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CREEP RESPONSE

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P. R. DAWSON
J. R. TILLERSON

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HEATED MINE ROOM AND PILLAR SECONDARY CREEP RESPONSE*

J. R. Tillerson and P. R. Dawson[†]
Members of Technical Staff
Sandia Laboratories,[‡] Albuquerque, New Mexico 87185

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[†] A U. S. Department of Energy Facility.

[‡] Cornell University, Ithaca, NY.

SUMMARY

Heated salt mine room and pillar simulations have been performed to provide information regarding parameters affecting room closure rates to designers of radioactive waste isolation facilities. A coupled secondary creep and heat transfer formulation with large strain capabilities was used to assess the effects of variations in creep law parameters, thermal properties, imposed boundary conditions, temporal integration, and meshing resolution on room closure rates. Results indicate that the greatest effect results from variations in parameters appearing in the creep constitutive equation.

INTRODUCTION

Rooms and passageways opened during mining tend to close subsequent to the excavation process as a result of deformations of the rock formations not only at the mine horizon but above and below the horizon. Depending on the type of host rocks, depth of the mine horizon, presence of heat sources, extraction ratios, and the in-situ stress field, closure of these rooms may be observed for a short period followed by stable conditions of either very little or no additional closure or the rooms may continue to close possibly with large amounts of slabbing associated with the roof and pillars.

The analysis of room and pillar mine configurations requires detailed attention to the type of deformation occurring in the rock media surrounding a room. Many rocks exhibit linear elastic behavior up to failure. For example, welded tuff shows almost no plastic deformation prior to brittle failure. Others, e.g. rock salt, tend to exhibit rate dependent behavior, such as viscoplasticity or creep, under conditions in the vicinity of a room and pillar. Just as important in any analytical effort are the joints and fractures in the host media. The presence of joints and fractures can grossly modify the behavior of a "rock mass" from the properties of small test specimens free from joints and fractures. Another uncertainty encountered in performing analyses is specifying the in-situ stress field that exists prior to the excavation process.

In the present article, the thermomechanical response of a room and pillar configuration in a thick, bedded salt formation is examined. Rock salt is relatively homogeneous and, due to its healing nature, is

relatively free from joints and fractures. Rock salt has been experimentally observed to creep upon application of a deviatoric stress field while showing nearly zero elastic limit.¹ In these analyses, the details of the excavation process have been neglected, in that a room is assumed to be instantaneously opened and deformation commences thereafter. The application of these analyses is to the storage of heat producing radioactive wastes in salt formations.

In this paper, the effects of variations in creep law parameters, thermal material properties, heat load, boundary conditions, temporal integration and meshing resolution on the predicted closure rates of mine rooms are studied. A coupled creeping viscoplastic flow and conductive heat transfer formulation has been employed to predict the mine response. A secondary creep constitutive equation has been selected to represent the viscoplastic behavior of the rock salt.

Numerous other studies have been reported for the closure of rooms mined in salt formations. Several of these utilize primary creep equations derived using data from model pillar or triaxial compression tests^{2,3,4,5,6} while some analyses of mine rooms have been performed using secondary creep models based on limited data for steady-state creep rates^{7,8}. The application of elastoviscoplastic models incorporating yield criteria for the transition from elastic to plastic deformations and both recoverable and permanent creep strains have also been reported.^{9,10} These various constitutive equations have been applied in conjunction with both finite element and finite difference solution methods. The

primary creep laws capture early history showing strain hardening but continue to show diminishing rates with time. These models may become non-conservative with time if actual rates of motion do not continue to diminish. Secondary creep models ignore the initial transient rates and may underpredict the motion in early times. However, for long periods of time, if secondary creep dominates the motion, the predictions will tend to be conservative if the last data from experiments are used as the steady creep rates. Tertiary creep models have not been widely used and require more investigation to assess the desired functional form and the appropriate testing programs and model parameters. The purpose of this paper is to study the effects of variations in material parameters in a particular material model on the room and pillar motion to aid in establishing requirements for testing and constitutive modeling. A more complete description of reported creep laws for rock salt and their advantages and limitations is given in Reference 11. Efforts are continuing to incorporate more complex constitutive models having primary, secondary, and tertiary regimes to fully model room and pillar response.

