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CONSTITUTIVE MODELS APPLIED IN THE ANALYSIS OF CREEP OF ROCK SALT

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ABSTRACT

Constitutive equations for the creep of rock salt that have been utilized in the analyses of salt deformations are summarized. Primary creep, secondary creep, and elastoviscoplastic models are discussed. The strains predicted by several of the primary creep constitutive models are compared for identical conditions of deviatoric stress and temperature. Steady-state creep rates are compared under identical conditions of deviatoric stress and temperature for the secondary creep equations.

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I. *INTRODUCTION*

The creep of rock salt has been studied by numerous investigators over the past two decades. Studies have encompassed the behavior of both single crystal and polycrystalline salt over a wide range of temperature and stress environments. Constitutive models for salt that reflect the observed creep behavior have been formulated from the experimental data as part of many of these investigations.

The purpose of this report is to summarize some of the creep constitutive equations that have been employed in the past and are currently being employed in the analyses of the mechanical response of rock salt. No attempt will be made to make comprehensive comparisons of the constitutive equations or to reach a final conclusion on which equation is best suited for WIPP analyses. Several review articles have been published that discuss the creep experiments of various investigators from which the models are derived. This report does not attempt to reproduce those efforts, but rather applies the general background given in the review articles to the summary of creep equations that have been reported.

This report presents a brief general discussion of both the constitutive models for creep and the numerical algorithms associated with solving these problems. Examples of the various types of creep models are discussed along with their application to geologic analyses. Finally, a brief assessment of creep models is presented.

II. CREEP, CONSTITUTIVE MODELS FOR CREEP, AND ASSOCIATED NUMERICAL ALGORITHMS

Creep can be defined in terms of the time dependent deformation of a material subjected to a constant stress state. Laboratory experiments are typically idealized into three stages of creep deformation for a specimen subjected to constant stress for long periods of time. These are described as (1) primary creep, demonstrating decreasing deformation rates,* (2) secondary creep, demonstrating constant deformation rates, and (3) tertiary creep, exhibiting increasing deformation rates and normally terminating with fracture or instability.

Experiments on rock salt have produced data that substantiate that all three creep regimes can be obtained depending on the stress state and temperature. The relative importance of each regime is controlled by the deformation mechanisms that are active under the imposed conditions of stress and temperature. These deformation mechanisms include defect-less flow, dislocation glide and climb, diffusional creep, growth of microfractures and other (possibly yet undefined) mechanisms. Further, the rate of creep occurring as a result of a particular mechanism is a function of the imposed environmental conditions.

Constitutive equations for materials undergoing creep deformations (frequently called creep "laws") have been developed from available experimental data. Often a creep law is determined by empirically fitting an arbitrarily chosen equation containing the necessary independent variables. In other instances, the form of the constitutive equation has been motivated from a model for the physical mechanisms dominating secondary creep. In this instance, the parameters appearing in the equations are determined such that the equations can approximate the data. Equations associated with deformation mechanisms have also been applied to primary creep without thorough physical justification.

Certain equations for primary creep and secondary creep are used most frequently. It will be helpful to review these equations in general terms before discussing specific cases. For primary creep, constitutive equations of the form

*Here the deformation rate refers to a tensor defined in terms of symmetric portion of the velocity gradient.

$$\dot{\epsilon} = f(\tau \text{ or } \epsilon)g(\theta)h(\sigma) \qquad (1)$$

have been frequently used, where ϵ is the creep strain, τ is time, θ is the temperature, σ is the stress, and f, g, and h represent functions. Creep laws using Equation (1) assume that the effects of time, temperature, and stress on the induced creep strain rate are separable. Functional forms of g that have been reported include power laws (θ^n) and exponential law forms ($\exp(-Q/R\theta)$). The exponential forms are related to activation energies (Q) associated with deformation mechanisms, while the power law form is apparently strictly empirical. The use of time (τ) or strain (ϵ) as the independent variable for f leads to the time-hardening or strain-hardening interpretations for the decreasing strain rate as a function of time, observed during constant stress creep tests. Life fraction rules for the function f have been proposed as an alternative to time and strain-hardening representations in which the proportion of total possible deformation that has occurred enters the constitutive model in place of time or strain. The stress function h has most frequently been expressed as a power law (σ^n) to reflect the possible nonlinearity associated with the stress state.

The distinction between strain-hardening and time-hardening is important in applications that have changing stress and temperature fields. Strain-hardening laws normally require that as the stress state changes, and thus moves from one constant stress and temperature creep curve to another curve, the shift occurs between points of equal total strain on the two constant stress curves. Time-hardening laws require that the change from one constant stress curve to another occurs between equal times on the two constant stress curves. These two interpretations can give very different results. Life fraction rules represent a means of compromising between time-hardening and strain-hardening by moving from one constant stress curve to another according to equal percentages of the total deformation that can be tolerated by the material. Time-hardening laws are the simplest to implement in a solution algorithm and are probably the most commonly used. They are most successfully applied when the problem involves a stress state that is constant in time, but can produce very poor results if this is not the case. Time is not an intrinsic material property and, in general, should not appear explicitly in the constitutive model.

Secondary creep (also called steady-state creep) is characterized by constant deformation rates under conditions of constant stress and temperature. Separable constitutive equations of the form

$$\dot{\varepsilon} = f'(\theta)g'(\sigma) \qquad (2)$$

have been used to model creep within this regime. Weertman [1] has proposed that the functions f' and g' be defined as

$$f'(\theta) = \frac{A\mu}{\theta} \exp\left(- \frac{Q}{R\theta}\right) \qquad (3)$$

and

$$g'(\sigma) = \left(\frac{\sigma}{\mu}\right)^n \qquad (4)$$

where μ is the shear modulus, Q is the activation energy, and R is the universal gas constant. Numerous investigators have found this law to be a good approximation for secondary creep involving dislocation climb (polygonization) at moderate stress levels. It has also been observed that the temperature dependence of μ leads to the fact that the quantity $\frac{A\mu}{\theta}\left(\frac{1}{\mu}\right)^n$ is nearly constant. At higher stress levels, where slip occurs, the stress function is expressed as an exponential function such as $\sinh(B\sigma)$. At very low deformation rates and elevated temperature, where the diffusion limiting Nabarro-Herring [2] or Coble [2] creep mechanisms dominate, a linear dependence between stress and deformation rate is obtained.

Tertiary creep exhibits increasing deformation rates that lead to failure. Some work has been done in developing constitutive models in terms of creep rupture theory that are appropriate for the tertiary creep regime. The onset of instability characterized by tertiary creep has been observed to be related to the total strain. However, little has been done to express either the transition from secondary to tertiary creep or creep rates in the tertiary creep range using constitutive equations for rock salt [3].

