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ANALYSIS OF STEADY STATE CREEP OF SOUTHEASTERN NEW MEXICO BEDDED SALT

W. Herrmann, W. R. Wawersik, H. S. Lauson

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ANALYSIS OF STEADY STATE CREEP
OF SOUTHEASTERN NEW MEXICO BEDDED SALT*

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ABSTRACT

Steady state creep rates have been obtained from a large suite of existing experimental creep data relating to bedded rock salt from the Salado formation of S.E. New Mexico. Experimental conditions covered an intermediate temperature range from 22°C to 200°C, and shear stresses from 1000 psi (7 MPa) to 6000 psi (31 MPa). An expression, based on a single diffusion controlled dislocation climb mechanism, has been found to fit the observed dependence of steady state creep rate on shear stress and temperature, yielding an activation energy of 12 kcal/mole (50 kJ/mole) and a stress exponent of 4.9. Multiple regression analysis revealed a dependence on stratigraphy, but no statistically significant dependence on pressure of specimen size. No consistent dilatancy or compaction associated with steady state creep was found, although some individual specimens dilated or compacted during creep. The steady state creep data were found to agree very well with creep data for both bedded and dome salt from a variety of other locations.

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1. Introduction

An analysis has been reported¹ of creep tests performed by Wawersik and Hannum,² Hansen,³ and Hansen and Mellegard^{4,5} on samples of bedded rock salt from the Salado formation in the Waste Isolation Pilot Plant study area near Carlsbad, New Mexico. Individual creep tests were fitted to both exponential and logarithmic transient creep laws. The analysis provided, among other things, consistent estimates of steady-state creep rates. In this report, an analysis is presented of the dependence of steady-state creep rate on shear stress and temperature, as well as a variety of other experimental variables.

The rock salt was medium grained (1 to 10 mm) to coarse grained (10 to 20 mm) consisting of 90 to 97 modal percent halite, the remainder being polyhalite, anhydrite and small amounts of clay and silt. Geologic characterization of the salt has been summarized by Powers et al.⁶ Further petrologic details have been described by Callender and Ingwell.⁷

Creep tests were performed in specially designed triaxial test machines with instrumentation which allowed determination of average axial and transverse strains of the specimens.^{8,9} Some tests were performed at Sandia Laboratories, Albuquerque, using large 4 in. (100 mm) diameter specimens.² Others were performed at RE/SPEC Inc. using smaller 2 in. (50 mm) diameter specimens.³⁻⁵ Specific specimen preparation and test procedures have been described in the original references.²⁻⁵ Test specimens were machined from core retrieved from two holes (AEC #7 and ERDA #9), and from two different nominal depths (about 2000 ft. and 2600 ft.). Petrographic observations suggested mineralogical differences in the salt from these two depths which might be expected to result in differences in mechanical behavior.⁷

In a number of cases, the same specimen was tested successively under different conditions. A creep test was conducted at one shear stress, temperature and confining stress until steady-state creep was approached. Either the shear stress or temperature was then increased and a new test initiated. Successive tests of this type are given a common test number, but successive test stage numbers in order to identify their relationship. In two cases, later stages were conducted at a lower shear stress (but identical temperature and confining stress) than the immediately preceding stage in order to investigate creep when the stress is dropped.

Tests covered a range of principal stress differences from 1000 to 6000 psi (7 to 41 MPa), temperatures from 22°C to 200°C, and confining stresses from 0 to 3000 psi (0 to 21 MPa). A test matrix of temperature, confining stress, shear stress and test stage has been given previously.¹

In order to deduce steady-state creep rates from the experimental data, strain-time records for each individual test had been fitted¹ to both exponential and logarithmic creep laws equivalent to the forms

$$e = e_0 + \dot{e}_s t + e_a \{1 - \exp(-\dot{e}_s t)\} \quad (1)$$

and

$$e = e_0 + \dot{e}_s t + e_c \ln(1 + \eta t) \quad (2)$$

where $\dot{e}_s$ is the steady-state creep rate and e_0 , e_a or e_c and η are constants for a given test at constant shear stress and temperature. Steady-state creep rates obtained by means of the two fits agreed quite well for most experiments. Only data relating to steady state creep for each test are

considered here. The relevant data are reproduced in Tables 1 and 2 which list the test file ID, test number and stage, the drill hole number and depth of core (ft) from which the specimen was cut, the specimen size (ins) temperature T ($^{\circ}\text{C}$), shear stress (principal stress difference) τ , confining stress σ_3 and hydrostatic pressure p (psi), together with the steady state axial creep rate $\dot{e}_{s1}$ and transverse creep rate $\dot{e}_{s3}$ (/sec) and their standard errors. Complete tabulations of fitting parameters are available in the report of the previous analysis.¹

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two tests which were questionable.*

It was found that the only statistically significant coefficient, besides a , n and Q , was Q_3 , that is A is dependent on level but there is no statistically significant dependence of n and Q on level. Moreover, there is no statistically significant dependence of A , n and Q on pressure, drill hole or specimen size and laboratory in which the tests were performed. Results are given in Table 3, which also shows standard errors of the fitting parameters, standard deviation of the fit to (6) and the coefficient of determination R^2 . It can be seen that, loosely speaking, more than 93% of the behavior is captured by the single expression (3) with values of the parameters given in Table 3.