COUPLED SECONDARY CREEP AND HEAT TRANSFER FORMULATIONS

The motion of the salt is predicted using the COUPLEFLO finite element program.¹² This program has been used for analyses of metal forming in addition to its applications in simulating the motion of geologic formations. The code is valid not only for large deformations but is also useful for the more mathematically rigorous large strain simulations. The heat transfer and mechanical solutions are coupled at each time increment for which a solution is obtained. The equations of motion in the code are based on a formulation for creeping incompressible non-Newtonian flow of a fluid-like material. The heat transfer equations result from a conductive-convective energy formulation. Constitutive models dependent upon the stress, strain, and temperature of the material have been incorporated in the code. Similarly, a temperature dependent conductivity and decaying heat sources are also easily simulated. The finite element equations have been formulated directly from Lamb's variational principle. However, Galerkin's method was used to formulate the energy equations, since no variational principle exists for the conductive-convective heat transfer equations.

Momentum Equations

The governing equations for creeping incompressible viscoplastic flow are given as follows¹²:

$$\text{Equilibrium:} \quad \sigma_{ij,j} + X_i = 0 \quad (1)$$

$$\begin{array}{l} \text{Deformation} \\ \text{Rate-Velocity:} \end{array} \quad \dot{\epsilon}_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \quad (2)$$

$$\text{Incompressibility:} \quad \dot{\epsilon}_{ii} = 0 \quad (3)$$

$$\text{Boundary Conditions:} \quad u_i = \bar{u}_i \text{ on } S_u \quad (4)$$

$$\sigma_{ij} v_j = \bar{T}_i \text{ on } S_\sigma \quad (5)$$

where σ_{ij} is the stress tensor, $\dot{\epsilon}_{ij}$ is the deformation-rate tensor, X_i is the body force vector, u_i is the velocity vector, θ is the temperature, v_j is the unit normal to the surface, S_u is the surface on which u_i is specified as $\bar{u}_i$, and S_σ is the boundary on which the traction vector $\bar{T}_i$ is specified. The deformation rate is defined exactly in terms of the velocity gradients of Eq. (2) and does not neglect higher order terms. The body forces, X_i , are dependent on the temperature and can be represented as

$$X_i = \rho g_i (1 - \alpha(\theta - \theta_{\text{ref}})) \quad (6)$$

where ρ is the reference temperature density, g is the gravitational vector, α is the volumetric expansivity, θ is the temperature and θ_{ref} is the material temperature in the reference (ambient) state.

The constitutive model used in conjunction with Equations (1)-(6) represents a relationship between applied deviatoric stresses and the resulting deformation-rates:

$$\dot{\epsilon}_{ij} = f(\theta, \dot{\epsilon}_{II}, \sigma'_{II}) \sigma'_{ij} \quad (7)$$

where $\dot{\epsilon}_{II}$ and σ'_{II} are the effective deformation-rate and effective deviatoric stress*, respectively. Secondary creep or non-Newtonian fluid behavior can be incorporated into the analysis using this model.

* $\dot{\epsilon}_{II} = (\frac{2}{3} \dot{\epsilon}_{ij} \dot{\epsilon}_{ij})^{1/2}$ and $\sigma'_{II} = (\frac{3}{2} \sigma'_{ij} \sigma'_{ij})^{1/2}$

The viscoplastic flow formulation based on Lamb's functional¹² has an auxiliary condition added to impose the incompressibility constraint placed on the mode of deformation. The variational statement resulting from the functional, including this constraint condition, is:

$$\delta J = \int_V \sigma'_{ij} \delta \epsilon_{ij} dv - \int_V \delta(p \epsilon_{ii}) dv - \int_V X_i \delta u_i dv - \int_S T_i \delta u_i ds = 0 \quad (8)$$

where the Lagrange multiplier p has the physical interpretation of pressure. Equations (1)-(5) represent the Euler equations for this functional. Following standard finite element procedures, approximating functions are introduced for the velocity and pressure within an element. Continuous quadratic interpolation functions have been specified for velocity and discontinuous linear approximations for the pressure. Because the pressure approximations are complete with respect to the deformation-rate approximations, incompressibility is imposed at all points within an element. Element contributions to the variation of the functional, described in terms of the approximating functions, are summed over the region to provide a matrix equation from which the velocity and pressure throughout the region are determined. Details of this finite element formulation are given in Reference 12.

