

# A Creep Model for Salt

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## ABSTRACT

The purpose of this paper is to propose a one-dimensional creep model for salt where strain rate is postulated to depend on stress, strain, and temperature. Time does not appear explicitly in the expression for strain rate, but enters indirectly through the strain which is a function of time in the laboratory creep test where stress and temperature are held constant. In the more general case, time dependence may enter through the functional dependence of stress, strain and temperature on time. This proposed model is in contrast to the commonly used power law approach where strain is assumed to be proportional to the product of stress, absolute temperature, and time each raised to a power determined by fitting the model to laboratory data. In the case of the power law, strain rate is obtained by differentiation of the strain function and time appears explicitly. The power law formulation for a laboratory creep test is apparently for transient creep only because the strain rate continues to decay with time and becomes asymptotic to zero rather than the finite strain rate of secondary creep. Strain rate in the proposed model becomes asymptotic to the steady-state strain rate as strain increases. Steady-state strain rates are estimated using the equation proposed by Heard (1972). Heard's laboratory data are used in the proposed creep model to simulate creep tests. The simulated creep test results are then handled in the same manner as laboratory creep data and the exponent on time is evaluated. For the two cases presented, the exponents on time resulting from the simulated creep test are reasonably close in value to those obtained in laboratory creep tests by others. These results indicate that, at least for the test results considered, the behavior of salt is consistent between constant strain rate tests and creep tests. Consequently, in the future, it may be possible to run constant strain rate tests and produce experimental data equivalent to creep tests that may take considerable more time in the laboratory.

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## INTRODUCTION

The time-dependent behavior of natural rock salt is of interest from several points of view which include the geological questions related to the genesis of anticlines, spines, domes, and other diapiric structures, as well as, the more practical questions related to the exploitation of petroleum and natural gas resources and the exploitation of the rock salt for commercial use. In addition, knowledge of the creep behavior of rock salt is of paramount importance in underground storage applications of petroleum products and nuclear wastes. The purpose of this paper is to generally discuss the time-dependent response of salt, to propose a one-dimensional model for this behavior, and to illustrate the model's capacity to simulate creep behavior using constant strain-rate test data.

## LABORATORY TESTS

Table 1 outlines the traditional approach to creep law development, as well as, the modifications that are being made to check for stress/strain or temperature-path dependency and size effects. The question of the adequacy of laboratory tests to predict the in situ response of structures in rock salt will not be addressed in this paper. For our purposes, we assume that the laboratory tests will provide us useful information for computerized modeling of the response of structures in cavities excavated in salt.

Two types of laboratory tests have been used to study time-dependent behavior of salt, the traditional creep test

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TABLE 1

## "Traditional" Approach to Creep Law Development

1. Assume:  $\epsilon = f(\sigma, T, t)$  transient  
 $\dot{\epsilon} = f(\sigma, T)$  steady-state.
2. Run laboratory creep test at constant  $T$  and  $\sigma$  (or load).
3. Determine constants in assumed creep law from laboratory results and modifications.
4. Stress, strain, and/or temperature path tests.
5. Bench scale laboratory tests—check for size effects.

and the constant strain-rate test. In the traditional creep test, typically, a right circular cylindrical sample of rock salt with a diameter approximately 2 to 10 cm and a length-to-diameter ratio of approximately 2:1 is subjected to a constant differential stress and temperature. The deformation of the sample is monitored, and the results are plotted as strain vs time. For high enough stresses and temperatures, the creep response exhibits three different phases. The first is the transient phase, where the strain rate decreases with time until it reaches the second phase, which is referred to as steady-state creep. In this second phase, the creep rate remains constant and is independent of time. Finally, the response enters the third or tertiary phase, which ends in rupture of the material.