In order to illustrate the quality of the fit, the secondary creep rate for each experiment was first scaled to nominal conditions and upper level using (3) and the parameters given in Table 3. Scaled creep rates were then plotted in Figs. 1 and 2, for comparison with the solid lines representing the fit. It is readily seen that the scatter in the data embrace about one decade in strain rate. Within this scatter, the single creep expression (3) appears to be quite adequate to describe the data, as shown by the multiple regression analysis. In particular, there is no evidence of a transition to a different activation energy Q at temperatures up to 200°C, or a different stress dependence at high stresses, within the range embraced by the data, as had been suggested previously

* Load drop tests which were omitted carried file numbers CA 106 and CA 113. Questionable tests which were omitted were RS 5502B which experienced a large stress drop early in the test, resulting in an anomalous strain history, and RS 6204 which was surmised to undergo cracking during creep.

by Munson^{13,14} on the basis of an analysis of a subset of the present data together with data from other experimenters using salt from other sources.

An identical analysis^{*} was performed using secondary creep rates deduced by the use of the logarithmic creep law (2) together with the definition of shear strain rate (7). Results were qualitatively similar, the resulting data also being given in Table 3. The values of A, n and Q for the two analyses are seen to agree within their standard errors. This was taken as evidence of the insensitivity of the secondary creep rates to the transient creep model.

Two analyses were also performed using steady state creep rates deduced from the two creep laws respectively, but using the definition of shear strain rate (8). Transverse strain data were missing for a number of tests, including all those at zero confining stress. In addition, some fits to the transverse strain histories provided negative secondary creep rates, which were deleted from these analyses. Consequently, the data sample was considerably reduced. To see if the use of (8) would improve the fit, the previous two analyses using (7) were also repeated with the smaller data samples. For steady state creep rates deduced from both creep laws the analyses using (7) and (8) resulted in coefficients A, n and Q which corresponded within their standard errors, with similar standard deviations. Consequently, it was concluded that the use of (8) did not improve the fit significantly.

* RS 7901A, for which $\dot{\epsilon}_{1s} < 0$, was deleted in this analyses in addition to CA 106, CA 113, RS 5502B and RS 6204.

The pressure dependence, or rather lack thereof, can be illustrated by plots of scaled secondary creep rates versus confining stress for each nominal shear stress and temperature state for which several tests were available. These plots are shown in Fig. 3. While a slight decrease in secondary creep rate with increase in pressure might be discerned in these plots, the scatter is such that the trend cannot be considered statistically significant, as indeed the multiple regression analyses have indicated.

Related to a pressure effect is the question of a volume change during creep. Initial loading of the specimen in a number of tests appeared to introduce a slight initial volume change. The volume change associated with secondary creep can be conveniently isolated from this and other spurious effects by defining the quantity

$$\eta_s = \frac{\dot{\phi}_s}{\dot{\gamma}_s} \quad (9)$$

where $\dot{\gamma}_s$ is the shear strain rate given by (4) and $\dot{\phi}_s$ is the dilatation rate given by

$$\dot{\phi}_s = \dot{e}_{1s} + 2 \dot{e}_{3s} \quad (10)$$

Scaled values of secondary creep rates were used to calculate η_s for each test for which transverse strain fits were available. Some plots of η_s versus shear stress at different constant temperatures are shown in Fig. 4.

Except for a few tests, which showed relative large amounts of dilation ($\eta > 0$) or compaction ($\eta < 0$), most tests showed a volume strain rate less than about 20% of the shear strain rate, with many tests exhibiting much smaller percentages. There does seem to be a slight tendency for tests at low confining stress to dilate, while those at high confining stress

tend to compact, this tendency disappearing as the shear stress and temperature increase. In any case, the average value of η_s for all tests does not differ significantly from zero, with the scatter distributed fairly evenly about zero at all shear stresses and temperatures.

3. Comparison With Other Data

There have been several studies of the creep of polycrystalline salt from other sources, which can be compared with the present data. A number of data are available for salt from the Tatum dome, Mississippi.^{15,16} These data include both uniaxial compression and triaxial extension data taken at two temperatures, 23°C and 66°C. Steady-state creep rates are shown plotted versus shear stress in Fig. 5. Solid lines represent (3) with coefficients from Table 3 (Exponential Creep). While the scatter in the data is quite large, the data are in fair agreement with the present fit. Some of the data¹⁶ are plotted versus temperature in Fig. 6. The data have been scaled to nominal shear stresses, using (3) and coefficients from Table 3, in order to compare with the present fit. The agreement is again fair, in view of the scatter.