Two important assumptions are incorporated into this formulation. The first is that inertia terms have been neglected in the equilibrium equations. For this creeping flow assumption to be valid, accelerations of the material must be small relative to other terms in Equation (1). The second assumption is that elastic strains are assumed to be

sufficiently small to be ignored (i.e., for a given strain increment the viscous component must be dominant over the elastic component).⁴

Energy Equations

The governing equations for conductive-convective heat transfer with an incompressible flow field are given by

$$\text{Energy:} \quad (k\theta_{,1})_{,1} - \rho C_p u_1 \theta_{,1} + \tilde{Q} = \rho C_p \dot{\theta} \quad (9)$$

$$\text{Boundary Conditions:} \quad \theta = \bar{\theta} \text{ on } S_\theta \quad (10)$$

$$\bar{q} = (k\theta_{,1} - \rho C_p u_1 \theta) v_1 \text{ on } S_q \quad (11)$$

$$\text{Initial Conditions:} \quad \theta(x, 0) = \bar{\theta}_0(x) \quad (12)$$

where k is the conductivity, C_p is the specific heat, $\tilde{Q}$ is the heat generation rate, $\bar{q}$ is the surface heat flux rate and v_1 is the unit normal vector to the surface, S_q , $\dot{\theta}$ is the temporal derivative of the temperature, $\frac{d\theta}{dt}$ and τ is the time. The heat generation rate can result from the viscous dissipation from the flow field and from the decay of the radioactive nuclear wastes. The conductivity of the salt has been represented as an exponential function of temperature.

The finite element formulation of the conductive-convective heat transfer equation is based on Galerkin's method. Weighted residuals (R_v and R_s) are formed using Equations (9) and (10) and a set of weighting functions (N_j) as follows:

$$R_v = \sum_{j=1}^n \int_V \left\{ (k\theta_{,1})_{,1} - \rho C_p u_1 \theta_{,1} + \tilde{Q} - \rho C_p \dot{\theta} \right\} N_j dv \quad (13)$$

$$R_s = \sum_{j=1}^n \int_{S_q} \{ (k\theta_{,1} - \rho C_p u_1 \theta) v_1 - q \} N_j dS . \quad (14)$$

Continuous quadratic finite element approximations for temperature are introduced within an element and the residuals are required to vanish for all values of the weighting functions N_j . Integration by parts and application of Green's theorem yield a matrix equation for nodal point values of θ and $\dot{\theta}$. The time derivative of temperature, $\dot{\theta}$, is approximated with a central difference expression. An implicit Crank-Nicholson method is used for temporal integration of the energy equation in which the average rate of heat generation is defined by

$$\bar{Q}_{ave} = \frac{1}{\Delta\tau} \int_{\tau}^{\tau+\Delta\tau} \bar{Q} d\tau \quad (15)$$

Thermomechanical Coupling and Solution Procedure

Coupling between the momentum and energy equations is incorporated in the finite element model. The temperature distribution is affected by viscous dissipation and changes in the region geometry. In the applications to be presented, the viscous dissipation is very small. The velocity field is influenced by the temperature distribution through temperature dependent material properties and body forces.

An incremental solution procedure follows the transient behavior of the geologic formation after the emplacement of the heat generating waste. At each step of the incremental method a new temperature distribution and velocity field are determined. The temperature history is integrated using a Crank-Nicholson method. The geometry is

moved ahead to reflect deformations occurring within the region using a simple Euler's integration of the velocity field. Because the deformation rate-velocity relationship (Equation (2)) is not limited to small strains, the velocity field can be integrated to large deformations without introducing errors of neglecting higher order terms. In problems with non-Newtonian viscosity, an iterative solution algorithm (variable stiffness or modified Newton-Raphson) is used to determine the nonlinear flow field. With this method, the finite element mesh flows with the material making the convective terms in Equation (9) identically zero. Temperature dependent material properties and body forces are evaluated using temperatures predicted at the beginning of the time increment. A flow chart describing this iterative procedure in detail is provided in Figure 1.

Figure 1. Quasi-Lagrangian Incremental Solution Procedure

ROOM AND PILLAR DESCRIPTION FOR THE BASELINE CASE

A generic room and pillar geometrical configuration (henceforth called the baseline case) typical of proposed underground nuclear waste repositories in salt was selected for studying effects of variations in geometrical and material parameters. Room size and spacing for an actual repository may be different, but the results presented here are intended to assess the sensitivity of the closure of the rooms to parameter variations. It is assumed that the rooms are mined at approximately an 825 m (2700 ft) depth.