The above primary creep and secondary creep models (Equations (1) and (2)) are separable in their form. This implies, for instance, that if two creep tests are performed at temperatures θ_1 and θ_2, with the stress state the same in each test, the ratio of strain rates between these tests must equal the ratio of strain rates of a second set of two creep tests performed at θ_1 and θ_2 but at a different stress state.

Currently, several efforts to develop constitutive models for the creep deformation of salt are being conducted. Some of the efforts have been motivated by the assumption that more than one mechanism is active for a particular combination of independent variables [5,6,7]. This assumption has led to constitutive models having additive primary or secondary creep functions and provides a means of having multiple activation energies and stress nonlinearities. A second effort currently being developed involves constructing a detailed deformation mechanism map that defines the transition zones between dominant creep mechanisms [7]. This effort provides a means of quantifying where a given mechanism dominates over other mechanisms, but alone does not fully account for more than one mechanism being active at a particular stress and temperature state.

Analyses of creep deformations of salt have been provided in recent years by numerical methods using finite element or finite difference methods in the space domain and various numerical techniques in the time domain. Some of the analyses use elastoplastic models to predict the stress state due to the applied loads. Creep deformations are then predicted using the computed stress state in conjunction with with creep law. Other analyses are formulated from a creeping flow formulation in which the elastic response is neglected.

Elastoplastic formulations normally assume linear elastic behavior for stress states lying below the yield surface (typically a Mohr-Coulomb failure criterion is used). Once the stress reaches the yield surface, the material deforms inelastically and independently of time. The stress state resulting from the elastoplastic analyses is introduced into the creep law to predict the creep strain increment for a specified time increment. Some analyses have applied a yield surface concept to the creep law in such a way that no creep deformations occur below a certain limiting stress.

Creeping viscous flow formulations have also been applied to the analysis of creep deformations. These formulations relate the applied stress field to the deformation rates of the material using the creep law as the constitutive model for a non-

Newtonian fluid. Normally such formulations neglect the elastic portion of the deformation and, thus, apply to problems in which creep strain increments dominate over elastic strain increments for a given time increment.

III. EXPERIMENTAL INVESTIGATIONS AND REVIEW ARTICLES

Numerous investigators have performed laboratory experiments to assess the quasi-static and creep behavior of single crystal and polycrystalline salt (halite). Among these are Burke et al. [9], Carter and Heard [10], Hansen and Mellegard [11], Heard [12], Le Comte [13], Lomenick [14], Menzel et al. [15], Nair [16], Poirier [17], Thompson and Ripperger [18], and Wawersik [4]. Several review articles summarize most of the available data [19,21].

In a report prepared by Dames and Moore Consultants [19] for the U. S. Department of Energy, creep data for rock salt has been reviewed relative to the geologic formations from which sample material was taken. Included in the report are reviews of salt properties for domal salt and for salt from the Salina, Permian, and Paradox basins. The report summarizes known values of density, water content, permeability, elastic moduli, and thermal properties, in addition to creep properties. For the Permian basin, specifically, the work associated with Project Salt Vault in Lyons, Kansas, model pillar tests performed by Lomenick and Bradshaw, laboratory tests of Hansen and Gnirk, and in situ tests of Reynolds and Gloyna are discussed and referenced. Creep laws derived from these sources, however, are not summarized for the Permian basin salt. For salt from other locations empirically based creep laws are presented. For salt from domal formations primary creep laws derived from the model pillar experiments by Lomenick and Bradshaw are summarized (the empirical fits included data from pillars made from bedded salt) and a secondary creep representation by Thompson and Ripperger [18] is presented. For Salina basin rock salt, the secondary creep law developed by Obert [20] is given.

Carter [21] has written a review article covering the known creep behavior of several rock types entitled "Steady State Flow of Rocks" in which he discusses the creep of halite. The article begins with a discussion of metals and ceramics that summarizes various creep mechanisms observed in those materials. Carter discusses specifically the creep of both single crystal and polycrystalline halite. For polycrystalline salt he notes that the results of most investigators are generally consistent with each other. He then concentrates on the reported data of Heard because his data cover the broadest combined range of pressure, temperature, and strain-rate. Nabarro-Herring creep and dislocation glide and climb (polygonization) are discussed including the strain rates at which the transition from one creep mechanism to another occurs. Applications center around activities of tectonic scale such as diapirism, folding, and mantle convection.

Baar [22] has published a monograph on rock salt mechanics. This text contains discussions on the geology and physical properties of rock salts as well as numerous references to in situ convergence measurements in salt mines. Baar calls attention to questionable assumptions made in formulating creep laws from laboratory data of creep rates. Baar's perception from mine observations is that strain-hardening observed in the laboratory does not exist in situ.* Further, creep limits (i.e., stress levels below which creep will not occur) are either zero or nearly zero for rock salt. Baar emphasizes that strain-hardening models that increase the octahedral stress required to initiate creep lead to unconservative designs.

Thoms and Martinez [23] have prepared a review of salt material properties as part of a project to store energy via compressed air in caverns within salt domes. This report is a general description of material mod[illegible] for time-independent plasticity and creep of salt and the numerical methods for anal[illegible] salt deformations using plasticity and creep models. The constitutive equations are discussed within the context of primary, secondary, and tertiary creep without relating the creep to specific deformation mechanisms. Much of this report emphasizes the short term response following the opening of cavities using quasi-static test results to evaluate parameters necessary for time-independent plasticity models.

The reviews of salt properties by Dames and Moore Consultants, Carter, Baar, and Thoms and Martinez provide a good summary of the work performed over the past ten years. The references cited in the reviews are quite extensive.

*It appears that Baar means that salt will reach the secondary regime quickly after being loaded and thus will demonstrate constant strain rates for constant stress conditions. The primary creep regime is embodied in what Baar terms stress relief creep.

IV. SPECIFIC CREEP MODELS AND APPLICATIONS

In many instances, the laboratory data from observed creep behavior of rock salt have been utilized to evaluate parameters for primary and secondary creep models. These creep models have subsequently been applied in the analyses of the creep of room and pillar mine geometries and other applications. Creep laws have also been generated by using in situ experimental data in conjunction with numerical solutions to obtain creep parameters that lead to the best match of predicted and measured deformations. We will consider creep equations obtained in both ways. Primary creep laws are discussed first, followed by secondary creep models. Elastoviscoplastic and creep rupture models for rock salt behavior are summarized.

