26
14/26/80 T.S.
1" to 11 TIS
SAND-80-2172
Unlimited Release
UC-70

(1)

A MODEL FOR TRANSIENT CREEP
OF SOUTHEASTERN NEW MEXICO ROCK SALT

MASTER

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

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of
Energy under Contract DE-AC04-76DP00789.

November 1980

Sandia National Laboratories

SF 2900-Q(3-80)

R237

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia Laboratories, operated for the United States
Department of Energy by Sandia Corporation.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Printed Copy \$4.50; Microfiche \$3.00

SAND-80-2172
Unlimited Release
Printed November 1980

A MODEL FOR TRANSIENT CREEP
OF SOUTHEASTERN NEW MEXICO ROCK SALT

W. Herrmann
Solid Dynamics Department 5530

W. R. Wawersik
Geomechanics Division 5532

H. S. Lauson
Computational Physics & Mechanics Division I 5531
Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

In a previous analysis, existing experimental data pertaining to creep tests on rock salt from the Salado formation of S.E. New Mexico were fitted to an exponential transient creep law. While very early time portions of creep strain histories were not fitted very well for tests at low temperatures and stresses, initial creep rates in particular generally being underestimated, the exponential creep law has the property that the transient creep strain approaches a finite limit with time, and is therefore desirable from a creep modelling point of view. In this report, an analysis of transient creep is made. It is found that exponential transient creep can be related to steady-state creep through a universal creep curve. The resultant description is convenient for creep analyses where very early time behavior is not important.

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Table of Contents

1. Introduction	5
2. Transient Creep Model.	7
3. Analysis of Multistage Tests	10
4. Analysis of Transient Creep.	13
5. Universal Creep Curve.	19
6. Conclusion	22
References	24
Tables	26
Figures.	31

1. Introduction

An analysis has been reported¹ of triaxial 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. Tests covered a nominal range of shear stresses (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). Material characterization and test procedures have been described elsewhere.¹⁻⁶

Strain-time records for individual creep tests had been fitted to both exponential and logarithmic transient creep laws. Steady-state creep rates obtained from both fits agreed well, and their dependence on stress and temperature have been analyzed elsewhere.⁶

The logarithmic transient creep expression had been found to fit individual strain-time records rather better than the exponential expression. In particular, while tests performed at relatively high stresses or temperatures were fitted about equally well by both expressions, the exponential creep expression did not give good fits to the very early time strain histories for tests conducted at low temperatures.¹ For these tests, the initial creep rates, in particular, were underestimated, seriously so at low stresses.

Despite this shortcoming of the exponential transient creep expression, it does have the property that the transient creep strain approaches a finite limit with time, while the transient creep strain in the logarithmic creep expression increases without limit. Where very early time creep behavior is not important, that is, for applications involving relatively long times, the convenience imparted by this property makes the exponential creep expression attractive for computational purposes.

An analysis is made in this paper of the exponential transient creep parameters. Previous suggestions that they are related to the steady-state creep rate are explored, and simple relationships are found to describe the data within the data scatter. These lead to a universal creep curve which is compared with results of individual creep tests.

2. Transient Creep Model

If the transient and steady-state creep can be described by the same mechanism, and if this mechanism is governed by simple first-order kinetics, then it is reasonable to assume that the rate of change of the creep rate should be proportional to the difference between its current and steady-state values, that is,

$$\frac{d\dot{e}}{dt} = - \frac{\dot{e} - \dot{e}_s}{t_r} \quad (1)$$

where $\dot{e}$ is the current creep rate, $\dot{e}_s$ is the steady-state creep rate, and t_r is the relaxation time appropriate to the creep mechanism.

Integration of (1) provides

$$\dot{e} = \dot{e}_s + (\dot{e}_1 - \dot{e}_s) \exp\left(-\frac{t}{t_r}\right) \quad (2)$$

where $\dot{e}_1$ is the initial creep rate ($\dot{e} = \dot{e}_1$ at $t = 0$). Another integration provides the familiar exponential creep law

$$e = e_0 + \dot{e}_s t + t_r (\dot{e}_1 - \dot{e}_s) \left\{ 1 - \exp\left(-\frac{t}{t_r}\right) \right\} \quad (3)$$

where e_0 is the instantaneous strain ($e = e_0$ at $t = 0$).

Equation (3) was originally presented as an empirical relation to describe transient creep,⁷ and has been used widely since then, primarily to describe high temperature creep in metals.⁸⁻¹⁰ Several authors¹¹⁻¹³ have arrived at analogous expressions on the basis of specialized dislocation models. It is not clear that these particular mechanisms are operative in the creep of rock salt at intermediate temperatures. However, it should be noted that such specific models are implicit in the form (3) and conversely the form (3) does not imply any specific mechanism. It is only necessary to assume a single dominant mechanism governed by (1) in order to derive it.

If we set

$$e_a = t_r (\dot{e}_1 - \dot{e}_s) \quad \xi = \frac{1}{t_r} \quad (4)$$

then (3) takes the form

$$e = e_o + \dot{e}_s t + e_a \{1 - \exp(-\xi t)\} \quad (5)$$

which has previously been used to obtain least squares fits to strain-time records for a large number of creep tests on S.E. New Mexico rock salt.¹ Before considering the data it is useful to pursue the properties of (5) somewhat further.

If it is assumed that the same mechanism controls transient and steady-state creep, then $\dot{e}_s$ and ξ should have the same stress and temperature dependence, and similarly $\dot{e}_1$ and $\dot{e}_s$,⁹ that is

$$\xi = B \dot{e}_s \quad \dot{e}_1 = D \dot{e}_s \quad (6)$$

where B and D are constants. From (4a), these would imply that e_a is a constant. These conditions have been found to be satisfied in high-temperature creep of several metals, although departures have been noted at low stresses, entailing correspondingly low steady-state creep rates.⁹

It is useful to decompose the creep rate (2) somewhat arbitrarily into primary and secondary parts by defining

$$\dot{e}_p = e_a \xi \exp(-\xi t) \quad (7)$$

where (4) has been used. If we similarly call

$$e_p = e_a \{1 - \exp(-\xi t)\} \quad (8)$$

the primary creep strain, then (7) and (8) can be solved to give

$$\dot{e}_p = \xi(e_a - e_p) \quad (9)$$

that is, the primary creep rate is a linearly decreasing function of primary creep strain. In fact (5) can be equally well derived from the phenomenological assumption (9). We note the properties $e_p = 0$, $\dot{e}_p = e_a \xi$ at $t = 0$, and $e_p = e_a$, $\dot{e}_p = 0$ as $t \rightarrow \infty$. Consequently, e_a is the asymptotic value of primary creep strain as time increases.

Returning to (8), it may be noted that the primary strain attains a value of approximately 99% of e_a in a time $t_c = 4.6 t_r$. This is also the time required for $\dot{e}_p$ to reduce to approximately 1% of its initial value, from (7). Thus t_c may be taken as an indication of the time required to approach steady state creep.

Finally, it should be noted that if the strains are not infinitesimal, then the proper strain measure to be used in the above expressions is the natural strain.