Triaxial creep data are available for rock salt from the Grand Saline and Hockley mines, Texas.¹⁷ The tests were conducted at 32°C. For convenience in plotting, they were scaled to 23°C using (3) and coefficients from Table 3, and are also shown in Fig. 5 where they are seen to be in excellent agreement with the present fit.

A few data points have been obtained in both triaxial compression and triaxial extension using salt from the West Hackberry dome, Louisiana.¹⁸ The data were taken at two temperatures (22°C and 60°C) at a nominal shear stress of 3000 psi. These data were scaled, using (3) and Table 3, to a nominal shear stress of 3125 psi, and are plotted in Fig. 6, where they are seen to be in excellent agreement with the present fit.

An extensive study¹⁹ of the creep of pure synthetic polycrystalline halite included a number of tests within the range of shear stresses and

temperatures of interest in this work. The relevant data are shown in Fig. 7 and 8. The latter have been scaled using (3) and Table 3. The agreement is again quite reasonable.

Finally, creep data are available for salt from the Asse anticline, West Germany.²⁰ The original data were unavailable, but they were fitted to (3). Reported values of the coefficients are*

$$A = 9.27 \text{ E} + 14 \quad / \text{sec}$$

$$n = 5.0$$

$$Q = 12.9 \text{ kcal/mole (54.0 kJ/mole)}$$

which may be compared with values in Table 3. The reported values of A and Q are in quite good agreement with the present data.

It is surprising that data from diverse sources agree with the present data within the order of magnitude or so scatter common to tests of this type. In particular, the various data appear to agree quite well with regard to the stress exponent n. Several of the data sets, taken by themselves, might indicate widely different values of the activation energy Q. However, this is probably due to the small number of data in these sets, together with a small temperature range and relatively large scatter. When plotted with the present data, the agreement is good. The general agreement of results for uniaxial compression, triaxial compression and triaxial extension further corroborates the lack of a pressure effect on steady state creep.

* Note that the value given here refers to $\dot{\gamma}$, which is related to the axial strain rate by (5).

4. History Effects

A limited examination of the effects of history is possible. It has been noted that a number of tests were performed on specimens which had been tested previously at a lower stress or temperature. In one case, the same specimen was tested three times at successively higher stresses. The test sequences on different specimens can be deduced from the test and stage numbers in Tables 1 and 2.

The test matrix was such that a number of pairs of tests may be identified, one of which was loaded directly to a given shear stress and temperature, while the other was loaded to the same shear stress and temperature after a prior stage at either a lower stress or temperature.

An examination of the data, together with plots in Figs. 1 and 2, reveals no effect of test stage on steady-state creep rate, within the scatter in the data at least for the histories represented in these tests. This suggests that steady-state creep rates may be unaffected by prior stress or temperature histories, providing that the stress and temperature increase monotonically.

Two tests were conducted on specimens which had been tested at a higher level of shear stress in a prior stage.* The strain-time records for these two tests differed qualitatively from the others, in that they exhibited virtually no decelerating creep over the time of the tests. The strain-time records for these tests were nevertheless fitted to (1). Results are shown in Table 4. The values of $\dot{\epsilon}_s$ for tests CA 106 and CA 113 may be compared directly with those for tests CA 104 and CA 111 which were

* These tests carried file numbers CA 106 and CA 113.

performed on the same specimens in prior stages at the same stresses and temperatures respectively, but with prior monotonic loading histories. The load drop tests CA 106 and CA 113 exhibit values of $\dot{\epsilon}_s$ more than an order of magnitude less than CA 104 and CA 111 respectively. These observations are in accord with experience in the creep of metals.

It has been suggested that recovery, which dominates early creep in load drop tests, may require much longer times or involve much larger total strain accumulations than those experienced in CA 106 and CA 113. Little further can be said about the results of these two tests, but it is clear that the present data for monotonic loading must be used with extreme caution for stress histories involving stress reversals. No information is available regarding creep under decreasing temperature histories, but a similar phenomenon may be expected.

5. Conclusions

An analysis has been performed of available data relating to the creep of bedded rock salt from the WIPP study area near Carlsbad, New Mexico. Usable data were obtained from 64 separate tests on 44 different samples taken from two drill holes and two levels representing different geologic strata. Tests were conducted in two laboratories on samples of two different sizes in a range of temperatures from 22°C to 200°C, shear stresses (stress differences) from 1000 to 6000 psi (7 to 41 MPa), and confining stresses from 0 to 3000 psi (0 to 20 MPa). The data were sufficient, albeit minimal, to allow statistical analysis.

The bulk of the data related to transient creep. Steady-state creep rates were deduced by making least squares fits to the data for each experiment, conducted at constant temperature, shear stress and confining stress, using both exponential and logarithmic transient creep models.¹ The resulting steady-state creep rates were then fitted to Weertman's expression to obtain the dependence on temperature and shear stress, and to explore the sensitivity of the results to confining stress, geologic level, drill hole location, specimen size and laboratory at which the tests were performed. Results of the two analyses using the two primary creep models agreed within their standard errors.