IV.1 Primary Creep Constitutive Equations and Applications

McClain and Starfield [24] have analyzed pillar deformations that were measured during Project Salt Vault. They used a primary creep equation determined from the model pillar tests of Lomenick [14] using salt principally from Lyons, Kansas. The creep constitutive equation reported is

$$\epsilon = 1.3 \times 10^{-37} \theta^{9.5} \tau^{0.3} \sigma^{3.0} \qquad (5)$$

where ϵ is the strain, θ is the average pillar temperature (K), τ is the time (hours) and σ is the average pillar vertical stress (psi). In order to generalize this law for conditions of varying stress and temperature, McClain and Starfield first expressed the differential strain as a function of the differential stress. This equation is then integrated with respect to time to obtain an expression for strain as a function of time. They next introduce a time scale shift suggested by Leaderman [25] to account for changing temperature. The generalized constitutive equation for creep under conditions of varying temperature and stress was then applied in the analysis of pillar deformations measured during Project Salt Vault. McClain and Starfield reported, however, that the measured deformations could be better simulated by modifying the original constitutive model obtained from Lomenick's data to be

$$\epsilon = 6.5 \times 10^{-37} \theta^{9.5} \tau^{0.37} \sigma^{3.0} \qquad (6)$$

where variables have the same dimensions as presented before. Coefficients in this law were obtained by trial-and-error to provide the best match to measured values. Computed deformations (obtained with parameters determined by trial-and-error) have been compared to measured values for a period of 1500 days following excavation.

Hardy and St. John [26] have extended the work of McClain and Starfield [24], using the primary creep model reported by McClain and Starfield as a best fit to the Project Salt Vault in situ measurements, and reanalyzed the pillar deformations occurring in Project Salt Vault. Hardy and St. John also include the results of a three-dimensional thermoelastic repository simulation.

Wahi, Maxwell, and Hofmann [27] have reported numerical simulations of Project Salt Vault pillar deformations. They used a two-dimensional, explicit, finite-difference method for the analyses in conjunction with creep law parameters reported by Starfield and McClain. Wahi, Maxwell, and Hofmann have also modified the primary creep law derived under conditions of constant stress and temperature to account for changing stress and temperature fields. In their analyses, they simulated the effects of excavation sequencing, but concluded that the sequencing had little effect on deformation of the pillars, given that heating did not begin for approximately six months after excavation ended.

In another report by Maxwell, Wahi, and Dial [28], the elastic and creep responses due to stresses caused by thermal expansion for a full scale repository have been simulated. A primary creep law was also used in these simulations. Parameters for the creep law were determined from creep tests reported by Hansen and Mellegard [11]. The creep equation used in the simulations was

$$\dot{\epsilon}_{creep} = 6.0195 \times 10^{-43}\left[S^{3.0} \exp(-4100/\theta)\right]^{\frac{1}{.4656}}\left[\epsilon_{creep}\right]^{-1.15} \qquad (7)$$

and

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{creep}\,\frac{\sigma_{ij}}{S} \qquad (8)$$

where θ is the temperature (K), $\dot{\epsilon}_{creep}$ is the generalized creep strain rate (s^{-1}), and S is defined by

$$S = \sqrt{\frac{1}{6}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right] + \sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2} \quad (Pa) .$$

or $S = \sqrt{J_2}$ (where J_2 is the second invariant of the stress tensor). A two-dimensional, explicit, finite-difference computer code was used in these analyses.

Ratigan and Callahan [29] have reported on a thermoviscoelastic simulation of pillar deformations associated with Project Salt Vault. The primary creep law utilized in their computations was determined from a combination of data reported by Bradshaw and McClain [24] and by Hansen [30]. The creep law reported is

$$\epsilon_{ij} = 6.885 \times 10^{-15} \left(\frac{\theta}{295.5}\right)^{9.5} \tau^{0.4} J_2 \sigma'_{ij} \tag{9}$$

where τ is the time (s), θ is the temperature (K), J_2 is the second invariant of the stress deviator (psi^2), σ'_{ij} is the stress deviator tensor (psi), and ϵ_{ij} is the strain tensor. Ratigan and Callahan employed a finite element code to perform the pillar simulations in which the creep strain rates have been computed from the stress field. This approach uses a form of Equation (9) that had been differentiated with respect to time.

Hansen [31,32] performed laboratory creep experiments on Jefferson Island salt. He performed a multiple regression analysis to determine the parameters appearing in an isothermal power law for primary creep. The creep equation is given as

$$\epsilon_1 = 7.18 \times 10^{-23} \tau^{0.38} (\Delta\sigma)^{2.52} \tag{10}$$

where ϵ_1 is the axial strain, τ is the time (s), and $\Delta\sigma$ is the differential axial stress (Pa). Hansen also discusses a creep law proposed by Fossum [33] in which the inelastic strain-rate ($\dot{\epsilon}$) is expressed as a function of the stress deviator (σ'), second invariant of the stress deviator (J_2), and the inelastic generalized strain ϵ. Specifically, this law is given as

$$\dot{\epsilon} = 2.99 \times 10^{-19} \left(\frac{(3J_2)^{\frac{1}{2}} - 68.1 \times 10^7 \epsilon^{0.326}}{(3J_2)^{0.286}}\right) \times \sigma' \tag{11}$$

where the dimension of J_2 and σ' are in Pascals and the dimension of $\dot{\epsilon}$ is s^{-1}. This law yields

$$\dot{\epsilon} \to 0 \quad \text{as} \quad (3J_2)^{\frac{1}{2}} - 68.1 \times 10^7 \, \epsilon^{0.326} \to 0 \, .$$

Values of strain above 2.0 percent cause the strain rate to quickly approach zero, thus allowing the total strain to asymptotically approach a predetermined maximum value. This maximum strain was evaluated from observation of laboratory creep tests.

Hansen has empirically determined primary creep laws for rock salt from Lyons, Kansas [30] and rock salt from southeast New Mexico [11,34]. The creep laws reported for these salts are

$$\epsilon_1 = 7.2 \times 10^{-18} \, \tau^{0.4} \, \sigma^{3.7} \, \theta^{9.5} \qquad \text{Lyons Salt} \tag{12}$$

$$\left.\begin{array}{l} \epsilon_1 = 1.1 \times 10^{-35} \, \tau^{0.4656} \, \sigma^{2.475} \, \theta^{8.969} \\ \epsilon_1 = 1.693 \times 10^{-39} \, \tau^{0.4808} \, \sigma^{2.676} \, \theta^{10.17} \end{array}\right\} \qquad \text{Southeast NM Salt} \tag{13}$$

where τ is the time (s), σ is the axial differential stress (psi), ϵ_1 is the axial strain, and θ is the temperature (K).