3. Analysis of Multistage Tests

The creep tests on S.E. New Mexico rock salt¹ involved a number of cases in which tests at successively higher stresses or temperatures were performed on the same specimen. These are identified as successive test stages. In order to compare transient creep parameters obtained from second or third stage tests with those from first stage tests, an analysis of the behavior of the exponential creep law in multistage tests is required.

Consider a first stage test performed on a virgin specimen. Assuming that creep is governed by (9), integration between limits $e_p = 0$, $t = 0$ and $e_p = e_{p1}$, $t = t_1$ provides

$$e_{p1} = e_{a1} \left\{ 1 - \exp(-\xi_1 t_1) \right\} \quad (10)$$

where e_{a1} and ξ_1 are constants appropriate to the constant shear stress and temperature of the first stage test. If e_{a2} and ξ_2 are constants appropriate to the shear stress and temperature of the second stage, integration of (9) between the limits $e_p = e_{p1}$, $t = t_1$ and $e_p = e_{p2}$, $t = t_2$ provides, (Fig. 1)

$$e_{p2}^* = e_{a2}^* \left\{ 1 - \exp(-\xi_2 t_2^*) \right\} \quad (11)$$

where

$$\begin{aligned} e_{p2}^* &= e_{p2} - e_{p1} & t_2^* &= t_2 - t_1 \\ e_{a2}^* &= e_{a2} - e_{p1}. \end{aligned} \quad (12)$$

Rewriting the last of these

$$e_{a2} = e_{a2}^* + e_{p1} \quad (13)$$

If $\dot{e}_{s1}$ is the secondary creep rate, e_1 is the total creep strain and e_{o1} is the instantaneous strain appropriate to the first stage, then e_{p1} is given by

$$e_{p1} = e_1 - \dot{e}_{a1} t_1 - e_{a1} \quad (14)$$

Recall that t_1 is the maximum time duration of the first stage test. Equation (11) has precisely the same form as (10), consequently the form of the creep law for a second stage test is identical to that for a first stage test (5), except that the total strain and time are taken relative to zero at the beginning of the second stage test. The secondary creep rate $\dot{e}_a$ is unaffected by the stage, as found in the analysis of steady-state creep rates of S. E. New Mexico rock salt.⁶ Likewise, ξ is unaffected by stage, but e_a^* for a second stage test requires correction by (13) before it can be compared with results of first stage tests.

Note that the duration of the second stage test is given, from (11), by

$$t_2^* = - \frac{1}{\xi_2} \ln \left(\frac{e_{a2}^* - e_{p2}^*}{e_{a2}^*} \right) \quad (15)$$

Had the entire test been performed on a virgin specimen under the conditions of the second stage, the test duration would have been

$$t_2' = - \frac{1}{\xi_2} \ln \left(\frac{e_{a2} - e_{p2}}{e_{a2}} \right) \quad (16)$$

Combining (15) and (16) and using (12)

$$t_2' = t_2^* + \frac{1}{\xi_2} \ln \left(\frac{e_{a2}^* + e_{p1}}{e_{a2}^*} \right) \quad (17)$$

where e_{p1} is given by (14). The equivalent test duration of a second stage test is therefore given by (17).

The above analysis can be repeated for a third stage test with analogous results, except that now the correction to e_a is given by

$$e_{a3} = e_{a3}^{\dagger} + e_{p2} \quad (18)$$

where

$$e_{p2} = (e_2^* - \dot{e}_{s2} t_2^* - e_{02}) + (e_1 - \dot{e}_{s1} t_1 - e_{01}) \quad (19)$$

Here ()^{*} refers to the second stage, as above, while ()[†] refers to the third stage. The equivalent test duration is

$$t_3' = t_3^{\dagger} + \frac{1}{\xi_3} \ln \left(\frac{e_{a3}^{\dagger} + e_{p2}}{e_{a3}^{\dagger}} \right) \quad (20)$$

where e_{p2} is given by (19).

It is useful to nondimensionalize the test duration by the time t_c required for the transient creep rate to reduce to 1% of its initial value

$$\bar{t} = \frac{t'}{t_c} = \frac{\xi t'}{4.6} \quad (21)$$

4. Analysis of Transient Creep

Strain-time histories for individual creep tests were previously fitted by the method of least squares to the exponential transient creep law (5). Complete tabulations of results have been given in the original reference,¹ together with plots of the data and fits for each experiment. Typical plots are reproduced in Fig. 2. It can be seen that, at low temperatures and stresses, initial creep rates are very high, compared to steady state creep rates, the ratio decreasing as either the stress or temperature are raised. The exponential creep law appears to underestimate the initial creep rate at low temperatures, seriously so at low stresses. At higher temperatures, the entire strain-time history is fitted very well. (Note that one test reproduced in Fig. 2 exhibits accelerating creep without a lengthy steady-state creep interlude. The accelerating portion of the strain history was truncated before making the fit for experimental records of this type. The tic mark on the curve of Fig. 2 indicates where the strain history was truncated.)

A number of tests exhibited experimental difficulties. Some of the tests at low temperatures and stresses, which reached total strains of only a few tenths percent, exhibited large data scatter due to limitations in instrumentation resolution. A few tests suffered some loss of strain data. Some other experiments suffered stress excursions which induced abnormalities in the strain-time records. Least squares fits had been made for these tests, and resulting values of $\dot{\epsilon}_s$, suitably weighted, had been used in an analysis of steady-state creep.⁶ While these various abnormalities did not seriously affect the estimate of the asymptotic steady-state creep rate, they tended to have a much larger effect on the transient creep parameters. After detailed study of the original data, a number of these tests were discarded for purposes of the present study.

In a few tests, the maximum test time did not appear to be sufficient to achieve steady state creep. In fitting individual creep experiments, a study had been performed in which some tests were repeatedly fitted after truncating the strain-time histories at successively earlier times.¹ This study indicated that while the fitted secondary creep rates were not very sensitive to such truncation, the primary creep parameters could vary by as much as an order of magnitude. For this reason, tests were deleted for which $\bar{t}$ given by (21) was less than unity.

Corrections to e_a and the maximum test time $t_{\max}$, discussed in the previous section, were applied to all second and third stage tests. In most cases, these corrections were small, in many cases negligibly so. Note that the most important parameter from previous stage fits used in the correction is the steady state creep rate $\dot{e}_s$. Corrections were made to second and third stage tests even when a previous stage was discarded for purposes of this study. Since the corrections were usually small, values of maximum strain and time can be read with sufficient accuracy from the graphs of Ref. 1.

Data for the surviving tests are given in Table 1. Note that the test I.D. corresponds to that given previously.¹ The temperature T is given in °C while the shear stress τ , confining stress σ_3 , and pressure p are given in psi, where

$$\tau = \sigma_1 - \sigma_3 \quad p = \sigma_3 + 1/3 \tau \quad (22)$$

σ_1 being the maximum principal stress while $\sigma_2 = \sigma_3$ is the confining stress in the triaxial compression test. All strain rates are in units of sec^{-1} while times are in sec. Tests which were omitted can be identified by comparison of Table 1 with Ref. 1.