While the secondary creep coefficient A was found to differ by a factor of 2.6 for the two geologic levels, the stress exponent n and activation energy Q were unaffected. No statistically significant dependence of secondary creep on drill hole, specimen size or laboratory was found.

A very slight tendency was observed for the secondary creep rate to decrease with pressure; however, the multiple regression analysis indicated that this tendency was not statistically significant, and in excess of 93% of the behavior was captured without a confining stress dependence. A related analysis of dilatancy of secondary creep showed a slight tendency for specimens to expand at low confining stress and to compact at high confining stress under conditions of low temperature and shear stress. This tendency disappeared as the shear stress and temperature increased.

Results of secondary creep rates obtained in this study agreed well with the results of creep measurements on salt from a variety of other sources. Within the range of shear stress and temperature covered by the present data, the stress exponent was found to be 4.9 and the activation energy was found to be 12 kcal/mole (50 kJ/mole). There was no indication of a change to another mechanism at the highest temperature (200°C) and shear stress (6000 psi or 31 MPa) covered in this study. Consequently, a single mechanism for the stress and temperature dependence of secondary creep is considered sufficient within this range.

Steady-state creep rates were found to be unaffected by prior stress or temperature histories, provided that the stress and temperature increased monotonically. The fact that reported triaxial compression and extension tests gave the same results within the scatter of the data suggests that the present results are applicable to both compressive and extensive loading. Load drop tests suggest that the present results are

not applicable when the stress history includes stress reversals. No information is available pertaining to decreasing temperature histories.

It should be emphasized that the present results are valid in a limited stress and temperature range. It is clear from data in polycrystalline halite¹⁹ that the steady-state creep mechanism changes to one with a higher activation energy at temperatures much above 200°C. The agreement of those data with the present data suggests that this is likely true also for the Southeast New Mexico rock salt, and that the present results cannot be extrapolated to higher temperatures without modification.

Existing data on pure single crystal sodium chloride suggest that different steady-state creep mechanisms are operative at higher stresses.¹³ While the data for a number of naturally occurring rock salts are remarkably similar, it is unclear whether they are directly comparable to those for pure NaCl. Little can therefore be said on the basis of the data quoted here regarding the range of validity of extrapolation of the present results to higher stresses.

Extrapolation to lower stresses is likewise uncertain. It has been suggested that creep may be absent below some (non negligible) threshold stress. The present data show significant creep rates at the lowest stresses tested. Much lower stresses result in creep rates which may be at the limit of resolution of present instrumentation, so that direct experimental assessment of this suggestion is likely to be difficult.

Finally, a comment with regard to the uncertainty in the fit to (3) is in order. While the data for most individual creep experiments are internally consistent, steady-state creep rates obtained from different specimens tested under nominally the same conditions may scatter by an

order of magnitude. The experimental technique and instrumentation have been carefully checked and calibrated to eliminate experimental errors.^{8,9} The scatter is attributed to variations in the material. Indeed, factors such as grain size, impurity distribution and content of accessory minerals vary from specimen to specimen.

While the individual data points may scatter by an order of magnitude, statistical analysis has resulted in a best fit to the data with a logarithmic standard deviation of 0.0887 (using results of the exponential transient creep law, Table 3). This implies that the steady-state creep rate is likely (with 95% confidence) to lie within a factor of $\exp(\pm .887)$ or a factor of 2.4 of the mean value predicted by (3) with coefficients from Table 3. Since the scatter is attributed to material variations, the uncertainty of a factor of 2.4 greater or less than the mean value applies to the analysis of phenomena on a sufficiently large scale so that material variations average out. Local properties may vary from the mean by a considerably larger factor.

The design process, when such large uncertainty intervals exist, requires care. Calculations using mean values are apt to be meaningless. Careful statistical analysis with attention to error propagation is necessary to achieve conservative predictions.