Russell [6] has investigated the possibility of using a combination of strain-hardening functions to model the primary creep regime and a Weertman secondary creep equation (Equation (2)) to model the steady-state regime. He assumes that the transition from primary to secondary creep occurs at 10 percent strain. For the primary regime, Russell has performed a fit to constant strain-rate data of Heard [12] using an empirically based equation of the form

$$\dot{\epsilon}^{-1} = \sum_{i=1}^{2} A_i \exp(-\lambda_i/\epsilon) \tag{14}$$

Parameters are given for two cases:

Case (1) Test Conditions	Parameters for Equation (14)
$\Delta\sigma = 250$ bar	$A_1 = 3.75331 \times 10^8$
$\sigma_3 = 2$ kbar	$\lambda_1 = 0.05935$
$\theta = 23°C$	$A_2 = \lambda_2 = 0$

Case (2) Test Conditions

$\Delta\sigma$ = 150 bar

σ_3 = 2 kbar

θ = 100°C

Parameters for Equation (14)

$A_1 = 0.464 \times 10^7$

$\lambda_1 = 0.02904$

$A_2 = 0.4084 \times 10^8$

$\lambda_2 = 0.08230$

where $\Delta\sigma$ is the stress difference (kbar), σ_3 is the confining stress (kbar), and $\dot{\epsilon}$ is the (axial) strain rate (s^{-1}). Russell reports that Equation (14), obtained from constant strain-rate tests, can be integrated to give the strain as a function of time to simulate a creep test. For the cases above, this yields for

$$\text{Case (1)} \quad \epsilon = 1.054 \times 10^{-3}\ \tau^{0.2703} \quad \text{and for} \tag{15}$$

$$\text{Case (2)} \quad \epsilon = 7.5 \times 10^{-4}\ \tau^{0.35}\ . \tag{16}$$

Thoms, Char, and Bergeon [35] have analyzed model pillar deformations using finite element techniques. In their analysis of a pillar, the load was applied to a pillar and the displacements were computed assuming elastic behavior. A second analysis was then performed assuming creeping viscous flow behavior of the salt to obtain the inelastic (creep) strain rates. The total strain was obtained by adding the elastic strain to the integrated creep strain rates. In their analyses for the creep deformations Thoms et al. define a "creep stiffness" [cc] as

$$\{\dot{\epsilon}\} = [cc]\{\sigma\}_T \tag{17}$$

where

$$[cc] = \frac{1}{E}\begin{bmatrix} 1 & -\nu & -\nu & 0 \\ & 1 & -\nu & 0 \\ \text{sym} & & 1 & 0 \\ & & & 2(1+\nu) \end{bmatrix}$$

$$\nu = 0.45$$

and

$$E = \frac{1}{B\left(J_2^{b_1}\right)\left(\theta^{b_2}\right)\left(\tau^{b_3}\right)}$$

in which B, b_1, b_2, and b_3 are material constants. J_2 is the second invariant of the stress deviator (psi^2); θ is the temperature (K); and τ is the time (hr). Thoms, Char, and Berge examined the pillar tests of Lomenick [14] and found that the deformation history of the pillars could be matched by selecting the following constants:

$$B = 15.6 \times 10^{-38} ,$$
$$b_1 = 0.974 ,$$
$$b_2 = 9.660 , \text{ and}$$
$$b_3 = -.750 .$$

For the pillar tests performed by Thoms et al. using Weeks Island salt, the parameters yielding good correlations to the measured pillar deformations are

$$B = 15.6 \times 10^{-38} ,$$
$$b_1 = 0.975 ,$$
$$b_2 = 9.65 , \text{ and}$$
$$b_3 = -.90 .$$

Menzel et al. [15] reported primary creep laws resulting from experiments performed on rock salt taken from German mines. The empirical equations for primary creep they reported are power laws of the form

$$\epsilon(\theta_1,\sigma,\tau) = \left[A \exp\left(\frac{\Delta\theta}{\theta_K} \cdot \frac{\theta_1}{\theta_o}\right) \cdot \frac{\mu + 1}{\eta}\right]^{\frac{\eta}{\mu+1}} \sigma^{\beta\left(\frac{\eta}{\mu+1}\right)} \tau^{\frac{\eta}{\mu+1}}$$

where $A = 1.43 \times 10^{-50}$, $\beta = 15$, $\mu = 6$, $\theta_K = 7.7$ K, $\eta = \frac{(\mu + 1) \cdot \theta_1}{\theta_1 + \mu \cdot \theta_o}$, $\theta_o = 295$ K, and σ is in kPa/cm^2.

Parrish and Gangi [5] have worked on development of a constitutive model pertaining to the primary regime observed in constant strain-rate experiments. The creep laws they present give stress as a function of time under conditions of constant strain rate as

$$\sigma(\tau) = \sigma_s(1 - \exp(\tau/\tau_o)) \qquad (18)$$

where σ is the stress and τ is the time. They have used least squares curve-fitting techniques to evaluate the best values for σ_s and τ_o for several of Heard's [12] constant strain-rate experiments. They have concluded that the data suggests a summation of terms:

$$\sigma(\tau) = \sigma_1(1 - \exp(\tau/\tau_1)) + \sigma_2(1 - \exp(\tau/\tau_2)) . \quad (19)$$

They feel that the use of two exponential functions is motivated by the possibility of having more than one deformation mechanism contributing to the creep of the salt. The different mechanisms would exhibit different activation energies and thus would require separate functions to describe their behavior.

Le Comte [13] performed creep experiments on single crystal and artificial polycrystalline rock salt over a temperature range from 0 to 300 C, a confining pressure range to 100 MPa and stress differences to 13.8 MPa. Le Comte concluded that individual creep curves could be well approximated by

$$\epsilon = A + B\tau^n \quad (20)$$

where A, B, and n are constants empirically determined from the data. Carter [36] includes in a report of the petrofabric analyses of Lyons, Kansas and Jefferson Island, Louisiana, rock salt a primary creep representation of Le Comte's [13] data for 1 kbar confining pressure tests over temperatures of 175 to 200 C. This equation is given as

$$\epsilon_t = 200\, \sigma^{1.4}\, \tau^{0.55} \exp\left(- \frac{19.7}{R\theta \times 10^{-3}}\right) \quad (21)$$

where ϵ_t represents the transient creep strain, σ is the stress (bars), τ is the time (s), θ is the temperature (K), R is the universal gas constant, and 19.7 is the value for E (activation energy) (kcal/mole).

It should be noted that several investigators have reported constitutive equations of the general form $\epsilon = f(\tau)$ or $\sigma = f(\tau)$. These equations apply to specific stress states or strain rates and are not applicable to general stress and temperature fields.

Primary creep laws presented by various investigators are summarized in Table 1. Only those laws that include stress, temperature, time (or strain) are included in the summary. The total accumulated creep strains predicted by some of these equations are presented in Table 2 for several combinations of constant stress, constant temperature, and time. Simple uniaxial stress was assumed (i.e., $\sigma = \sigma_1$, $\sigma_2 = \sigma_3 = 0$) for computing accumulated creep strains. As can be seen, the computed strains vary widely with some reaching values in excess of unity. These variations may be due to the origin of the material, to the testing procedure used, or to the extrapolation of stress, temperature, and time to values used in this comparison that are beyond the range of parameters considered during testing. Hansen [30] has tabulated a similar comparison of accumulated strains for primary creep laws resulting from tests on Lyons, Kansas and southeast New Mexico salt. Creep strains vary by more than a factor of two for the different laws within a period of two days under conditions of 3000 psi stress difference and 22.5°C temperature.

