance. Cleavages are commonly curved and are associated with intense photoelastic effects. The latter are also present along grain boundaries and along irregular fractures in the specimens. Small idiomorphs of anhydrite are present throughout and shear zones contain large amounts of such particles - probably following grain boundaries. Photoelastic lamellae are present though not common. They are generally very fine or closely-spaced and are strongly curved near grain boundaries indicating rotation probably associated with grain boundary shearing. Most are (110), but in one instance (100) lamellae were observed.

The overall deformation is cataclastic with little contribution of plastic flow. Although from specimen shape it appears to be homogeneous, it is not as attested by the fault and other features. Fracturing and slip along grain boundaries and cleavages accounts for most of the strain.

Specimen 8/4: 25°C Creep, 10 days at 4500 psi for 11.23% ϵ_1 , 5 days at 6000 psi for 13.4% ϵ_1 . At 1500 psi confining pressure: Total $\epsilon_1 = 24.63$. Specimen appears to be homogeneously deformed, slightly barrel-shaped and no through-going fractures. Does not appear to be nearly so ground up as 16/9.

Thin section examination gives the same impression as does macroscopic examination of the deformed cylinder. Cleavages are much straighter and sharper than in 16/9 and there are far fewer fractures. Intense photoelastic effects are present along many grain boundaries and along some cleavage planes indicating intense plastic flow and probably sliding along these areas. Photoelastic lamellae, most commonly parallel to (110) but a few parallel to (100) are observed in many crystals, much more so than in 16/9. They are much straighter than in 16/9 and are much less intense.

The specimen has deformed by uniform flow accommodated in part by a homogeneous translation gliding within grains and by sliding, accompanied by intense plastic flow, along grain boundaries and pre-existing or early-induced cleavages.

Specimen 8/9: Deformed at 2000 psi confining pressure at a stress rate of 20 psi/min. to 8025 psi and 17.7% ϵ . The specimen has shortened very homogeneously and is nearly a right circular cylinder.

Thin section analysis also reveals homogeneous deformation. Cleavages are straight and sharp and occasionally show intense photoelastic effects as do grain boundaries. Many of the crystals show from very faint to intense photoelastic lamellae, dominantly parallel to (110), indicating that plastic flow has contributed appreciably, if not dominantly to the creep strain.

In summary, the specimen has shortened dominantly by plastic strain along (110) slip planes in the crystals accompanied by sliding along grain boundaries and cleavage fractures.

Specimen 16/3: Deformed at 2000 psi confining pressure at a stress rate of 20 psi/min. to $13\frac{3}{4}\% \epsilon_1$ at a maximum stress level of 6800 psi. Specimen has deformed very homogeneously and is a right circular cylinder.

Thin section analysis also shows that cleavages are straight and sharp. However, intense photoelastic effects at cleavage boundaries associated with (110) slip in their vicinity appear to me to have been created by the sectioning process. While, overall, the behavior seems to be and probably is similar to 8/9, the higher stress of 8/9 would more likely have caused these effects. This specimen must therefore be sectioned again.

APPENDIX BLYONS, KANSAS BEDDED SALT (LSMF)

- Specimen 2/15: Undeformed. The material is a coarse-grained (0.4" avg. diameter) impure laminated salt core. Alternate layers of white, relatively pure salt are interbedded with gray layers of variable thickness. The nature of the impurity, which occurs mainly along salt crystal boundaries, has not been determined but it appears to be clay. Two thin-sections were cut normal to the cylinder axis and cleaved during grinding for fabric analysis. 162 a -axes show a marked concentration parallel to the core axis with a more or less random orientation along the periphery.
- Specimen 3/1: Specimen deformed at 500 psi confining pressure in creep at a stress difference of 4500 psi to a longitudinal strain of 27.5%. The core is of uniform barrel shape with no discontinuities. While barreling is more uniform than J.I. 16/9, there appears to be a milky, ground cataclastic texture near the central, most highly strained, part.
- Two thin sections were cut from the center of this specimen, but they proved to be of poor quality because of plucking from the central sheared areas of segments surrounded by fractures. Thin section examination reveals extensive fracturing and limited shear zones associated with intense photoelastic effects. Internally, photoelastic lamellae are few and the deformation appears to be dominantly cataclastic in nature. Because of the coarse-grained nature of the specimen and poor section quality, only 75 a -axes could be measured in the two sections. There is a scattered maximum somewhat off the core axis and scattered a -axes around the periphery. The pattern is not nearly so strong as for the undeformed material suggesting some rotation, apparently dominantly by fracturing, but the data are sparse. That the maximum concentration near the core axis is inclined to it somewhat may have resulted from a section not exactly parallel to the core axis.
- Specimen 1/7: Specimen deformed to 13% ϵ_1 at 500-1000 psi and 25°C at a stress rate of 675 psi/min. to a maximum stress of 10,458 psi. The specimen has apparently deformed homogeneously and is a right circular cylinder.
- Thin section analysis reveals dominantly ductile deformation, although a few short shear zones associated with plastic deformation are evident and cleavages are slightly curved in some areas. Many grains show very faint photoelastic lamellae, but in general the (110) slip planes are not well-developed and only clumps of dislocations, indicated by point photoelastic effects, are observed. The specimen

appears to have deformed mainly by homogeneous plastic deformation associated with some shearing concentrated in short, irregular zones, along grain boundaries and along cleavages.

Specimen 3/4: Specimen deformed at 100°C under 2000 psi confining pressure at a stress rate of 18 psi/min. to a maximum stress level of 4724 psi and a total strain of 14%. The cylinder has been very homogeneously deformed and is still a right circular cylinder.

Thin section analysis shows that the specimen has shortened homogeneously also with few shear zones and apparently very little sliding along grain boundaries and cleavages. Photoelastic lamellae are very few and faint and all aspects of this section indicate that the specimen has deformed dominantly by homogeneous plastic flow.