Values of $\dot{e}_s$, $\dot{e}_1$, e_a , ξ , t_r and $\bar{t}$ are shown in Table 1 followed by a slash and their standard errors. Only values corresponding to axial strain records are shown. The standard errors are taken either directly from Table 2 of reference 1, or for derived quantities, were calculated by a first order error analysis.

Preliminary multiple regression analyses¹⁵ of the dependence of ξ and corrected e_a on the various parameters of the tests revealed no statistically significant dependence on confining pressure p , on location from which the test specimen has been recovered from the geology in terms of drill hole and geologic level, on specimen size (2 inch or 4 inch) or laboratory in which the specimen was tested (SLA or Re/SPEC Inc), or on test stage. Consequently all of these factors were ignored in subsequent analyses.

In order to test the assumption (6) that the initial creep rate $\dot{e}_1$ is proportional to steady creep rate $\dot{e}_s$, a plot of $\dot{e}_1$ vs $\dot{e}_s$ was made, Fig. 3. With the exception of three low stress tests performed at 22°C, this plot suggests that a straight-line indeed gives a reasonable representation of the data. A least-squares fit was made¹⁴ to

$$\ln \dot{e}_1 = \ln \dot{e}_s + \ln D \quad (23)$$

The value of the proportionality constant D is given in Table 2, together with the logarithmic standard deviation of the fit. Figure 3 shows a straight line representing the fit for comparison with the data together with lines at one standard deviation distance from the fit. While the three lowest points (CA108, CA121 and RS7904), which were omitted from the fit, fall well outside the uncertainty interval, it should be noted that results of other tests conducted under similar conditions do fall within the uncertainty interval.

In order to test the assumption in (6) that the relaxation frequency ξ is proportional to the steady-state creep rate $\dot{e}_s$, a similar plot of ξ vs $\dot{e}_s$ was prepared, Fig. 4. This plot exhibits a bimodal behavior, in that data at steady state creep rates above about $\dot{e}_s \sim 10^{-7}$ per sec. can be represented reasonably well by proportionality, while data at lower steady-state creep rates depart from this behavior. Results are qualitatively similar to those observed by Webster, Cox and Dorn⁹ in iron and stainless steel. Results at lower creep rates suggest a change in functional dependence of ξ on stress and temperature. This departure has been attributed,^{8,9} in metals, to an increase in the contribution by grain-boundary sliding to creep strain at lower stresses. Examination of the salt specimens reveals frequent evidence of both transgranular and intergranular cracks, which conceivably lead to an analagous effect. In fact, at the lower temperatures used in this test series, insufficient slip systems are active in NaCl crystals at low stresses to accommodate the observed strains without sliding on cracks or grain boundaries.

As in the stainless steel,^{8,9} data scatter is pronouncedly greater at steady state creep rates below the transition in Fig. 4. The data are insufficient to support any dependency of ξ on $\dot{e}_s$, and are as well represented by a constant value. Note that the separation between the two regions does not correlate well with stress, as suggested by Webster, Cox and Dorn⁹. Data points at the same shear stresses and temperatures are found in both regions.

The above observations suggest a representation of the relaxation frequency ξ as follows

$$\begin{aligned} \xi &= B \dot{e}_s & \text{for } \dot{e}_s &\geq \dot{e}^* \\ \xi &= C & \text{for } \dot{e}_s &\leq \dot{e}^* \end{aligned} \quad (24)$$

Note that B, C and $\dot{e}^{**}$ must satisfy the compatibility condition

$$B \dot{e}^{**} = C \quad (25)$$

A logarithmic least-square fit was made to the data,¹⁴ in order to find best values for B and C. Results are given in Table 2, together with the logarithmic standard deviation of the fit.* Figure 4 shows straight lines representing the fits together with lines at one standard deviation distance from the fit.

Figure 5 shows lines calculated from the fits in Figs. 3 and 4 compared to the data for e_a . Except for the three points at the lowest steady-state creep rate which were omitted from the fits, it can be seen that the lines provide a reasonable representation within the scatter of the data.

The lack of pressure dependence of transient creep can be illustrated by plotting values of the asymptotic transient creep strain e_a versus confining stress for various tests conducted at nominally the same shear stresses and temperatures, (Fig. 6). While there might be a slight tendency for e_a to reduce with confining stress, the scatter is large, and the trend is not statistically significant, as suggested by preliminary multiple regression analyses.

A pressure effect is usually connected with dilatancy. A measure of transient dilatancy, paralleling that of steady-state dilatancy considered previously,⁶ can be defined as

$$\eta_p = \frac{\dot{e}_{1a} + 2 \dot{e}_{3a}}{\dot{e}_{1a} - \dot{e}_{3a}} = \frac{\dot{e}_{1p1} + 2 \dot{e}_{3p1}}{\dot{e}_{1p1} - \dot{e}_{3p1}} \quad (26)$$

* Tests CA108, CA121 and RS7904 were omitted again from the fit.

where $()_1$ refers to the axial component, $()_3$ refers to the transverse component and $\dot{e}_{p,1} = \xi e_a = \dot{e}_1 - \dot{e}_3$ is the initial primary creep rate. Values of e_a obtained from fits to transverse strain histories¹ were corrected according to the results of Sect. 3, and used together with corresponding corrected values of e_a for axial strain histories given in Table 1 to calculate values of transient dilatancy η_p . These are plotted vs. shear stress for various temperatures in Fig. 7. Again, while some individual tests show significant expansion or compaction, no consistent trends with either shear stress or temperature are evident.

5. Universal Creep Curve

The relations of $\dot{e}_1$ and ξ to $\dot{e}_s$ may be used to construct a universal creep curve.⁹ At high creep rates, from (3), (6) (24) and (25)

$$\epsilon = t_n + \frac{D-1}{B} \left\{ 1 - \exp(-Bt_n) \right\} \quad (27)$$

where, for $\dot{e}_s \geq \dot{e}^*$

$$\epsilon = (e - e_0) \quad t_n = \dot{e}_s t \quad (28)$$

while, for $\dot{e}_s \leq \dot{e}^*$

$$\epsilon = (e - e_0) \frac{\dot{e}^*}{\dot{e}_s} \quad t_n = \dot{e}^* t \quad (29)$$

The experimental creep data for each test may be compared with the universal curve if the strain and time are suitably scaled. This can be done directly for first stage tests. For second and third stage tests, the data must be suitably shifted to account for earlier stages using the results of Sect. 3.