IV.2 Secondary Creep Constitutive Equations and Applications

Hedley [37] has examined the convergence rates of rooms in 5 different salt mines and used an equation similar to those used to describe isothermal, secondary creep for a description of the results. He develops the equation

$$\dot{\varepsilon} = 15 \times 10^{-8}\, \sigma^{2.7} \tag{22}$$

where $\dot{\varepsilon}$ is the room convergence rate (in/in/day x 10^{-6}) and σ is the pillar stress (psi).

Obert [20] studied the deformation behavior of model pillars constructed from salt, trona, and potash ore. He included primary creep and attempted to fit a model of the form

$$\varepsilon = \frac{\sigma}{E_m} + \frac{\sigma}{3\eta_m}\,\tau + \frac{\sigma}{E_k}\left[1 - e^{\frac{-E_k \tau}{3\eta_k}}\right] \tag{23}$$

(where E_m, η_m, E_k, and η_k are material parameters, σ is the pillar stress, and τ time) to the observed behavior of the pillars, but found that by using constant parameters the linear model could not accurately fit the results. Instead, Obert reports that a power law of the form

$$\dot{\varepsilon} = D\sigma^n \tag{24}$$

could accurately describe the steady-state creep observed in the constant force pillar tests. For halite Obert reports values of n of 3.0 to 3.1 and strain rates for model salt pillars made of Michigan salt and Kansas salt of 1.0×10^{-10} and $0.3 \times 10^{-10}\ s^{-1}$ for axial stress levels of 1000 psi and ambient temperature. Obert did not observe the transition to tertiary creep for strains up to 25 percent.

Thompson and Ripperger [18] performed experiments on rock salt taken from Grand Saline, Texas and from Hockley, Texas. They used a power law of the form

$$\dot{\varepsilon} = C\left(\frac{\sigma}{\sigma_o}\right)^n \tag{25}$$

to model the isothermal steady-state behavior observed in the experiments. An empirical fit to the data gave the values of C, σ_o, and n as $11.4 \times 10^{-7}\ min^{-1}$, 2500 psi and 5.25, respectively.

Heard [12] has provided creep laws corresponding to the constant strain rate tests performed on annealed isotropic aggregates of halite under conditions 2 kbar confining pressure, 23 to 400°C temperature, and 10^{-1} to $10^{-8}\ s^{-1}$ strain rates. In regions of steady-state creep, governed by polygonization by dislocation climb, Weertman's model (Equation (2)) consistently fit the data using mean coefficients defined by

$$\dot{\varepsilon} = 3 \times 10^{-6} \exp(23.5 \times 10^3/R\theta)\sigma^{5.5} \tag{26}$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}), θ is the temperature (K), σ is the differential stress (bar) and R is the universal gas constant (cal/mole K). At low temperatures and high strain rates, appreciable strain hardening was observed. For high stresses, Heard reports that the deformation mechanism is predominantly slip (dislocation pile-up). He reports a creep law of the form

$$\dot{\varepsilon} = 4.5(\pm 0.7) \exp(-26.0(\pm 2.3)/2.30\ R\theta) \sinh(\sigma/46.9(\pm 3.0)) \tag{27}$$

to approximate the salt behavior for this mechanism. Heard provides a transition value for the two models at high stresses as $\dot{\varepsilon}/D \approx 10^9\ cm^{-2}$, where D is the diffusivity of the rate-controlling diffusing species. For very low strain rates (on the order of

$3 \times 10^{-14}\ s^{-1}$) Heard suggests that Nabarro-Herring creep would dominate. A linear relationship between stress difference and strain rate of the form

$$\dot{\varepsilon} = \frac{abD}{\ell^2 R\theta}\sigma \tag{28}$$

exists for Nabarro-Herring creep where

ℓ = average grain diameter

a = constant (≈ 5)

b = atomic volume

R = universal gas constant

The transition from creep described by Weertman's law (Equation (26)) for polygonization to Nabarro-Herring creep is reported by Heard at strain rates defined by $\dot{\varepsilon}/D \approx 10^2$ to $10^3\ cm^{-2}$ for halite. Further, he gives a temperature limitation of $\theta > 170°C$ for Nabarro-Herring to occur. Heard reports that equivalent viscosities for rock salt range from 10^{18} to 5×10^{21} poise. Heard points out that Nabarro-Herring creep was not observed in his experiments and is not expected to occur under geologic applications.

Heard [38] has applied these creep laws to the analysis of heated salt pillars at 600-800 m depth obtaining times that rooms will remain open as

2500 to 1000 years	at 303 K
220 to 70 years	at 323 K
1.6 to 0.3 years	at 373 K

where constant stress and temperature were assumed throughout the pillar.

Hansen and Mellegard [11] estimated activation energies for salt from southeast New Mexico. They reported that values range from 8460 cal/mole to 19715 cal/mole. They note that these values are within the range of values reported by Le Comte. Hansen and Mellegard also have estimated the coefficient for the stress power law appearing in secondary creep laws of the form proposed by Weertman [1]. They report that, with the limited data available, the exponent on stress appears to be on the order of 6.

Dawson and Tillerson [39] have performed thermomechanically coupled creep analyses of isothermal and heated room and pillar geometries as part of an emplacement alternatives study for WIPP. They used creep data reported by Wawersik [40] for creep of polycrystalline rock salt from southeastern New Mexico to empirically determine the coefficients appearing in Weertman's secondary creep model. The equation they used is

$$\sigma'_{II} = 4.33 \times 10^7 \exp(1773.33/\theta)\dot{\epsilon}_{II}^{1/3} \qquad (29)$$

where

$$\sigma'_{II} = \left(\frac{3}{2}\,\sigma'_{ij}\sigma'_{ij}\right)^{\frac{1}{2}} \text{ (Pa)} \qquad \text{Cauchy Stress Deviator}$$

$$\dot{\epsilon}_{II} = \left(\frac{2}{3}\,\dot{\epsilon}_{ij}\dot{\epsilon}_{ij}\right)^{\frac{1}{2}} (s^{-1}) \qquad \text{Deformation Rate}$$

$$\theta = \text{Temperature (K)} .$$

Dawson and Tillerson predicted closure rates for three design alternatives each having effective heat loads of 150 kw/acre. Their analyses were carried out using a finite element code that is based on a formulation for creeping incompressible flow coupled with conductive-convective heat transfer.