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Table 1
Steady State Creep Rates from Exponential Fit (Eq. 1)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	T	σ_3	P	$\dot{\epsilon}_{S1}$	ERROR	$\dot{\epsilon}_{S3}$	ERROR
RS5501A	1	1	7	2	2729.0	24	1530	510	1020	8.216E-10	2.356E-10	1.200E-09	1.000E-11
RS5501B	1	2	7	2	2729.0	24	3024	518	1526	3.283E-08	2.010E-09	1.824E-08	7.600E-10
RS5501C	1	3	7	2	2729.0	24	4305	519	1954	1.394E-07	3.400E-09	5.436E-08	1.810E-09
RS5502A	2	1	7	2	2715.0	100	1497	589	1088	2.575E-09	1.440E-09	0.	0.
RS5503A	3	1	7	2	2715.0	24	1495	2034	2532	3.586E-09	1.560E-10	0.	0.
RS5503B	3	2	7	2	2715.0	24	2968	2015	3004	2.714E-08	9.300E-10	9.878E-09	3.970E-10
RS5503C	3	3	7	2	2715.0	24	4244	2044	3459	9.418E-08	3.570E-09	4.173E-08	1.800E-09
RS5504A	4	1	7	2	2711.0	24	3037	2012	3024	1.765E-08	3.600E-10	9.114E-09	4.200E-10
RS5504B	4	2	7	2	2711.0	24	4309	2008	3444	9.287E-08	2.570E-09	3.854E-08	1.130E-09
RS5505A	5	1	7	2	2711.0	100	1509	1990	2493	4.109E-08	7.100E-10	1.905E-08	3.100E-10
RS5505B	5	2	7	2	2711.0	100	2631	2010	2887	5.104E-07	2.300E-09	2.312E-07	1.000E-09
RS5506	6	1	7	2	2715.5	100	2702	2003	2904	4.774E-07	3.000E-09	2.132E-07	1.300E-09
RS6201	1	1	9	2	2668.5	24	1535	0	512	3.817E-11	5.827E-10	0.	0.
RS6202	2	1	9	2	2668.5	74	1544	0	515	1.582E-08	4.700E-10	0.	0.
RS6203	3	1	9	2	2622.0	107	1515	0	505	4.242E-08	5.900E-10	0.	0.
RS6205	5	1	9	2	2674.5	24	3088	2360	3389	2.711E-08	3.600E-10	1.161E-08	1.700E-10
RS6206	6	1	9	2	2674.5	73	3041	2602	3616	4.516E-07	2.600E-09	1.880E-07	1.400E-09
RS6207	7	1	9	2	2679.0	105	3066	2510	3532	1.653E-06	4.100E-08	8.195E-07	2.960E-08
RS6208	8	1	9	2	2635.0	105	1559	2978	3498	4.696E-08	3.900E-10	2.211E-08	2.500E-10
RS6209	9	1	9	2	2678.0	24	1520	0	507	2.162E-09	4.680E-10	0.	0.
RS6210A	10	1	9	2	2636.0	24	1481	2518	3112	3.391E-09	1.920E-10	2.396E-09	1.040E-10
RS6210B	10	2	9	2	2636.0	24	3177	2425	3451	2.685E-08	6.300E-10	1.315E-08	2.900E-10

Table 1 (continued)

Steady State Creep Rates from Exponential Fit (Eq. 1)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	T	σ_3	P	$\dot{\epsilon}_{S1}$	ERROR	$\dot{\epsilon}_{S3}$	ERROR
RS6211	11	1	9	2	2679.0	103	1495	0	498	1.345E-07	3.200E-09	0.	0.
RS6212A	12	1	9	2	2678.3	106	1558	2450	2969	8.451E-08	1.280E-09	3.991E-08	8.500E-10
RS6212B	12	2	9	2	2678.3	107	3118	2570	3609	3.489E-06	1.190E-07	1.631E-06	5.600E-08
RS6213	13	1	9	2	2605.5	24	4505	1971	3473	8.758E-08	1.670E-09	4.315E-08	7.900E-10
RS6214	14	1	9	2	2678.7	24	5864	1467	3422	5.749E-07	7.800E-09	2.811E-07	3.400E-09
CA 102A	1	1	9	4	2078.0	22	1999	486	1152	1.022E-09	2.500E-11	0.	0.
CA 102B	1	2	9	4	2078.0	22	4493	506	2004	7.714E-08	3.100E-09	4.496E-08	1.710E-09
CA 109	2	1	9	4	2083.0	22	2974	501	1492	2.950E-09	7.000E-11	2.641E-09	4.500E-11
CA 110	2	2	9	4	2083.0	22	4436	528	2097	6.712E-08	3.310E-09	2.521E-08	4.790E-09
CA 103A	3	1	9	4	2078.5	22	1692	3005	3569	4.707E-10	1.150E-11	0.	0.
CA 103B	3	2	9	4	2078.5	22	4157	3015	4401	3.342E-08	1.430E-09	1.866E-08	8.900E-10
CA 104	4	1	9	4	2083.5	22	2920	3014	3987	2.534E-09	5.800E-11	5.999E-10	4.670E-11
CA 105	4	2	9	4	2083.5	22	4437	3032	4511	1.482E-08	2.400E-10	7.332E-09	1.270E-10
CA 108	5	1	9	4	2625.0	22	1186	520	915	1.076E-10	3.500E-12	0.	0.
CA 111	5	2	9	4	2625.0	22	2247	515	1264	2.374E-09	3.900E-11	1.694E-09	2.700E-11
CA 112	5	3	9	4	2625.0	22	3298	517	1616	2.524E-08	3.200E-10	1.395E-08	1.100E-10
CA 121	6	1	9	4	2677.0	22	1127	3009	3385	1.656E-10	9.700E-12	0.	0.
CA 122	6	2	9	4	2677.0	22	3355	3012	4130	1.588E-08	4.900E-10	9.392E-09	2.740E-10
CA 118	7	1	9	4	2672.5	100	994	33	364	1.153E-08	4.100E-10	0.	0.
CA 107	8	1	9	4	2624.0	100	1075	513	871	8.925E-09	7.300E-11	4.575E-09	2.660E-10
CA 114	9	1	9	4	2686.0	100	988	514	843	2.730E-09	2.700E-11	1.166E-09	2.410E-10