Applying (14) to a second stage test

$$(e_2 - e_0)^* = \dot{e}_{s2} t_2^* + e_{p2}^* \quad (30)$$

where $()^*$ implies that strain and time are taken relative to zero at the beginning of the second stage test (0^* in Fig. 1). Using (12), and (17), relative to the origin at $0'$, this becomes

$$(e_2 - e_0) = \dot{e}_{s2} t_2' + e_{p2} \quad (31)$$

where

$$(e_2 - e_0) = (e_2 - e_0)^* + \dot{e}_{s2} \frac{1}{\xi_2} \ln \left(\frac{e_{s2}^* + e_{p1}}{e_{s2}^*} \right) + e_{p1} \quad (32)$$

$$t_2' = t_2^* + \frac{1}{\xi_2} \ln \left(\frac{e_{s2}^* + e_{p1}}{e_{s2}^*} \right)$$

and e_{p1} is given by (14). The measured values of strain $(e_2 - e_0)^*$ and time t^* for a second stage test need correction by (32) for comparison with the universal creep curve. Similarly for a third stage test, the corrections are

$$(e_3 - e_0) = (e_3 - e_0)^\dagger + \dot{e}_{s3} \frac{1}{\xi_3} \ln \left(\frac{e_{s3}^\dagger + e_{p2}}{e_{s3}^\dagger} \right) + e_{p2} \quad (33)$$

$$t_3' = t_3^\dagger + \frac{1}{\xi_3} \ln \left(\frac{e_{s3}^\dagger + e_{p2}}{e_{s3}^\dagger} \right)$$

where e_{p2} is given by (19).

Digitized strain time points for a number of creep tests, taken directly from the experimental data tapes, have been suitably shifted and scaled, and are plotted for comparison with the universal creep curve in Fig. 8. Tests run at similar temperatures and shear stresses are plotted together. Not all tests are shown, however tests have been selected to give an indication of the spread in the bulk of the data. Note that tests with $\dot{e}_s > \dot{e}^*$ as well as tests with $\dot{e}_s < \dot{e}^*$ are included. Second and third stage tests are also included together with first stage tests. The solid line represents the universal creep curve with mean values of B and D, while the dashed lines represent the envelope of curves obtained when B and D are varied separately within their standard errors given in Table 2.

While there is obviously a considerable spread in data for tests conducted at nominally the same stress and temperature, they do scatter about the universal curve. Note that data lie both above and below the universal curve at all temperatures and stresses. In view of the consistency of the data for experiments on individual samples the scatter from sample to sample would appear to be due to material variations of core taken from different locations in the geology. No consistent variation could be found with depth, the difference in steady-state creep rate for upper and lower geologic layers noted previously⁶ having evidently been normalized out.

It should be recalled at this point that most of the tests which were omitted from this study correspond to low stress and temperature conditions. Some of them suggest higher values of the ratio of initial to final creep rates D , than found in Fig. 3. Many are, in fact, comparable to tests CA108, CA121 and RS790⁴ which were omitted from the present fit although they are plotted in Figs. 3 to 5. It should also be recalled that for many of the tests which were included, particularly those at low temperatures and stresses, the exponential creep expression did not fit the early time data well. In particular the initial creep rate was underestimated. Consequently it should be emphasized once again that the present fits do not describe the early time portions of creep curves very well, and should not be used to deduce physical mechanisms of creep without a detailed study of the individual creep curves themselves.

6. Conclusion

An effort has been undertaken to correlate the parameters of the exponential transient creep expression which had previously been fitted to individual experimental creep curves obtained on rock salt from the Salada formation in S. E. New Mexico. Simple correlations with steady-state creep rates were found which lead to a non-dimensionalized universal transient creep curve. Scaled results from different tests conducted under nominally identical test conditions scatter about the universal curve, the scatter being attributed to material variations of core from different positions in the geology.

A transition in transient behavior is seen, not unlike that attributed in metals to the appearance of grain boundary sliding at low stress levels. The existence of visible cracks, coupled with the small number of active slip systems at low stresses and temperatures, suggests that crack and grain boundary sliding is a likely mechanism in the salt below the transition. The transition does not appear to occur at either a critical stress or temperature. Within the scatter of the data, a critical creep rate appears to serve as well as any other criterion.

The appearance of a transition in the transient creep behavior suggests that a transition might be present in the steady-state behavior also. No such transition is obvious when the present data are taken alone.⁶ Munson¹⁶ has suggested such a transition on the basis of the present data taken together with the data of Heard¹⁷ obtained at higher temperatures and stresses using pure polycrystalline halite. This question deserves further study.

The proposed empirical description, based on the exponential transient creep expression, has certain advantages related to computational simplicity. However, at low temperatures, the exponential creep law does not give a good fit to the early time creep data for many tests. In particular, the initial

creep rate tends to be underestimated, seriously so for many tests conducted at low stress levels. While a number of tests at low stresses and temperatures are fitted quite well by the present empirical description, others conducted under nominally identical conditions are not.

The data scatter for early time creep at low stresses and temperatures is very large. It would be unwise to extrapolate the present fits to even lower stresses, with correspondingly lower steady-state creep rates (that is, below creep rates of about 10^{-10} per sec).

The empirical transient creep description obtained here, in conjunction with the steady-state creep description obtained previously,⁶ provide a simple and convenient basis for the construction of constitutive models for use in numerical solutions of creep problems. The data of Heard¹⁷ suggest a transition in behavior at higher temperatures and stresses, so that this description cannot be extrapolated upwards. The above considerations also suggest that it should not be extrapolated downwards. Nevertheless, the present description provides a reasonable fit, within the scatter of the data, in the stress-temperature range covered by the tests, particularly for applications where the very early time creep behavior is not important.

REFERENCES

1. W. Herrmann, W. Wawersik and H. S. Lauson
Creep Curves and Fitting Parameters for Southeastern New Mexico
Bedded Salt.
Sandia National Laboratories SAND-80-0087, March (1980).
2. W. R. Wawersik and D. W. Hannum
Interim Summary of Sandia Creep Experiments on Rock Salt from
the WIPP Study Area, Southeastern New Mexico.
Sandia Laboratories SAND-79-0115, February (1979).
3. F. D. Hansen
Triaxial Quasi-Static Compression and Creep Behavior of Bedded
Salt from Southeastern New Mexico.
Re/Spec Inc. RSI-0055, June (1977).
Sandia Laboratories SAND-79-7045, (1979).
4. F. D. Hansen and K. D. Mellegard
Creep Behavior of Bedded Salt from Southeastern New Mexico at
Elevated Temperatures.
Re/Spec Inc. RSI-0062, November (1977).
Sandia Laboratories SAND-79-7030, (1979).
5. F. D. Hansen and K. D. Mellegard
Further Creep Behavior of Bedded Salt from Southeastern New
Mexico at Elevated Temperatures.
Re/Spec Inc. - to be published.
Sandia Laboratories SAND-to be published.
6. W. Herrmann, W. Wawersik and H. S. Lauson
Analysis of Steady State Creep of Southeastern New Mexico Bedded
Salt.
Sandia National Laboratories SAND-80-0558, March (1980).
7. P. G. McVetty
Working Stresses for High-Temperature Service.
Mech. Eng. 56; 149 (1934).
8. F. Garofalo, C. Richmond, W. F. Domis and F. von Gemmingen
Strain-Time, Rate-Stress and Rate-Temperature Relations During Large
Deformations in Creep.
in Joint Intl. Conf. on Creep, ASME, ASTM and Inst. Mech. Eng.
New York and London, August (1963).
9. G. A. Webster, A. P. D. Cox and J. E. Dorn
A Relationship Between Transient and Steady-State Creep at Elevated
Temperatures.
Metal Sci. J. 3; 221 (1969).