Tillerson and Dawson [41] have also performed a parameter study for a room closure simulation in which secondary creep law parameters, thermal properties, applied heat load, and assumed boundary conditions have been varied. Specifically, they have examined power law exponents for stress in a Weertman's creep law (Equation (2)) of 3 and 5 and activation energies of 10.4 and 12.9 kcal/mole. Other parameters in Weertman's equation were determined empirically using data reported by Wawersik [40]. The closure rates were significantly affected in both heated and isothermal applications.

Munson [7] has developed a preliminary deformation mechanism map (such as proposed by Ashby [42]) for salt. The deformation mechanism map was constructed with the aid of creep data reported by Poirier [17], Kingery and Montrone [43], Burke et al. [9], Heard [12], and Hansen and Mellegard [11]. He uses the data from these sources to define boundaries on the deformation mechanism map that represent the change from one dominant mechanism to another. Munson discusses four creep mechanisms and indicates that there is a fifth, yet undefined, mechanism possible. The four known mechanisms are defect-less flow, dislocation glide, dislocation climb creep (including pipe and volume modes) and diffusional creep (including Coble (grain boundary diffusion) and Nabarro-Herring (volume diffusion)).

Munson has constructed a preliminary constitutive model for rock salt. The basis of the model is a secondary creep equation that allows for two competing mechanisms, namely the dislocation climb creep and the undefined mechanism. For dislocation climb creep a power law dependence in stress is assumed such that

$$\dot{\epsilon}_{s_1} = S_1 \exp(-Q_1/R\theta)\sigma^{n_1} \tag{30}$$

where $\dot{\epsilon}_{s_1}$ is the dislocation climb creep secondary strain rate, Q_1 is the activation energy for the mechanism, n_1 defines the stress dependence for creep, S_1 is a constant, σ is the stress, R is the universal gas constant, and θ is the temperature. For the undefined mechanism Munson uses a creep law of the form

$$\dot{\epsilon}_{s_2} = S_2 \exp(-Q_2/R\theta)f_2(\sigma) \ . \tag{31}$$

The complete steady-state response is obtained by adding together strain rates defined by the two mechanisms to obtain

$$\dot{\epsilon}_s = \dot{\epsilon}_{s_1} + \dot{\epsilon}_{s_2} \ . \tag{32}$$

To accommodate the primary creep regime within the model, Munson first assumes that the role of primary creep is to supply dislocations that form a stable substructure from which secondary creep occurs. Further, he assumes that primary creep exhibits the same activation energies as does secondary creep. This allows Munson to incorporate a primary regime by modifying the secondary models as

$$\dot{\epsilon} = F\dot{\epsilon}_s \ . \tag{33}$$

F is an exponential function that diminishes to zero as the accumulated transient strain approaches a predetermined value according to the equation

$$F = \begin{cases} \exp\left(\dot{\Delta}\left(1 - \frac{\epsilon_t}{\epsilon_t^*}\right)\right) & \epsilon_t \le \epsilon_t^* \\ 1 & \epsilon_t > \epsilon_t^* \end{cases} \tag{34}$$

where $\dot{\Delta}$ is the transient strain rate change and ϵ_t^* is the transient strain limit.

Wawersik [40] has used an equivalent viscosity

$$\eta = \frac{(\sigma_1 - \sigma_3)}{3\dot{\epsilon}_1} \tag{35}$$

to compare with data reported by Ode [44], Heard [12], and others. He found that rock salt from the 2100 to 2000 ft. level of drillhole AEC #7 yields viscosity values of 10^{13} to 10^{17} poise for 1000 psi stress difference, 500 psi mean stress and temperatures ranging from 24 to 130°C. Extrapolated values reported by other investigators mentioned above ranged from 10^{14} to 10^{21} poise.

Mraz [45] reports that based on observed underground conditions, rock salt behaves as an elastic-perfectly plastic substance. He indicates that salt exhibits a well defined elastic limit of 212 psi. Further, Mraz reports an equivalent viscosity for plastic deformations of 2.2×10^{18} poise for rock salt consisting of 58.5% halite, 40.2% sylvite, 0.5% carnallite, and 0.8% clay.

The secondary creep laws reported by the various investigators are summarized in Table 3. For each equation the units required for stress, temperature and time (as given in the reference) are listed and the source of sample material is given. The secondary creep rates predicted by each law for several combinations of stress and temperature are presented in Table 4. In these comparisons, a state of uniaxial stress has been assumed so that the axial stress, stress difference, and effective stress are all equal. It should be noted that the activation energies are quite different between Heard's equation and that of Dawson and Tillerson. This can be attributed to the possibility that different mechanisms are dominant in the regimes where data is obtained for these laws. Extrapolation to the conditions where the comparisons are made leads to the difference in strain rates. This suggests the need to account for more than one mechanism occurring simultaneously.

IV.3 Elastoviscoplastic Constitutive Equations and Applications

Winkel, Gerstle and Ko [46] have reported on analyses performed using elastoviscoplastic material models for potash. The bulk behavior was assumed to be elastic while the deviatoric response was modeled with a combination of springs, dashpots and sliding elements. The values of material parameters were evaluated from 2-3/4 inch diameter specimens fabricated from potash ore from the Carlsbad area. The octahedral yield stress (k_{OCT}) was expressed as a function of mean stress (σ_m).

$$k_{OCT} = a + b \exp(c\sigma_m) \tag{36}$$

where

$$a = 1145 \text{ psi}$$

$$b = 1000 \text{ psi}$$

$$c = .00153 \frac{1}{\text{psi}}$$

For stress states below yielding, linear viscoelastic response was assumed for the deviatoric deformations, while for stresses above yielding, viscoplastic response was assumed. Winkel et al. list the parameters for the New Mexico potash in their paper and compare these to parameters reported by Serata [47] for a similar material model for salt. They used this material model to predict the closure rates of holes drilled into pillars in a potash mine near Moab, Utah. The comparison of predicted values with measured values are given for the material parameters derived from Carlsbad potash and the parameters from Serata's model for salt.

Serata [47] has published numerous articles on the analysis of time-dependent deformations of salt cavities and openings. One model for salt uses a yield stress. For stresses below this yield stress, creep is viscoelastic (recoverable); whereas, for stresses above the yield stress, the creep is viscoplastic (permanent). The yield stress is a function of strain rate and total strain. For zero strain rate at 100°C the yield strength given by Serata is 500 psi. This value increases with increasing strain rate. Serata observes that the transition from viscoelastic to viscoplastic behavior is characterized by Poisson's ratio approaching 0.5 and by the strain rate changing from a diminishing value with time to a constant value for constant stress. This transition occurs between 700 and 800 psi according to Serata. Serata has also incorporated a loss in the shear strength due to accumulated strain as a function of mean stress.