Table 1 (continued)

Steady State Creep Rates from Exponential Fit (Eq. 1)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	T	σ_3	P	$\dot{\epsilon}_{S1}$	ERROR	$\dot{\epsilon}_{S3}$	ERROR
CA 116	9	2	9	4	2686.0	100	2356	517	1332	4.951E-08	4.361E-08	6.022E-08	7.650E-09
CA 117	10	1	9	4	2671.0	100	914	3027	3332	2.091E-09	1.600E-11	0.	0.
CA 119	10	2	9	4	2671.0	100	2209	3019	3755	5.217E-08	2.340E-09	1.399E-08	2.800E-09
CA 115	11	1	9	4	2688.0	200	994	526	857	1.742E-07	4.400E-09	9.602E-08	3.070E-09
CA 120	12	1	9	4	2656.0	200	997	2951	3283	2.415E-07	3.300E-09	1.086E-07	9.400E-09
CA 100	13	1	7	4	2777.0	22	4714	521	2092	4.168E-07	5.700E-09	2.765E-07	3.730E-09
CA 101	14	2	7	4	2741.0	22	2106	11	713	4.205E-09	4.410E-10	5.162E-10	0.
RS7901	1	1	9	2	2501.2	24	1510	0	503	3.044E-09	7.800E-11	0.	0.
RS7901A	1	1	9	2	2503.7	24	1502	0	501	4.242E-11	6.856E-11	0.	0.
RS7901B	1	2	9	2	2503.7	75	1477	0	492	4.009E-09	1.030E-10	0.	0.
RS7902	2	1	9	2	2442.2	24	2984	2509	3504	4.594E-09	9.600E-11	2.208E-09	4.900E-11
RS7903	3	1	9	2	2442.8	24	2983	508	1502	8.367E-09	1.710E-10	4.231E-09	1.250E-10
RS7904	4	1	9	2	2509.1	24	1536	3006	3518	1.598E-09	3.600E-11	0.	0.
RS7904A	4	1	9	2	2501.2	24	1532	3005	3516	3.103E-10	8.000E-12	4.970E-11	1.701E-11
RS7904B	4	2	9	2	2501.2	105	1508	3008	3511	1.756E-08	4.200E-10	7.531E-09	3.250E-10
RS7905	5	1	9	2	2439.2	75	1506	3001	3503	2.416E-09	2.100E-11	1.080E-09	2.300E-11
RS7906	6	1	9	2	2442.8	105	1483	3003	3499	9.686E-09	4.460E-10	4.932E-09	3.680E-10
RS7907	7	1	9	2	2439.2	210	1471	3003	3493	2.575E-06	1.700E-08	1.336E-06	1.100E-08
RS7908	8	1	9	2	2441.9	210	789	0	263	5.731E-08	7.600E-10	0.	0.
RS7909	9	1	9	2	2442.2	210	791	507	771	9.215E-08	3.200E-10	4.578E-08	2.200E-10
RS7910	10	1	9	2	2443.8	210	797	2992	3258	5.712E-08	5.700E-10	3.634E-08	2.400E-10

Table 2

Steady State Creep Rates from Logarithmic Fit (Ec. 2)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	T	σ_3	P	$\dot{\epsilon}_{s1}$	ERRGR	$\dot{\epsilon}_{s3}$	ERROR
RS55013	1	2	7	2	2729.0	24	3024	518	1526	1.294E-08	2.990E-09	7.083E-09	1.318E-09
RS5501C	1	3	7	2	2729.0	24	4305	519	1954	6.891E-08	2.670E-09	3.496E-08	1.370E-09
RS5502A	2	1	7	2	2715.0	100	1497	589	1088	1.361E-09	1.830E-09	0.	0.
RS5503A	3	1	7	2	2715.0	24	1495	2034	2532	2.012E-09	2.560E-10	0.	0.
RS5503B	3	2	7	2	2715.0	24	2968	2015	3004	1.481E-08	1.050E-09	5.045E-09	3.850E-10
RS5503C	3	3	7	2	2715.0	24	4244	2044	3459	4.801E-08	2.900E-09	1.840E-08	1.510E-09
RS5504A	4	1	7	2	2711.0	24	3037	2012	3024	5.153E-09	5.060E-10	0.	0.
RS5504B	4	2	7	2	2711.0	24	4309	2008	3444	4.979E-08	2.200E-09	2.187E-08	1.270E-09
RS5505A	5	1	7	2	2711.0	100	1509	1990	2493	2.837E-08	6.100E-10	1.361E-08	3.800E-10
RS5505B	5	2	7	2	2711.0	100	2531	2010	2887	4.244E-07	3.600E-09	1.962E-07	2.100E-09
RS5506	6	1	7	2	2715.5	100	2702	2003	2934	4.153E-07	6.100E-09	1.852E-07	2.700E-09
RS6202	2	1	9	2	2668.5	74	1544	0	515	1.215E-08	5.600E-10	0.	0.
RS6203	3	1	9	2	2622.0	107	1515	0	505	2.857E-08	8.400E-10	0.	0.
RS6205	5	1	9	2	2674.5	24	3088	2360	3389	1.839E-08	6.700E-10	8.208E-09	2.740E-10
RS6206	6	1	9	2	2674.5	73	3041	2602	3616	4.085E-07	5.600E-09	1.588E-07	2.700E-09
RS6207	7	1	9	2	2679.0	105	3066	2510	3532	1.474E-06	4.800E-08	7.093E-07	2.330E-08
RS6208	8	1	9	2	2635.0	105	1559	2978	3498	4.153E-08	6.200E-10	2.026E-08	4.300E-10
RS6209	9	1	9	2	2678.0	24	1520	0	507	4.785E-10	8.798E-10	0.	0.
RS6210A	10	1	9	2	2606.0	24	1481	2518	3012	2.480E-09	2.040E-10	1.437E-09	2.120E-10
RS6210B	10	2	9	2	2606.0	24	3077	2425	3451	1.623E-09	8.200E-10	8.217E-09	4.040E-10
RS6211	11	1	9	2	2679.0	103	1495	0	498	1.100E-07	3.100E-09	0.	0.