10. A. Ahmadiéh and A. K. Mukherjee
Stress-Temperature-Time Correlation for High Temperature Creep Curves.
Matl. Sci. & Eng. 21; 115 (1975).
11. J. C. M. Li
A Dislocation Mechanism of Transient Creep.
Acta. Met. 11; 1269 (1963).
12. N. S. Akulov
On Dislocation Kinetics.
Acta. Met. 12; 1195 (1964).
13. G. A. Webster
A Widely Applicable Dislocation Model of Creep.
Phil. Mag. 14; 775 (1966).
14. H. Jefferson
TJMARI - A Fortran Subroutine for Nonlinear Least Squares Parameter Estimation.
Sandia Laboratories SLL-73-0305, March (1974).
15. The analyses were kindly performed by D. D. Sheldon of Sandia National Laboratories using the program of W. J. Dixon "BMDP Biomedical Computer Programs (P Series) P2R Stepwise Regression" University of California Press (1977).
16. D. E. Munson
Preliminary Deformation-Mechanism Map for Salt (With Application to WIPP).
Sandia Laboratories SAND-79-0076, Jan. (1979).
17. H. C. Heard
Steady-State Flow in Polycrystalline Halite at Pressures of 2 Kilobars, in Flow and Fracture of Rocks, ed. H. C. Heard et al, Am. Geophys. Union (1972).

TABLE 1.
TRANSIENT CREEP PARAMETERS

TEST ID	TST STG	T T	σ_3 P	$\dot{\epsilon}_s$ $\dot{\epsilon}_i$	ξ ξ_r	$\dot{\epsilon}_a$ $\dot{\epsilon}_f$
RS5501B	1	24	518	3.283E-08/ 2.010E-09	1.380E-05/ 1.213E-06	1.263E-02/ 7.182E-04
	2	3024	1526	2.072E-07/ 1.833E-08	7.246E+04/ 6.354E+03	1.307E+00
RS5501C	1	24	519	1.094E-07/ 3.400E-09	2.796E-05/ 2.463E-06	3.693E-02/ 1.347E-03
	3	4305	1954	1.142E-06/ 9.840E-08	3.577E+04/ 3.147E+03	2.543E+00
RS5502A	2	100	589	2.575E-08/ 1.440E-09	6.660E-06/ 5.760E-07	1.923E-02/ 1.030E-03
	1	1497	1088	1.538E-07/ 1.311E-08	1.502E+05/ 1.299E+04	1.305E+00
RS5503B	3	24	2015	2.714E-08/ 9.300E-10	2.780E-05/ 2.220E-06	6.593E-03/ 3.206E-04
	2	2968	3034	2.104E-07/ 1.716E-08	3.597E+04/ 2.873E+03	2.561E+00
RS5503C	3	24	2044	9.418E-08/ 3.570E-09	3.367E-05/ 2.730E-06	2.717E-02/ 9.710E-04
	3	4244	3459	1.009E-06/ 8.114E-08	2.970E+04/ 2.408E+03	3.144E+00
RS5504A	4	24	2012	1.765E-08/ 3.600E-10	1.339E-05/ 5.900E-07	1.074E-02/ 2.103E-04
	1	3037	3024	1.615E-07/ 6.942E-09	7.468E+04/ 3.291E+03	3.036E+00
RS5504B	4	24	2038	8.287E-08/ 2.570E-09	2.194E-05/ 1.650E-06	3.181E-02/ 1.033E-03
	2	4309	3444	7.808E-07/ 5.723E-08	4.558E+04/ 3.428E+03	2.437E+00
RS5505A	5	100	1990	4.139E-08/ 7.100E-10	1.690E-05/ 1.170E-06	1.653E-02/ 4.330E-04
	1	1509	2493	3.204E-07/ 2.067E-08	5.917E+04/ 4.096E+03	3.432E+00
RS5505B	5	100	2010	5.004E-07/ 2.300E-09	6.759E-05/ 2.600E-06	5.122E-02/ 1.045E-03
	2	2631	2897	3.953E-06/ 1.508E-07	1.480E+04/ 5.691E+02	5.098E+00
RS5506	6	100	2033	4.774E-07/ 3.000E-09	8.806E-05/ 5.100E-06	4.703E-02/ 1.063E-03
	1	2702	2934	4.619E-06/ 2.574E-07	1.136E+04/ 6.577E+02	8.442E+00
RS6202	2	74	0	1.502E-08/ 4.700E-10	7.971E-06/ 8.940E-07	5.715E-03/ 3.520E-04
	1	1544	515	6.057E-08/ 5.848E-09	1.255E+05/ 1.407E+04	3.136E+00
RS6203	3	107	0	4.242E-08/ 5.900E-10	4.006E-06/ 1.530E-07	3.205E-02/ 7.200E-04
	1	1515	535	1.708E-07/ 5.720E-09	2.496E+05/ 9.534E+03	1.577E+00
RS6205	5	24	2350	2.711E-08/ 3.600E-10	1.260E-05/ 5.600E-07	1.145E-02/ 2.200E-04
	1	3088	3389	1.714E-07/ 5.995E-09	7.937E+04/ 3.527E+03	3.532E+00

TABLE 1. (Cont'd)
TRANSIENT CREEP PARAMETERS

TEST ID	TST STG	T T	σ_3 P	$\dot{\epsilon}_s$ $\dot{\epsilon}_i$	ξ t_r	ϵ_a T
RS6206	6 1	73 3041	2512 3616	4.516E-07/ 2.600E-09 2.251E-06/ 1.481E-07	7.142E-05/ 5.533E-06 1.400E+04/ 1.084E+03	2.520E-02/ 7.000E-04 5.873E+00
RS6207	7 1	105 3066	2510 3532	1.653E-06/ 4.100E-08 4.477E-06/ 3.726E-07	7.828E-05/ 9.860E-06 1.277E+04/ 1.446E+03	3.607E-02/ 2.390E-03 1.445E+00
RS6208	8 1	105 1559	2978 3498	4.696E-08/ 3.900E-10 3.043E-07/ 3.173E-08	2.986E-05/ 3.510E-06 3.349E+04/ 3.937E+03	8.618E-03/ 3.210E-04 8.442E+00
RS6210A	10 1	24 1481	2518 3012	3.391E-09/ 1.920E-10 4.286E-08/ 6.838E-09	3.388E-05/ 5.470E-06 2.952E+04/ 4.765E+03	1.165E-03/ 7.301E-05 4.485E+00
RS6210B	10 2	24 3077	2425 3451	2.685E-08/ 6.300E-10 1.829E-07/ 1.060E-08	1.536E-05/ 9.100E-07 6.510E+04/ 3.857E+03	1.016E-02/ 3.347E-04 2.298E+00
RS6211	11 1	103 1495	0 498	1.345E-07/ 3.200E-09 4.349E-07/ 3.350E-08	1.553E-05/ 1.490E-06 6.439E+04/ 6.178E+03	1.934E-02/ 1.080E-03 1.503E+00
RS6212A	12 1	106 1558	2450 2969	8.451E-08/ 1.280E-09 3.794E-07/ 2.529E-08	2.520E-05/ 1.960E-06 3.968E+04/ 3.086E+03	1.170E-02/ 4.200E-04 2.699E+00
RS6212B	12 2	107 3118	2570 3609	3.489E-06/ 1.190E-07 2.129E-05/ 1.354E-06	2.979E-04/ 2.000E-05 3.357E+03/ 2.254E+02	5.974E-02/ 2.104E-03 1.479E+01
RS6213	13 1	24 4505	1971 3473	8.758E-08/ 1.670E-09 5.371E-07/ 2.463E-08	9.999E-06/ 4.930E-07 1.000E+05/ 4.931E+03	4.496E-02/ 1.060E-03 2.051E+00
RS6214	14 1	24 5864	1457 3422	5.749E-07/ 7.800E-09 5.030E-06/ 2.984E-07	6.874E-05/ 4.270E-06 1.455E+04/ 9.037E+02	6.481E-02/ 1.620E-03 4.259E+00
CA 102B	1 2	22 4493	506 2004	7.714E-08/ 3.100E-09 2.385E-07/ 2.617E-08	1.038E-05/ 1.010E-06 9.634E+04/ 9.374E+03	2.036E-02/ 1.531E-03 1.329E+00
CA 109	2 1	22 2974	501 1492	2.950E-09/ 7.000E-11 2.921E-08/ 2.780E-09	3.704E-06/ 3.709E-07 2.700E+05/ 2.697E+04	7.090E-03/ 2.480E-04 3.440E+00
CA 110	2 2	22 4436	528 2007	6.712E-08/ 3.310E-09 3.243E-07/ 3.736E-08	8.634E-06/ 1.091E-06 1.158E+05/ 1.464E+04	2.979E-02/ 2.101E-03 1.447E+00