Langer [48] has reported elastoplastic-creep rheological models for rock salt. In these models, the total deformation is composed of elastic, inelastic, and creep components as

$$\varepsilon = \varepsilon_e + \varepsilon_n + \varepsilon_p + \varepsilon_s \tag{37}$$

where ε_e is the elastic strain defined by

$$\varepsilon_e = \frac{\sigma}{E_o} \tag{38}$$

ε_n is the plastic strain defined by

$$\varepsilon_n = \frac{\sigma}{E_k} \left(1 - \exp(-E_k \tau/\eta_k)\right) , \tag{39}$$

ε_p is the primary creep defined by

$$\varepsilon_p = (\sigma - \sigma_{kr}) \sum_{i=1}^{\eta} \frac{1}{E}\left(1 - \exp\left(- \frac{E_i}{\eta_i} \tau\right)\right) , \tag{40}$$

ε_s is the secondary creep defined by

$$\varepsilon_s = (\sigma - \sigma_{F\ell}) \frac{\tau}{\eta_{p\ell}} , \tag{41}$$

where E_o, E_R, η_R, E_i, η_i and $\eta_{p\ell}$ are material parameters. For stress states defined by $\sigma < \sigma_{kr}$ and $\sigma < \sigma_{F\ell}$ only the elastic and plastic strains are computed. For stress states such that $\sigma > \sigma_{kr}$ and $\sigma \geq \sigma_{F\ell}$, both the primary and secondary creep strain components are included in the total. For stress states defined by $\sigma > \sigma_{kr}$ and $\sigma < \sigma_{F\ell}$, only the primary creep component is added to the elastic and plastic components of strain. In place of the constant viscosity described by $\eta_{p\ell}$, Langer also discusses the use of nonlinear laws with power law and exponential stress dependence.

IV.4 Creep Rupture Models

Nair and Singh [16] studied creep rupture criteria under isothermal conditions for rock salt using a linear cumulative damage theory. Nair and Singh performed triaxial extension tests and observed that induced axial tensile strain causes failure. The stress difference (logarithm) was plotted versus the time to failure. This curve is well approximated by a straight line. For multiaxial states of stress, Nair and

Singh suggest a substitution of the maximum principal stress difference for the stress that controls the time to failure.

V. SUMMARY AND ASSESSMENT

As outlined in the previous section, a variety of primary and secondary creep models have been empirically evaluated to describe the long term behavior of rock salt from laboratory and field data. Some investigators have tied the form of their equations to the physical mechanisms controlling creep, while others have simply used curve fitting techniques.

The bulk of the work performed to date has been within the context of primary creep. Primary creep laws are necessary to describe the short term creep response of salt and are effective in providing constitutive equations for computational methods that are applied to analyze relatively short term phenomena. However, salt is known to deform in the secondary creep regime for a large portion of its total deformation under a wide range of stress and temperature conditions. Primary creep laws exhibiting monotonically decreasing strain rates as either a function of time or strain become non-conservative (in terms of mine closure) as secondary creep becomes dominant. For time periods extending well beyond the time span of measured data used to formulate the law, little confidence can be placed in computations based solely on primary creep laws. This is emphasized by Baar, who cites several examples of constant convergence rates observed in mines. The convergence measurements represent an integrated effect over the pillar height (and include motion in the floor and ceiling) and, therefore, do not provide conclusive evidence that all of the material is deforming in a secondary creep mode. However, the measurements do strongly suggest that primary creep models are inadequate.

Secondary creep models, on the other hand, are useful for predictions of deformations in which the secondary phase dominates. Secondary creep laws with parameters determined using the deformation rates evaluated at the end of creep tests tend to be conservative over long time periods since the experimentally observed creep rates are usually still decreasing at the end of the creep test. Creep data reported by Wawersik [3] and Hansen and Mellegard [11] represent the data that is most applicable to WIPP analyses since the data is derived from New Mexico salt tested over appropriate conditions.

The use of some elastoviscoplastic models causes difficulty in properly accounting for the zero (or nearly zero) yield limit and the inseparable time-dependent and time-independent plasticity exhibited by salt during the initial loading phases. Further, the definition of a unique yield surface is questionable in light of the time-dependent behavior of salt.

The combined work of the investigators summarized herein covers a variety of constitutive equations for primary creep and secondary creep. All aspects of the creep response of rock salt have not, however, been represented by a single comprehensive constitutive model. Additional data are needed to quantify fully the observed behavior. Among the areas requiring research emphasis are (i) criteria that define the transition from primary to secondary creep or from secondary to tertiary creep and (ii) formulations that account for possible history effects on secondary creep rates.

APPENDIX A. STRESS AND STRAIN MEASURES

In most of the work reviewed, the stress and strain measures used were either poorly defined or inadequate for the implied application. Many reported using engineering strain, for instance, as defined by

$$[\varepsilon] = [F] - [I] \tag{42}$$

where F is the deformation gradient and I is the identity matrix. This strain measure is not objective, and thus will not be invariant to coordinate rotations. Thus, to apply it to general multiaxial conditions of stress and strain with possibly large rotations could lead to appreciable errors. Similarly, the logarithmic strain is not objective and is inappropriate for large strain and large rotation analyses. Strain rates derived from the engineering or natural strain measures suffer the same inadequacy. However, the deformation rate tensor

$$d_{ij} = \frac{1}{2}(\dot{u}_{i,j} + \dot{u}_{j,i}) \tag{43}$$

is objective. It can be shown that constant strain rate tests are not equivalent to constant deformation rate tests. Further, usual procedures to convert primary creep laws from the form $\varepsilon = f(\sigma,\theta,\tau)$ to $\dot{\varepsilon} = f(\sigma,\theta,\varepsilon)$ become more complex when large strain measures are used.

Many of the stress measures reported appear to be based on the original geometry of the system without properly accounting for large strains occurring during large deformations (such as by using the Piola-Kirchoff stress). The Cauchy stress, which properly defines stress during large strain, has been used by some investigators. Not accounting for changes in stress as pillars deform in either laboratory models or mines can lead to the interpretation that salt deformations occur all within the primary creep regime when the deformation may be the result of secondary creep.

It is important that equations developed as constitutive models for salt be usable by anyone working in the field. For this to happen, it is necessary that stress and strain measures be well defined and be consistent with the reference configuration specified to describe the system.