A contrast to the classical creep test is the other type of test used for studying the time-dependent response of salt, the constant strain-rate test. In this test, a laboratory sample of approximately the same size as that used in the creep test is strained at a constant rate and temperature while force on the sample is monitored. This force can then be converted into stress as a function of time. The deformation of the sample is monitored during the test. Figure 1 shows typical stress/strain curves resulting from constant strain-rate tests on manufactured polycrystalline halite (data per H. Heard, 1972). The curves shown are for different strain rates as indicated on the figure. Note that as strain increases, each of the constant strain-rate curves bends over and tends to become parallel to the strain axis. At this stage, the straining continues at constant stress and temperature, which is the definition of steady-state creep.

To the author's knowledge, the creep model presented in this paper is the first attempt to simulate a creep test from the constant strain-rate data and thereby, to investigate the consistency of salt behavior and its sensitivity to test conditions.

### MATHEMATICAL MODELS DESCRIBING CREEP BEHAVIOR

Several mathematical models have been proposed to represent measured creep or time-dependent response. In the transient creep range, a commonly suggested formula is the so-called "power law" where strain is assumed to depend on the product of a constant  $\times$  temperature to a power  $\times$

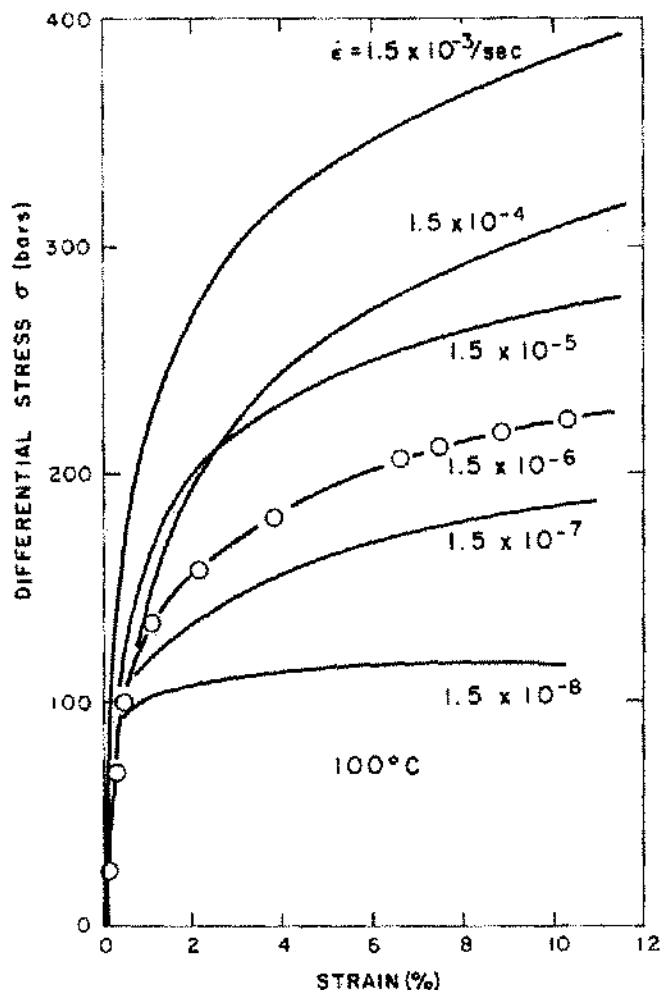


Figure 1. Stress-Strain Curves at Various Strain Rates, (Heard, 1972).

stress to a power  $\times$  time to a power. This formulation fits the data reasonably well. However, several deficiencies in the "power law" formulation are apparent. The deficiencies are discussed below.