TABLE 1. (Cont'd)
TRANSIENT CREEP PARAMETERS

TEST ID	TST STG	T T	σ_3 P	$\dot{\epsilon}_s$ $\dot{\epsilon}_i$	ξ t_r	ϵ_a t
CA 1038	3 2	22 4157	3015 4401	3.342E-08/ 1.430E-09 1.413E-07/ 1.489E-08	1.355E-05/ 1.460E-06 7.380E+04/ 7.952E+03	7.959E-03/ 6.787E-04 1.737E+00
CA 104	4 1	22 2920	3014 3997	2.534E-09/ 5.800E-11 2.321E-08/ 1.620E-09	3.322E-06/ 2.440E-07 3.010E+05/ 2.211E+04	6.225E-03/ 1.690E-04 2.826E+00
CA 105	4 2	22 4437	3032 4511	1.492E-08/ 2.400E-10 1.313E-07/ 5.868E-09	2.578E-06/ 1.150E-07 3.879E+05/ 1.730E+04	4.517E-02/ 1.055E-03 2.559E+00
CA 108	5 1	22 1186	520 915	1.076E-10/ 3.500E-12 7.014E-09/ 5.565E-10	6.433E-06/ 4.970E-07 1.554E+05/ 1.201E+04	1.072E-03/ 2.500E-05 9.263E+00
CA 111	5 2	22 2247	515 1254	2.374E-09/ 3.900E-11 1.820E-08/ 9.144E-10	2.167E-06/ 1.060E-07 4.615E+05/ 2.257E+04	7.301E-03/ 2.240E-04 2.538E+00
CA 112	5 3	22 3298	517 1616	2.524E-08/ 3.200E-10 2.184E-07/ 1.010E-08	8.623E-06/ 4.130E-07 1.160E+05/ 5.554E+03	2.240E-02/ 4.688E-04 2.483E+00
CA 121	6 1	22 1127	3019 3385	1.656E-10/ 9.700E-12 6.708E-09/ 5.673E-10	8.698E-06/ 6.950E-07 1.150E+05/ 9.186E+03	7.522E-04/ 2.531E-05 4.554E+00
CA 122	6 2	22 3355	3012 4130	1.588E-08/ 4.900E-10 7.734E-08/ 7.954E-09	9.603E-06/ 9.740E-07 1.041E+05/ 1.056E+04	6.400E-03/ 5.120E-04 2.350E+00
CA 107	8 1	100 1075	513 871	8.925E-09/ 7.300E-11 3.222E-08/ 1.064E-09	3.468E-06/ 1.430E-07 2.884E+05/ 1.189E+04	6.717E-03/ 1.300E-04 1.765E+00
CA 114	9 1	100 988	514 843	2.730E-09/ 2.700E-11 4.450E-09/ 3.005E-10	2.471E-06/ 3.820E-07 4.047E+05/ 6.256E+04	6.961E-04/ 5.561E-05 1.442E+00
CA 117	10 1	100 914	3027 3332	2.091E-09/ 1.600E-11 5.075E-09/ 6.249E-10	3.399E-06/ 6.460E-07 2.942E+05/ 5.592E+04	8.779E-04/ 7.710E-05 3.120E+00
CA 119	10 2	100 2209	3019 3755	5.217E-08/ 2.340E-09 1.467E-07/ 1.919E-08	3.379E-06/ 5.480E-07 2.959E+05/ 4.800E+04	2.798E-02/ 3.345E-03 1.282E+00

TABLE 1. (Cont'd)
TRANSIENT CREEP PARAMETERS

TEST ID	IST STG	T T	σ_3 P	$\dot{\epsilon}_s$ $\dot{\epsilon}_i$	ξ t_r	σ_a t
CA 115	11 1	200 994	526 857	1.742E-07/ 4.400E-09 6.939E-07/ 8.070E-08	3.289E-05/ 4.710E-06 3.040E+04/ 4.354E+03	1.580E-02/ 9.400E-04 2.066E+00
CA 120	12 1	200 997	2951 3293	2.415E-07/ 3.300E-09 6.228E-07/ 4.986E-08	1.605E-05/ 1.910E-06 6.231E+04/ 7.415E+03	2.376E-02/ 1.270E-03 1.774E+00
RS7901	1 1	24 1510	0 503	3.044E-09/ 7.800E-11 3.411E-08/ 1.734E-09	1.459E-05/ 7.500E-07 6.854E+04/ 3.523E+03	2.129E-03/ 4.600E-05 2.436E+00
RS79018	2 2	75 1477	0 492	4.019E-09/ 1.030E-10 1.102E-08/ 2.762E-09	6.078E-06/ 2.160E-06 1.645E+05/ 5.847E+04	1.154E-03/ 1.948E-04 1.823E+00
RS7902	3 1	24 2984	2509 3504	4.594E-09/ 9.600E-11 4.542E-08/ 6.227E-09	5.352E-06/ 7.770E-07 1.868E+05/ 2.713E+04	7.629E-03/ 3.560E-04 5.960E+00
RS7903	4 1	24 2983	508 1502	8.367E-09/ 1.710E-10 6.569E-08/ 3.115E-09	2.872E-06/ 1.430E-07 3.482E+05/ 1.734E+04	1.996E-02/ 4.300E-04 2.254E+00
RS7904	5 1	24 1536	3006 3518	1.598E-09/ 3.600E-11 5.248E-08/ 2.658E-09	3.401E-05/ 1.650E-06 2.940E+04/ 1.426E+03	1.496E-03/ 2.991E-05 5.635E+00
RS79048	6 2	105 1508	3508 3511	1.756E-08/ 4.200E-10 6.568E-08/ 3.350E-09	3.078E-06/ 1.750E-07 3.249E+05/ 1.847E+04	1.563E-02/ 6.128E-04 1.179E+00
RS7905	7 1	75 1506	3001 3503	2.416E-09/ 2.100E-11 8.427E-09/ 3.087E-10	2.170E-06/ 1.000E-07 4.608E+05/ 2.124E+04	2.770E-03/ 6.200E-05 1.830E+00
RS7907	9 1	210 1471	3003 3493	2.575E-06/ 1.700E-08 9.951E-06/ 3.660E-07	1.838E-04/ 8.400E-06 5.441E+03/ 2.486E+02	4.013E-02/ 7.700E-04 2.464E+00
RS7908	10 1	210 789	0 263	6.781E-08/ 7.600E-10 4.285E-07/ 7.986E-09	7.200E-06/ 1.400E-07 1.389E+05/ 2.701E+03	5.009E-02/ 5.200E-04 1.472E+00
RS7909	11 1	210 791	507 771	9.215E-08/ 3.200E-10 4.232E-07/ 5.793E-09	6.284E-06/ 1.000E-07 1.591E+05/ 2.532E+03	5.268E-02/ 3.800E-04 2.239E+00
RS7910	12 1	210 797	2992 3258	6.712E-08/ 5.700E-10 2.164E-07/ 6.143E-09	3.984E-06/ 1.430E-07 2.510E+05/ 9.009E+03	3.748E-02/ 7.400E-04 1.504E+00