Table 2 (continued)

Steady State Creep Rates from Logarithmic Fit (Eq. 2)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	T	σ_3	P	$\dot{\epsilon}_{S1}$	ERROR	$\dot{\epsilon}_{S3}$	ERROR
RS6212A	12	1	9	2	2678.3	106	1558	2450	2969	6.508E-08	2.310E-09	2.969E-08	1.720E-09
RS6212B	12	2	9	2	2678.3	107	3118	2570	3609	1.554E-06	2.580E-07	7.247E-06	1.210E-06
RS6213	13	1	9	2	2605.5	24	4535	1971	3473	5.380E-08	1.800E-09	2.651E-08	8.600E-10
RS6214	14	1	9	2	2678.7	24	5864	1467	3422	4.397E-07	7.900E-09	2.158E-07	4.000E-09
CA 102A	1	1	9	4	2078.0	22	1999	486	1152	5.128E-10	1.640E-11	0.	0.
CA 102B	1	2	9	4	2078.0	22	4493	566	2004	4.827E-08	4.880E-09	2.780E-08	2.750E-09
CA 109	2	1	9	4	2083.0	22	2974	561	1492	2.062E-09	9.100E-11	2.099E-09	5.700E-11
CA 110	2	2	9	4	2083.0	22	4436	528	2307	3.376E-08	7.520E-09	-4.099E-09	8.728E-09
CA 103A	3	1	9	4	2078.5	22	1692	3005	3569	1.813E-10	1.060E-11	0.	0.
CA 103B	3	2	9	4	2078.5	22	4157	3015	4401	2.291E-08	1.870E-09	1.155E-08	1.380E-09
CA 104	4	1	9	4	2083.5	22	2920	3014	3987	2.027E-09	5.400E-11	4.529E-10	2.230E-11
CA 105	4	2	9	4	2083.5	22	4437	3032	4511	8.495E-09	1.900E-10	4.017E-09	1.000E-10
CA 108	5	1	9	4	2625.0	22	1186	529	915	4.560E-11	6.170E-12	0.	0.
CA 111	5	2	9	4	2625.0	22	2247	515	1264	1.431E-09	3.600E-11	1.416E-09	4.500E-11
CA 112	5	3	9	4	2625.0	22	3298	517	1616	1.746E-08	3.500E-10	1.210E-08	1.600E-10
CA 121	6	1	9	4	2677.0	22	1127	3039	3385	2.841E-11	7.570E-12	0.	0.
CA 122	6	2	9	4	2677.0	22	3355	3012	4139	1.262E-09	4.200E-10	7.579E-09	2.410E-10
CA 118	7	1	9	4	2572.5	100	994	33	364	8.647E-09	7.520E-10	0.	0.
CA 107	8	1	9	4	2524.0	100	1075	513	871	6.764E-09	1.600E-10	3.700E-09	4.240E-10
CA 114	9	1	9	4	2636.0	100	988	514	843	2.610E-09	3.700E-11	5.931E-10	6.472E-10

Table 2 (continued)