The "power law" formulation is sometimes referred to as the state-variable approach wherein the assumption is made that the strain depends only on the values of stress and temperature at a particular time and is not dependent on the path that was used to get to the present state. A state-variable representation is generally valid when considering conservative processes that do not dissipate energy. In the case of salt creep, the deformation process does dissipate energy, and consequently, a state-variable approach may not be appropriate. Also, questions relative to the effects of gradients in temperature and stress, as well as sample size effects and the presence of non-salt minerals must be considered. The question of laboratory-determined properties vs in situ properties of salt persists, along with the question of whether or not a salt sample can be replaced in the laboratory to the stress conditions in which it existed underground

prior to removal from the salt rock mass. Other questions related to the "power law" formulation include the question of when time should start. Generally, the assumption is made that the time in the "power law" formulation starts when any changes in stress and/or temperature begin. However, philosophically, time does not appear to be an intrinsic material parameter and should perhaps be replaced by strain, as shown later. Recent work by Wawersik (1978) indicates a mean stress effect that is not accounted for in the usual "power law" formulation. That a "power law" formulation is applicable only to the transient regime is apparent because the strain rate continues to decrease with time and eventually becomes asymptotic to zero rather than to a steady-state creep rate as the experimental data indicate.

With respect to steady-state creep, Heard (1972), using constant strain-rate tests, found that for laboratory-prepared polycrystalline halite at 2 kilobars of confining pressure, creep data in the steady-state range are consistent with Weertman's (1957) models of creep by dislocation climb. Heard's data are well fit by

$$\dot{\epsilon} = A \exp(-E/RT) \sigma^n$$

where

$$A = 3 \times 10^{-6} \text{ sec}^{-1},$$

$$E = 23.5 \text{ kcal/mole},$$

$$T = \text{absolute temperature},$$

$$R = \text{universal gas constant, and}$$

$$n = 5.5.$$

Constant strain-rate tests on single crystals of halite were reported by Carter and Heard (1970). This work gives insight into the slip systems that give rise to temperature and rate-dependent deformation halite crystals.

We conclude that much more is known about the mechanisms that account for steady-state creep of pure halite than about transient creep and the transition between transient and steady-creep. Work is in progress to develop a better understanding of these mechanisms, particularly the transition between transient and steady-creep. In addition, work is under way to study the applicability of results obtained on pure polycrystalline halite samples to natural rock salt samples that contain impurities such as anhydrite, clay minerals, etc.

## PROPOSED CREEP MODEL

The proposed model for creep behavior is empirical and is presently not explicable by fundamental mechanisms of salt deformation. This model takes the form of strain rate as a function of stress difference, temperature, and strain. Time does not explicitly appear as an independent variable but is replaced by strain with the idea that strain may be more representative of the structure of the material than the parameter time. In either case, the deformation history of the sample to be tested in the laboratory is essentially unknown, particularly for samples from diapiric structures; therefore, whether time or strain is used in the formulation

may be less important than the microstructure of the salt as influenced by its previous history.

In order to check the validity of this model, data from Heard (1972) on laboratory-prepared, annealed polycrystalline salt samples were used. Table 2 illustrates the procedure and form of the equations involved. The data referred to in step 1 of Table 2 are obtained from curves such as those shown in Fig. 1 for a uniform temperature of 100°C. For a constant differential stress, such as 150 bars, a set of curves such as those shown in Fig. 1 will yield a data table with columns of strain rate and strain for constant temperature and stress. Strain-rate values must be corrected for the deformability of the test apparatus before fitting the curves. The constants  $A_i$  shown in the equation in Table 2 depend on both stress and temperature. The form of this dependency has not yet been established, but it is likely that stress would appear raised to a power while temperature would enter in an exponential as previously shown in the steady-state formulation.

Results from the curve fitting for two cases are shown in Figures 2 and 3. Since only three data points were available for the 23°C test, a single term was used for the curve fit shown in Figure 2. For Figure 3, the curve for the strain rate of  $1.5 \times 10^{-4}$  (shown in Fig. 1) was assumed to be anomalous in the transient region and was not included in the data set used to determine the two-term approximation. Also in Figure 3, the steady-state was assumed to have been reached for a strain of 10%, and the steady-state model proposed by Heard (1972) was used to calculate the value shown on the curve. Additional data points and terms in the series are obviously needed to give more confidence in this curve-fitting exercise. However, in both Figures 2 and 3, the form assumed appears to reasonably describe the experimental data.