The rooms in the simulations are 4.57 m (15 ft) high and 4.57 m (15 ft) wide. The distance from the centerline of one pillar to the centerline of the next pillar is 22.94 m (75 ft). The extraction ratio (percentage of material mined from a horizon based on planform area) for this geometry is approximately 20%. The region of analysis has been limited to a two-dimensional section of a storage room and the adjacent pillar having unit depth into the drift. This assumes that the storage rooms are long and that the heat sources resulting from discrete canister locations can be modeled as a uniform "line" source along the drift. These assumptions allow two-dimensional analyses to be performed. Because several drifts will exist side by side, planes of symmetry have been assumed to exist vertically along the pillar centerline and along the room centerline. This further limits the region of the analyses to an area between the centerline of a room and the centerline of a pillar. The finite element mesh used in this study is shown in Fig. 2.

In the thermal analyses the centerlines of the rooms and the pillars are required to be adiabatic. The regional thermal analyses extend 75 m

Figure 2. Finite Element Mesh for Baseline Case

(246 ft) above and below the midheight of the pillar. The upper and lower boundaries were maintained at the ambient temperature. These imposed conditions were deemed reasonable since the temperature gradients remained small near these boundaries throughout the analysis. The salt surfaces around the room are assumed to be adiabatic since continuous ventilation of the tunnels during waste storage is not expected.

The waste canisters are assumed to be 3.05 m (10 ft) in length and are emplaced vertically beneath the center of the room. The canisters are buried so that 3.05 m of backfill can be placed above the top of the canister [i.e., the canister lies from 3.05 m (10 ft) to 6.10 m (20 ft) below the room and the hole is refilled after emplacement]. The initial thermal load from the wastes is equivalent to 18.5 W/m^2 (75 kW/acre) over the heated area. A half-life of thirty years is used to represent the rate of decay of the waste heat production. All the canisters are assumed to be simultaneously emplaced and initially the entire region is at 313 K. The heat load may be plausible for a commercial repository.

In the secondary creep deformation analyses, salt along the center-lines of the room and the pillar is not allowed to have horizontal components of displacement. Vertical displacements along these boundaries are permitted, however. An overburden stress equal to the weight of material lying above the region of analyses was applied along a surface lying 15 m (49.2 ft) above the midheight of the pillar. No vertical displacements were permitted at a distance 15 m (49.2 ft) below the midheight of the pillar and temperature dependent body forces (allowing

for thermal expansion) were included in the analyses. The effect of variations in overlying layers has been neglected, and edge effects due to cross drifts or other changes in geometry have also been neglected. Similarly, the effects of abutment pillars, shaft barrier pillars, or the salt at the edge of the storage facility have been neglected; since these effects tend to unload the pillars between the rooms, the creep rates predicted in these analyses should be higher than those anticipated in analyses which would include these effects.

The salt is assumed to be homogeneous and isotropic. The thermal conductivity, which varies from 5 W/mK at 300 K to 3 W/mK at 500 K, has been modeled analytically using the exponential function specified in Table 1. Values of density, expansivity and specific heat are also given in Table 1.

A thermally-activated secondary creep equation has been selected to represent the creep behavior of the rock salt in which a single, thermally-activated mechanism controls the rate of deformation. The secondary creep equation specifies a nonlinear dependence of (viatoric stress on the deformation-rate in the form of a power law. The effect of the mean stress on creep rates is neglected and the limiting stress below which creep ceases is assumed to be zero. For the Baseline case, the parameters necessary for this equation were determined from creep data reported by Wawersik¹⁴ and are listed in Table 2. Also given in Table 2 are creep rates predicted by this creep constitutive equation for several conditions of stress and temperature. Other cases (A-F) in Table 2 correspond to parameter variations which will be discussed in the next section.

The calculated thermal response for three points around the room perimeter are shown in Figure 3 for the first ten years after the waste has been emplaced. The temperature of the room floor along the centerline exhibits the fastest temperature rise of the points shown due to its proximity to the heat source. Ten years after emplacement of the least producing canisters, the temperature rise at the floor is approximately 60°C. The other points located at the pillar midheight and roof centerline exhibit similar behavior.