Steady State Creep Rates from Logarithmic Fit (Eq. 2)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	τ	G_3	P	$\dot{\epsilon}_{S1}$	ERROR	$\dot{\epsilon}_{S3}$	ERROR
CA 116	9	2	9	4	2686.0	100	2356	517	1302	9.650E-08	4.360E-08	4.110E-08	1.735E-08
CA 117	10	1	9	4	2671.0	100	914	3027	3332	1.980E-09	3.200E-11	0.	0.
CA 119	10	2	9	4	2671.0	100	2209	3019	3755	4.476E-08	2.390E-09	3.687E-09	3.368E-09
CA 115	11	1	9	4	2688.0	200	994	526	857	1.353E-07	6.900E-09	7.518E-08	5.430E-09
CA 120	12	1	9	4	2668.0	200	997	2951	3283	2.361E-07	3.100E-09	1.331E-07	7.000E-09
CA 100	13	1	9	4	2777.0	22	4714	521	2092	3.919E-07	1.140E-08	2.612E-07	8.000E-09
CA 101	14	2	9	4	2741.0	22	2106	11	713	3.455E-09	7.170E-10	3.841E-10	5.424E-10
RS7901	1	1	9	2	2501.2	24	1510	0	503	1.467E-09	7.200E-11	0.	0.
RS7901B	1	2	9	2	2503.7	75	1477	0	492	3.664E-09	2.230E-10	0.	0.
RS7902	2	1	9	2	2442.2	24	2984	2509	3504	3.844E-09	6.000E-11	1.939E-09	4.100E-11
RS7903	3	1	9	2	2442.8	24	2983	508	1502	5.292E-09	1.470E-10	2.771E-09	1.190E-10
RS7904	4	1	9	2	2509.1	24	1536	3006	3518	4.436E-10	3.240E-11	0.	0.
RS7904A	4	1	9	2	2501.2	24	1532	3005	3516	1.751E-10	1.650E-11	-4.079E-11	3.230E-11
RS7904B	4	2	9	2	2501.2	105	1508	3008	3511	1.190E-08	4.900E-10	4.335E-09	4.270E-10
RS7905	5	1	9	2	2439.2	75	1536	3001	3503	2.035E-09	2.700E-11	9.192E-10	3.410E-11
RS7906	6	1	9	2	2442.8	105	1488	3003	3499	8.644E-09	4.960E-10	4.291E-09	5.630E-10
RS7907	7	1	9	2	2439.2	210	1471	3003	3493	2.080E-06	4.100E-08	1.075E-06	2.300E-08
RS7908	8	1	9	2	2441.9	210	789	0	263	2.479E-08	5.500E-10	0.	0.
RS7909	9	1	9	2	2442.2	210	791	507	771	6.855E-08	7.200E-10	3.353E-08	5.200E-10
RS7910	10	1	9	2	2443.8	210	797	2992	3258	5.004E-08	8.600E-10	2.774E-08	5.500E-10

Table 3

Secondary Creep Constants

	Exponential Creep Table 1	Logarithmic Creep Table 2
A (lower level) /sec	6.70 E+14/1.42	8.20 E+14/1.47
A (upper level) /sec	2.50 E+14/0.53	2.58 E+14/0.46
n	4.90 /0.27	4.93 /0.24
Q kcal/mole	12.0 /0.65	12.2 /0.58
kJ/mole	50.2 /2.72	51.1 /2.43
Log Standard Deviation	0.887	0.740
Coeff of Determination	0.936	0.953

Values are followed by a slash and their standard errors, the exponent of the error being understood to be the same as that of the value.

Table 4

Results for Load Drop Tests, Exponential Fit (Eq. 1)

ID	TEST	STAGE	HOLE	SIZE	DEPTH	T	τ	α_3	P	$\dot{\epsilon}_{S1}$	ERROR	$\dot{\epsilon}_{S3}$	ERROR
CA 106	4	3	9	4	2083.5	22	2948	3953	4016	1.891E-10	0.	0.	0.
CA 113	5	4	9	4	2625.0	22	2265	514	1269	3.021E-10	1.400E-11	5.919E-10	4.230E-11

Fig. 1. Scaled Exponential Secondary Creep Rate vs. Shear Stress
(T: ○ 22°C, × 70°C, □ 100°C, ◇ 200°C)

Fig. 2. Scaled Exponential Secondary Creep Rate vs. Temperature
 (τ : $\circ$ 1000 psi, $\times$ 1500 psi, ∇ 2000 psi, $\diamond$ 3000 psi,
 $\triangle$ 4500 psi, $\star$ 6000 psi.)

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Fig. 5. Scaled Secondary Creep Rates vs Shear Stress for Tatum Dome Salt^{15,16}
 (T: ● 23°C, □ 66°C) and Grand Saline and Hockley Mine Salt¹⁷
 (T: ▲ 23°C) Solid Symbols: Triaxial Extension

Fig. 6. Scaled Secondary Creep Rates vs Temperature for Tatum Dome Salt¹⁶
 (τ : $\circ$ 750 psi, $\diamond$ 2000 psi $\square$ 3000 psi) and West Hackberry Dome Salt¹⁸
 (τ : $\triangle$ 3000 psi) Solid Symbols: Triaxial Extension

Fig. 7. Secondary Creep Rates vs Shear Stress for Polycrystalline Halite¹⁹
(T: ○ 23°C, □ 100°C, ◇ 200°C)

Fig. 8. Scales Secondary Creep Rates vs Temperature for Polycrystalline Halite¹⁹
 (τ : ◇ 500 psi, ○ 1000 psi, △ 3000 psi, ▽ 4500 psi.)

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