The data points used for the curve fitting were supplied by Heard and have been corrected for distortion of the apparatus during the transient phase of the response. Consequently, the strain rates are slightly different than those that could be obtained directly from curves such as those shown in Figure 1.

TABLE 2

### Consistency of Salt Behavior

Is it possible to reconstruct a creep curve from constant strain-rate test data?

1. Fit data from (Heard, 1972) to the following form

$$(\dot{\epsilon})^{-1} = \sum A_i \exp(-\lambda_i/\epsilon).$$

2. Integrate to obtain

$$t = \sum A_i [\epsilon \exp(-\lambda_i/\epsilon) - \lambda_i E_1(\lambda_i/\epsilon)]$$

Where:

$$E_1(x) = \int_x^\infty \frac{e^{-u}}{u} du = \text{exponential integral of the first order.}$$

3. Calculate  $t$  corresponding to a particular  $\epsilon$  and plot as a function of time.

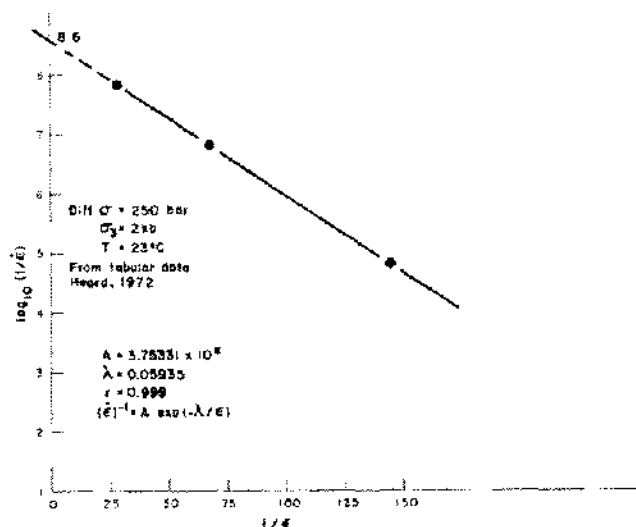


Figure 2. Logarithm of Inverse Strain Rate vs. Inverse Strain for  $T = 23^\circ\text{C}$ .

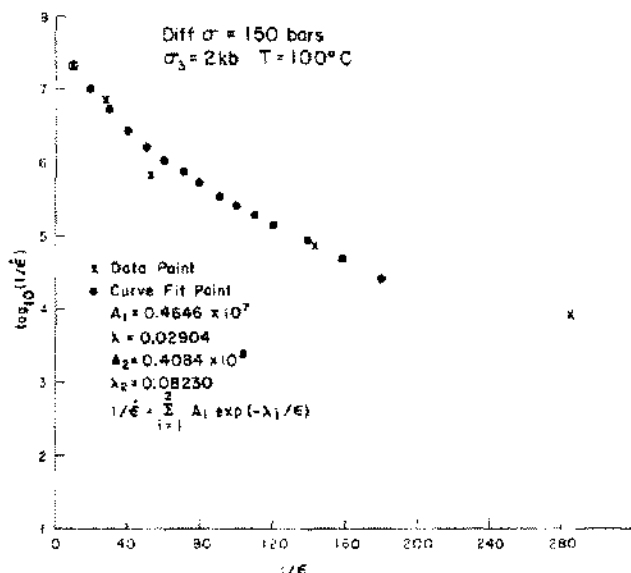


Figure 3. Logarithm of Inverse Strain Rate vs. Inverse Strain for  $T = 100^\circ\text{C}$ .

## RESULTS

Results obtained from following the procedure outlined in Table 2, using corrected data from Figure 1 at 150 bars differential stress and  $100^\circ\text{C}$ , are shown in Figures 4 and 5. Figure 4 presents a strain vs time, simulated creep test that has the attributes of the classical creep test in the transient range and approaches steady state for  $\epsilon < \sim 10\%$ , which agrees well with original data used.