TABLE 2

Transient Creep Parameters

$$B = 127 \pm 42$$

$$C = 6.85 \times 10^{-6} \pm 3.76 \times 10^{-6} \text{ per sec}$$

$$D = 5.56 \pm .79$$

$$C^* = 5.30 \times 10^{-8} \text{ per sec}$$

$$\text{Logarithmic Standard Deviation in } \dot{\epsilon}_t = .190$$

$$\text{Logarithmic Standard Deviation in } \xi = .745$$

FILE 00121

FILE 00085

FILE R56212B

FILE R57908

Fig. 2. Axial Strain Histories (points) with Exponential Fits, Eq. (5), (solid lines).

Fig. 3. Initial vs. Steady State Creep Rate.

T : $\circ$ 1000 psi $\diamond$ 1500 psi $\square$ 3000 psi
 $\triangle$ 3000 psi ∇ 4500 psi $+$ 5000 psi
 T : $\circ$ 22°C $\bullet$ 70°C $\bullet$ 100°C $\bullet$ 200°C

Fig. 4. Relaxation Frequency vs. Steady State Creep Rate.

Fig. 5. Asymptotic Transient Creep Strain vs. Steady State Creep Rate.

τ : $\circ$ 1000 psi $\diamond$ 1500 psi $\square$ 3000 psi
 $\triangle$ 3000 psi ∇ 4500 psi $+$ 5000 psi
 T : $\circ$ 22°C $\bullet$ 70°C $\bullet$ 100°C $\bullet$ 200°C

Fig. 6. Asymptotic Transient Creep Strain vs. Confining Pressure.

Fig. 7. Primary Dilatancy vs. Shear Stress at Constant Temperature.
 σ_3 : + 0 psi, $\circ$ 500 psi, $\times$ 2000 psi, $\square$ 2500 psi, $\diamond$ 3000 psi.

Fig. 8a. Universal Creep Curve. Data for $T = 24^\circ\text{C}$, $\tau = 1500$ psi.

Fig. 8b. Universal Creep Curve. Data for $T = 24^\circ\text{C}$, $\tau = 3000$ psi.

Fig. 8c. Universal Creep Curve. Data for $T = 24^{\circ}\text{C}$, $\tau = 4500$ psi.

Fig. 8d. Universal Creep Curve. Data for $T = 100^\circ\text{C}$, $\tau = 1500$ psi.

Fig. 8e. Universal Creep Curve. Data for $T = 100^\circ\text{C}$, $\tau = 3000$ psi.

Fig. 8f. Universal Creep Curve. Data for $T = 200^\circ\text{C}$, $\tau = 1000 \text{ psi}$.

UNLIMITED RELEASE

DISTRIBUTION:

U. S. Department of Energy, Headquarters
Office of Nuclear Management
Washington, DC 20545

ATTN: Eugene F. Beckett (1)
Project Coordinator (WIPP)

Colin A. Heath, Director (2)
Division of Waste Isolation

Sheldon Meyers
Raymond G. Romatowski
R. Stein
Carl L. Cooley

U. S. Department of Energy
Albuquerque Operations Office
P. O. Box 5400

Albuquerque, NM 87185
ATTN: D. T. Schueler, Manager (2)
WIPP Project Office

J. M. McGough

G. Dennis, Director
Public Affairs Division

S. C. Taylor, C&TI Division
(for Public Reading Rooms)

U. S. Department of Energy
Carlsbad WIPP Project Office
Room 113, Federal Building
Carlsbad, NM 88220

U. S. Department of Energy
c/o Battelle
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201
ATTN: Jeff O. Neff

Battelle Memorial Institute
Office of Nuclear Waste Isolation
505 King Avenue
Columbus, OH 43201
ATTN: Neil Carter, General Manager (3)
R. Heineman
W. Carbiener
P. Hoffman
M. Lemcoe
J. Monsees
G. Raines
R. Robinson
ONWI Library

Westinghouse Electric Corporation
P. O. Box 40039
Albuquerque, NM 87196
ATTN: R. C. Mairson (1)

Hobbs Public Library
509 N. Ship Street
Hobbs, NM 88248
ATTN: Ms. Marcia Lewis, Librarian

Lokesh Chaturvedi
Department of Civil Engineering
Box 3E
New Mexico State University
Las Cruces, NM 88003

Bechtel Inc.
P. O. Box 3965
San Francisco, CA 94119
ATTN: R. A. Langley

National Academy of Sciences, WIPP Panel
Frank L. Parker, Chairman
Department of Environmental and
Water Resources Engineering
Vanderbilt University
Nashville, TN 37235

Konrad B. Krauskopf, Vice Chairman
Department of Geology
Stanford University
Stanford, CA 94305

Dr. Karl P. Cohen, Member
928 N. California Avenue
Palo Alto, CA 94303

Neville G. W. Cook, Member
Dept. of Material Sciences and Engineering
University of California at Berkeley
Heart Mining Building, #320
Berkeley, CA 94720

Merril Eisenbud, Member
Inst. of Environmental Medicine
New York University Medical Center
Box 817
Tuxedo, NY 10987

Fred M. Ernsberger, Member
Glass Research Center
PTC Industries, Inc.
Box 11472
Pittsburgh, PA 15238

Roger Kasperson, Member
Center for Technology, Environment and
Development
Clark University
Worcester, MA 01610

DISTRIBUTION: (Cont'd)

Richard R. Parizek, Member
Department of Hydrogeology
Pennsylvania State University
University Park, PA 16802