TABLE 1

SALT PROPERTIES

Density:	$\rho = 2167 \text{ kg/m}^3$
Specific Heat:	$c_p = 888 \text{ J/(kg K)}$
Volumetric Thermal Expansivity:	$\alpha = 1.2 \times 10^{-4} \text{ 1/K}$
Thermal Conductivity:	$k = 10.8 e^{-2.55 \times 10^{-3} T_w / (\text{mK})}$

TABLE 2
SECONDARY CREEP EQUATION PARAMETERS

$$\dot{\epsilon}_{II} = A e^{-Q/RS} \sigma_{II}^n$$

Case	Constitutive Model Parameters			Creep Rates (ns^{-1})		
	A	Q	n	$\sigma'_{II} = 6.9 \text{ MPa}$ $\theta = 297 \text{ K}$	$\sigma'_{II} = 6.9 \text{ MPa}$ $\theta = 403 \text{ K}$	$\sigma'_{II} = 6.9 \text{ MPa}$ $\theta = 473 \text{ K}$
Baseline	4.1×10^{-24}	10.4	3	.033	3.3	23.
A	1.23×10^{-23}	10.4	3	.10	10.	68.
B	1.17×10^{-37}	10.4	5	.033	3.3	23.
C	2.58×10^{-37}	10.4	5	.10	10.0	68.
D	4.1×10^{-25}	10.4	3	.0033	0.33	2.3
E*	1.18×10^{-33}	23.6	5.47	1.6×10^{-4}	5.6	428.
F	1.02×10^{-22}	12.9	3	1.05×10^{-2}	3.3	36.

* Model parameters determined by Parrish⁽¹⁵⁾ for data reported by Heard.⁽¹⁶⁾

Q is the activation energy
R is the universal gas constant

Figure 3. Temperature Profiles for the Baseline Case

The creep response of the room and pillar configuration for the baseline parameters is shown in Figure 4. The height of the room (obtained by subtracting the roof displacement and floor displacement from the original room height) after five years is more than 3.5 m. Before deformations of this magnitude are reached, however, significant overlapping of the finite element mesh has occurred near the corners of the rooms thereby limiting the accuracy of the solution in this region. The other closure histories for various parameter variations are also shown in Figure 4. These will be discussed in detail in the next section.

Figure 4. Room Closure Sensitivity to Creep Law Variations

PARAMETER STUDY SIMULATIONS OF ROOM CLOSURE

It is important to designers to understand both qualitatively and quantitatively how system parameters within their control can affect the overall system response either individually or synergistically. Similarly, analysts supporting design efforts must know to what degree the variability of experimentally measured parameters influences their predictions. The emphasis of this paper is to demonstrate the manner in which variations in creep law coefficients, thermal properties, thermal loading, boundary conditions, meshing resolution, and temporal integration affect the predicted thermal and mechanical response of the room and pillar geometry previously discussed. Of particular interest to the design of a nuclear waste repository is the rate of closure of the storage room.

Coefficients in the creep constitutive model naturally have a crucial impact on the predicted rates of closure. It is, therefore, necessary to examine the thermomechanical response of a mine configuration for plausible variations in creep equation coefficients. These results are then useful not only to the designers but also in defining additional laboratory tests which can concentrate upon developing data to accurately define the most important parameters in a model. Similarly, guidance is provided to the one who fits the data to a selected model by indicating which parameters should receive the most attention and evaluation. For purposes of these discussions the term "creep rates" will be applied to the value of $\dot{\epsilon}_{II}$ which is predicted for a selected set of

constitutive model parameters (A, Q, n) and given values of deviatoric stress and temperature. The term "room closure rate" applies to the rate of convergence of the roof and floor in the finite element model of the mine opening.