Similar results are shown in Figures 6 and 7 for the data curve fit given in Figure 2 (room temperature and a stress difference of 250 bars). Again, the creep curve simulated from the constant strain-rate data appears reasonable.

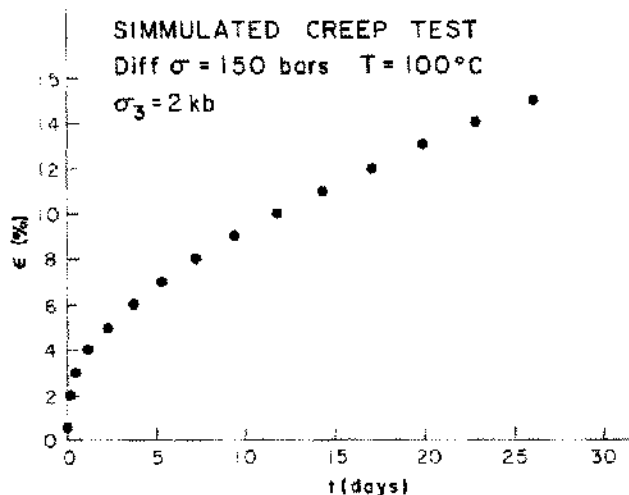


Figure 4. Simulated Creep Test for  $T = 100^\circ\text{C}$ .

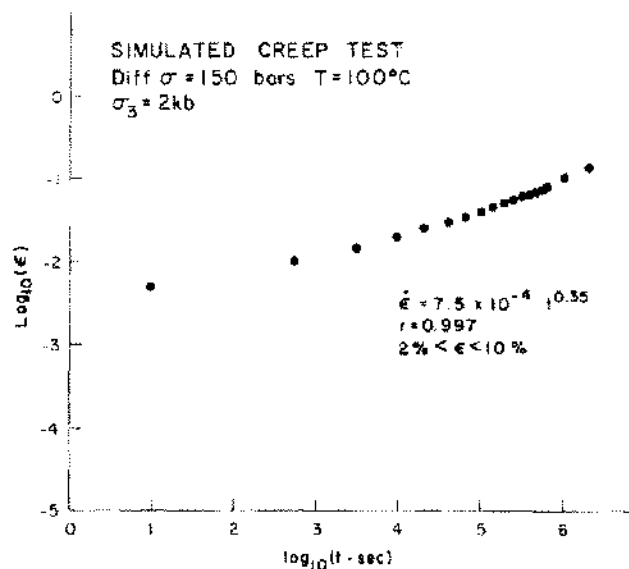


Figure 5. Logarithmic Plot of Strain vs. Time for  $T = 100^\circ\text{C}$ .

Figure 5 indicates that the power on time is approximately 0.35 for strain between 2 and 10%, and Figure 7 indicates that the power on time for that case is approximately 0.27 for strain between 1 and 10%. Both of these powers fall within one standard deviation of the average power on time as reported by Hansen (1977) for natural rock salt creep tests. These powers on time also agree with the 0.3 reported by Lomenick (1968) for creep tests on model pillars of natural salt.

## DISCUSSION AND CONCLUSION

The results presented in this paper indicate that the power on time in the power law creep formula may be obtained with a high degree of consistency from constant strain-rate test data in the

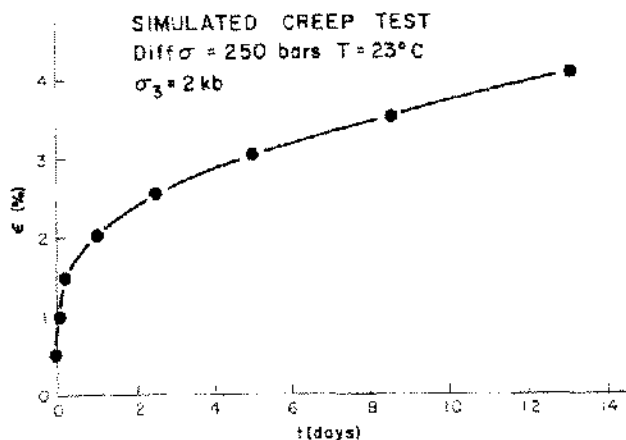


Figure 6. Simulated Creep Test for  $T = 23^{\circ}\text{C}$ .