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TABLE 1 PRIMARY CREEP CONSTITUTIVE EQUATIONS

Equation Number	Investigator	Primary Creep Law	Units (θ, τ, σ)	Data Source
5	McClain and Starfield	$\epsilon = 1.3 \times 10^{-37} \theta^{9.5} \tau^{0.3} \sigma^{3.0}$	K, hours, psi	Lomenick's pillar studies
6	McClain and Starfield	$\epsilon = 6.5 \times 10^{-37} \theta^{9.5} \tau^{0.37} \sigma^{3.0}$	K, hours, psi	Project Salt Vault
7	Maxwell, Wahi, and Dial	$\dot{\epsilon}_c = .4656[(3.1386 \times 10^{-20}) S^{3.0} \exp(\frac{-4100}{\theta})]^{\frac{1}{.4656}} / \left(\epsilon_c^{\frac{1}{.4656}-1} \right)$	K, s, Pa	SENM Salt
9	Ratigan and Callahan	$\epsilon_{ij} = 6.87 \times 10^{-15} (\frac{\theta}{295.5})^{9.5} \tau^{0.40} J_2 \sigma_{ij}$	K, s, psi	Project Salt Vault
13	Hansen	$\epsilon_1 = 1.1 \times 10^{-35} \tau^{0.4656} \sigma^{2.475} \theta^{8.969}$	K, s, psi	SENM Salt
17	Thoms, Char, Bergeron	$\epsilon_{ij} = \frac{1.45\sigma_{ij} - .45\delta_{ij}\sigma_{KK/3}}{15.6 \times 10^{-38} (J_2)^{.974} \theta^{9.66} \tau^{-.75}}$ $i = j$	K, hr, psi	Weeks Island Salt
21	Carter	$\epsilon_t = 200 \sigma^{1.4} \tau^{0.55} \exp(\frac{-19.7}{R\theta \times 10^{-3}})$	K, s, bar	LeComte data

TABLE 2 PRIMARY CREEP STRAINS

Temperature K	Stress Difference (MPa)	Time (sec)	Strain Predicted by Creep Law Number (See Table 1): (5)	(6)	(7)	(9)	(13)	(21)
296	6.895	10^6	2.11×10^{-4}	2.078×10^{-3}	1.188×10^{-3}	3.897×10^{-4}	2.66×10^{-3}	4.107×10^{-7}
		10^7	4.22×10^{-4}	4.871×10^{-3}	3.469×10^{-2}	9.789×10^{-4}	7.77×10^{-3}	1.457×10^{-6}
		10^8	8.26×10^{-4}	1.142×10^{-2}	1.014×10^{-2}	2.459×10^{-3}	2.27×10^{-2}	5.170×10^{-6}
	13.79	10^6	1.684×10^{-3}	1.662×10^{-3}	9.502×10^{-3}	3.118×10^{-3}	1.479×10^{-2}	1.084×10^{-6}
		10^7	3.364×10^{-3}	3.998×10^{-2}	2.766×10^{-2}	7.831×10^{-3}	4.322×10^{-2}	3.846×10^{-6}
		10^8	6.59×10^{-3}	9.137×10^{-2}	8.115×10^{-2}	1.967×10^{-2}	1.263×10^{-2}	1.364×10^{-5}
373	6.895	10^6	1.89×10^{-3}	1.196×10^{-3}	2.072×10^{-2}	3.505×10^{-3}	2.12×10^{-2}	4.148×10^{-4}
		10^7	3.77×10^{-3}	4.871×10^{-3}	6.054×10^{-2}	8.804×10^{-3}	6.18×10^{-2}	1.472×10^{-3}
		10^8	7.53×10^{-3}	1.027×10^{-1}	1.071×10^{-2}	2.211×10^{-2}	1.81×10^{-1}	5.222×10^{-3}
	13.79	10^6	1.52×10^{-2}	9.569×10^{-3}	1.658×10^{-1}	2.804×10^{-2}	1.177×10^{-1}	1.095×10^{-3}
		10^7	3.00×10^{-2}	3.898×10^{-2}	4.827×10^{-1}	7.043×10^{-2}	3.438×10^{-1}	3.879×10^{-3}
		10^8	6.02×10^{-2}	8.217×10^{-1}	1.416	1.769×10^{-1}	1.00	1.378×10^{-2}

TABLE 3 SECONDARY CREEP CONSTITUTIVE EQUATIONS

Investigators	Secondary Creep Law	Units (stress, temperature, time)	Data Source
Hedley (37)	$\dot{\varepsilon}_A = 15 \times 10^{-14} \sigma_o^{2.7}$	psi, -, days	Salt Mine Convergence Measurements
Obert (20)	$\dot{\varepsilon}_A = D\sigma_o^{3.0}$	Coefficient D not given	Michigan Salt Kansas Salt
Thompson & Ripperger (18)	$\dot{\varepsilon} = 11.4 \times 10^{-7} \left(\frac{\Delta\sigma}{2500} \right)^{5.5}$	psi, -, minutes	Grand Saline and Hockley Texas Salt
Heard (12)	$\dot{\varepsilon} = 3 \times 10^{-6} \exp\left(- \frac{11833}{T} \right)(\Delta\sigma)^{5.5}$	bar, K, seconds	Artifically annealed salt aggregates
Dawson & Tillerson (39)	$\varepsilon'_{II} = 1.232 \times 10^{-23} \exp\left(- \frac{5200}{T} \right) \sigma_{II}'^{3.0}$	Pa, K, seconds	SENM Salt

σ_o - average pillar stress

$\Delta\sigma$ - stress difference

σ_{II} - effective deviatoric stress

$\dot{\varepsilon}_A$ - axial strain rate

$\dot{\varepsilon}$ - strain rate

$\dot{\varepsilon}_{II}$ - effective deformation rate

TABLE 4 SECONDARY CREEP RATES

Temperature	Stress Difference	Equation (22) (Hedley)	Equation (24) (Obert)	Equation (25) (Thompson & Ripperger)	Equation (26) (Heerd)	Equation (29) (Dawson & Tillerson)
296 K	6.895 MPa	2.13×10^{-10} s^{-1}	$0.3 - 1.0 \times 10^{-10}$ s^{-1} +	1.23×10^{-10} s^{-1}	1.57×10^{-13} s^{-1}	$.95 \times 10^{-10}$ s^{-1}
	13.79 MPa	1.42×10^{-9} s^{-1}	†	5.57×10^{-9} s^{-1}	$.71 \times 10^{-11}$ s^{-1}	$.76 \times 10^{-9}$ s^{-1}
373 K	6.895 MPa	*	*	*	$.6 \times 10^{-9}$ s^{-1}	$.356 \times 10^{-8}$ s^{-1}
	13.79 MPa	*	*	*	$.272 \times 10^{-7}$ s^{-1}	$.285 \times 10^{-7}$ s^{-1}
473 K	6.895 MPa	*	*	*	$.492 \times 10^{-6}$ s^{-1}	$.677 \times 10^{-7}$ s^{-1}
	13.79 MPa	*	*	*	$.222 \times 10^{-4}$ s^{-1}	$.543 \times 10^{-6}$ s^{-1}

* Isothermal Laws

\+ Rates given explicitly in references

† Rates not given in reference