Thomas H. Pigford, Member
Department of Nuclear Engineering
University of California
Berkeley, CA 94720

Roger W. Staehle, Member
Dean, Institute of Technology
University of Minnesota
Lind Hall
Minneapolis, MN 55455

John W. Winchester, Member
Department of Oceanography
Florida State University
Tallahassee, FL 32306

D'Arcy A. Shock
233 Virginia
Ponca City, OK 74601

National Academy of Sciences
Committee on Radioactive Waste Management
2101 Constitution Avenue, NW
Washington, DC 20418
ATTN: John T. Holloway (2)

WIPP Public Reading Room
Atomic Museum, Kirtland East AFB
Albuquerque, NM 87185
ATTN: Ms. Gwynn Schreiner

WIPP Public Reading Room
Carlsbad Municipal Library
101 S. Hallagueno St.
Carlsbad, NM 88220
ATTN: Lee Hubbard, Head Librarian

Thomas Brannigan Library
106 W. Hadley Street
Las Cruces, NM 88001
ATTN: Don Dresp, Head Librarian

Roswell Public Library
301 N. Pennsylvania Avenue
Roswell, NM 88201
ATTN: Ms. Nancy Langston

Bruno Giletti
Department of Geological Sciences
Brown University
Providence, Rhode Island 02912

Raymond Siever
Department of Geological Sciences
Harvard University
Cambridge, Massachusetts 02138

John Handin
Center of Tectonophysics
Texas A&M University
College Station, Texas 77840

John Lyons
Department of Earth Sciences
Dartmouth College
Hanover, New Hampshire 03755

George Pinder
Department of Civil Engineering
Princeton University
Princeton, New Jersey 08540

New Mexico Advisory Committee on WIPP
NMIMT Graduate Office
Socorro, NM 87801
ATTN: Marvin H. Wilkening, Chairman (2)

State of New Mexico
Environmental Evaluation Group
320 March Street
P. O. Box 968
Santa Fe, NM 87503
ATTN: Robert H. Neill, Director (2)

NM Department of Energy & Minerals
P.O. Box 2770
Santa Fe, NM 87501
ATTN: Larry Kehoe, Secretary
Kasey LaPlante, Librarian

J. E. Magruder
Sandia Carlsbad Representative
401 North Canal Street
Carlsbad, NM 88220

John Gervers
Coordinator, Governor's Task Force for WIPP
State Capitol, Rm. 247
Santa Fe, NM 87503

Gesellschaft fur Strahlen-und
Umweltforschung MBH Munchen
Institut fur Tieflagerung
3392 Clusthal-Zellerfeld
Berliner Strasse 2
Federal Republic of Germany
ATTN: K. Kuhn
P. Uerpmann

Reinhard Kramer
Kernforschung Karlsruhe
Postfach 3640
7500 Karlsruhe
Federal Republic of Germany

DISTRIBUTION: (Cont'd)

Michael Langer
Bundesanstalt für Geowissenschaften
und Rohstoffe
Postfach 510 153
3000 Hannover 51
Federal Republic of Germany

Klaus Eckart Maass
Hahn-Meitner-Institut für Kernforschung
Glienicke Strasse 100
1000 Berlin 39
Federal Republic of Germany

Rolf-Peter Randl
Bundesministerium für Forschung und
Technologie
Postfach 200 706
5300 Bonn 2
Federal Republic of Germany

Helmut Rothemeyer
Physikalisch-Technische Bundesanstalt
Bundesanstalt 100, 3300 Brunswick
Federal Republic of Germany

D'Appolonia Consulting Engineers, Inc.
10 Duff Road
Pittsburgh, PA 15235
ATTN: L. Jarolimek

D'Appolonia Consulting Engineers, Inc.
2350 Alamo, SE
Suite 103
Albuquerque, NM 87106
ATTN: A. K. Kuhn

Dr. Paul R. Dawson
254 Upson Hall
Dept. Mech. & Aerospace Engr.
Cornell University
Ithaca, NY 14853

D. E. Maxwell
Science Applications, Inc.
2450 Washington Avenue, Suite 120
San Leandro, CA 94577

J. G. McCray
Department of Nuclear Engineering
University of Arizona
Tucson, AZ

Oak Ridge National Laboratory
Box Y
Oak Ridge, TN 37830
ATTN: C. Clairborne

RE/SPEC Inc.
P. O. Box 725
Rapid City, SD 57701
ATTN: Dr. P. Gnirk
W. C. McLain
Arlo Fossum

Rockwell International
Atomics International Division
Rockwell Hanford Operations
P. O. Box 800
Richland, WA 99352
ATTN: Dave Turner

Svensk Karnbransleforsörjning AB
Project KBS
Karnbranslesakerhet
Box 5864
10248 Stockholm, SWEDEN
ATTN: Fred Karlsson

Billy J. Thorne, Vice President
Civil Systems Inc.
2201 San Pedro NE, Suite 214
Albuquerque, NM 87110

Prof. M. F. Ashby
University of Cambridge
University Engineering Department
Trumpington Street
Cambridge CB1 2PX ENGLAND

Prof. George M. Pharr
Mechanical Engineering Materials Science
Department
Rice University
Houston, TX 77001

Woodward-Clyde Consultants
Library Western Region
3 Embarcadero Center, Suite 700
San Francisco, CA 94111
ATTN: Anne T. Harrigan, Librarian

1112 C. R. Mehl
1112 G. Miller
1116 S. R. Dolce
1120 T. L. Pace
2645 L. D. Bertholf
3310 W. D. Burnett
4413 N. R. Ortiz
4500 E. H. Beckner
4510 W. D. Weart
4511 D. W. Powers
4512 T. O. Hunter (5)
4512 C. L. Christensen
4512 D. R. Fortney
4512 R. V. Matalucci
4512 M. A. Molecke
4512 D. E. Munson

DISTRIBUTION: (Cont'd)

4514 M. L. Merritt
4530 R. W. Lynch
4537 L. D. Tyler
4538 R. C. Lincoln
4541 L. W. Scully
4541 H. C. Shefelbine
4542 Sandia WIPP Central Files (2), TSI
4543 R. R. Beasley
4732 A. R. Sattler
4738 J. R. Wayland
4745 J. R. Tillerson
5500 O. E. Jones
5510 D. B. Hayes
5511 J. W. Nunziato
5511 G. R. Hadley
5520 T. B. Lane
5521 R. D. Krieg
5521 C. M. Stone
5521 L. J. Branstetter
5530 W. Herrmann (20)
5531 S. W. Key
5531 W. T. Brown
5531 S. E. Montgomery
5531 H. S. Morgan
5531 H. S. Lauson (5)
5532 B. M. Butcher
5532 W. R. Wawersik (10)
5532 L. W. Teufel
5532 D. J. Holcomb
5532 W. A. Olsson
5532 R. H. Price
5532 D. H. Zeuch
5541 W. C. Luth
8316 J. R. Spingarn
8266 Tech Library
3141 Tech Library (5)
3151 Tech Writing (3)
For DOE/TIC (Unlimited Release)
DOE/TIC (25)
(R. P. Campbell, 3154-3)