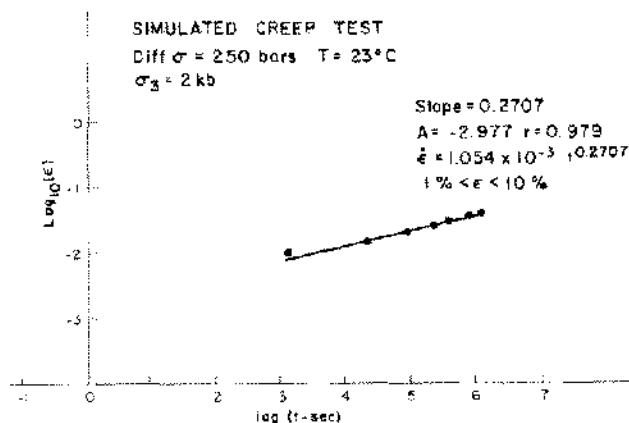


Figure 7. Logarithmic Plot of Strain vs. Time for  $T = 23^{\circ}\text{C}$ .

proposed creep model. These results give us hope that data from manufactured polycrystalline halite tests will prove very useful in the study of natural rock salt and that the dependency of salt response on load path is of minimal importance. However, the results presented here should be considered indicative, rather than definitive, because of the lack of sufficient data, particularly in the transition zone between the transient and steady-state creep. Also,

these results are empirically based and consequently do not have the firm mechanistic basis of the steady-state creep models.

If this or a similar approach, stands the test of further investigation, it will allow a single mathematical representation of the time-dependent behavior for transient through steady-state creep. In addition, it will allow the use of data obtained from constant strain-rate tests to complement data from the standard creep tests.

#### ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy through its contract with Union Carbide Corporation, Nuclear Division. The technical context of this work has been influenced by my conversations with Dr. Hugh Heard, Lawrence Livermore Laboratories, who provided the corrections for his test apparatus deformability during the transient phase of his constant strain-rate tests; with Dr. Wolfgang Wawersik, Sandia Laboratories; and with Dr. Arlo Fossum, RE/SPEC Inc.

#### REFERENCES

- Carter, N.L., and Heard, H.C. 1970. Temperature and Rate Dependent Deformation of Halite. *Am. J. Sci.* 269:193-249.
- Hansen, F.D. 1977. Case History Rock Mechanics Examination of the Jefferson Island Salt Mine: II. Laboratory Evaluation of Strength and Creep Deformation. Office of Waste Isolation, Union Carbide Corporation, Nuclear Division, Y/OWI/SUB-77/22303/5.
- Heard, H.C. 1972. Steady-State Flow in Polycrystalline Halite at Pressure of 2 Kilobars. *Flow and Fracture of Rocks*. Amer. Geophysical Union, Geophysical Monograph Series 16:191-209.
- Lomenick, T.F. 1968. Accelerated Deformation of Rock Salt at Elevated Temperature and Pressure and Its Implications for High-Level Radioactive Waste Disposal. (Ph.D. Thesis, Univ. of Tennessee) Oak Ridge National Laboratory, Union Carbide Corporation, Nuclear Division, ORNL-TM-2102.
- Wawersik, W.R. 1978. Effects of Pressure, Deviator Stress and Temperature on Transient Creep of Rock Salt at Low Confining Pressure (Abstract). *EOS, Trans. Am. Geophysical Union*; 59 (4).
- Weertman, J. 1957. Steady-State Creep Through Dislocation Climb, *Applied Physics J.* 28:362-364.