The room and pillar deformations have been simulated for several combinations of coefficients for the Weertman secondary creep law (Table 2). Cases A and D exhibit the same degree of stress nonlinearity and thermal activation energy as the baseline case, but variations in the coefficient A give creep rates greater by a factor of 3 for Case A and lower by a factor of 1/10 for Case D for identical conditions of stress and temperature. Cases B and C exhibit a higher degree of nonlinearity ($n=5$) than does the baseline case while having the same thermal activation energy. Case B demonstrates the same creep rates as the baseline case for an effective deviatoric stress of 6.9 MPa (1000 psi), but gives higher creep rates for stress levels above 6.9 MPa (1000 psi). Case C provides creep rates identical to Case A for an effective deviatoric stress of 6.9 MPa (1000 psi) but again gives higher creep rates than Case A for higher stress levels. Case E represents a least squares fit by Parrish¹⁵ to steady-state creep data for annealed aggregates reported by Heard¹⁶. This equation has a higher thermal activation energy than the baseline case. At low temperatures, creep rates predicted using Case E are lower than the baseline case, but at elevated temperatures creep rates are higher. Case F was selected to have an activation energy of 12.9 kcal/mole and the same creep rate as the baseline case

at $\sigma'_{II} = 6.9$ MPa and $\theta = 403$ K. In Table 3 creep rates predicted by the baseline equation and Cases (A)-(F) are compared to experimental creep rates reported by Wawersik¹⁷.

Simulations of room closure for the various creep constitutive models included computing both the thermal and mechanical response for each case. The mechanical response varies for differences in the creep constitutive models giving rise to different room geometries (i.e., amounts of closure) as time proceeds. Variations in the temperatures at the floor, pillar midheight, and ceiling were only a few degrees due to differences in room geometry.

Significant differences in the room closure rates are evident in Figure 5 for variations in the creep law coefficients studied. These coefficients were selected in an attempt to develop reasonable bounds on possible behavior. As noted in Table 2, the creep rates predicted by the constitutive model listed as Case D are 10 times lower than for the baseline case for the same stress and temperature. The room closure rates do not, however, scale in that same manner. The closure rate obtained using Case A is only twice that obtained for the baseline case while Case D has about 18% of the baseline closure rate between 5 and 6 years after emplacement of the waste.

The degree of nonlinearity in stress is also an important consideration in modeling the response of an opening in salt. For the baseline case and Case B, the same creep rates are predicted by both equations for the conditions shown in Table 2. For deviatoric stresses above the 6.9 MPa (1000 psi) level, the Case B predicts higher creep rates than does the baseline equation. The amounts of room closure are significantly different for the room and pillar model (see Figure 6)

TABLE 3
COMPARISON OF CREEP LAW PREDICTED RATES
TO EXPERIMENTAL CREEP RATES

Test Conditions			Experimental Creep Rates	Predicted Creep Rates ($\times 10^{-8}/\text{sec}$)						
σ_{II}	P**	θ		Baseline Case	A	B	C	D	E	F
(MPa)	(MPa)	(°C)	($\times 10^{-8}/\text{sec}$)							
8.3	3.5	22	.014*	.0052	.0155	.010	.022	.0005	3.4×10^{-5}	.0016
15.2	3.5	22	.20*	.0318	.0954	.210	.463	.0032	9.2×10^{-4}	.0096
15.9	3.5	22	.033*	.0364	.109	.263	.580	.0036	1.2×10^{-3}	.011
22.8	3.5	22	1.93*	.1075	.322	1.594	3.52	.0108	8.5×10^{-3}	.033
33.1	3.5	22	31.20	.329	.985	10.3	22.7	.0329	.065	.099
7.9	20.7	22	.008*	.0045	.0134	.008	.018	.0004	2.6×10^{-5}	.0014
6.9	0.2	100	1.0	.119	.356	.161	.356	.0119	.053	.090
6.9	3.5	100	.25	.119	.356	.161	.356	.0119	.053	.090
7.2	3.5	100	.81	.135	.404	.200	.440	.0135	.067	.010
16.2	3.5	100	8.98	1.538	4.61	11.5	25.4	.1538	5.67	1.17
6.4	20.9	100	0.18	.0948	.284	.111	.244	.0095	.035	.072
15.9	20.7	100	3.61	1.454	4.36	10.5	23.12	.1454	5.12	1.11
6.9	3.7	200	14.6	2.264	6.78	3.08	6.78	.2264	43.1	3.60
6.9	20.8	200	19.7*	2.264	6.78	3.08	6.78	.2264	43.1	3.60

+ From W. Wawersik¹⁶

* Upper bound values

** Continuing Pressure

Figure 5. Creep Rate Effects on Room Closure

Figure 6. Effect of Stress Nonlinearity on Room Closure

where the increase in the degree of stress nonlinearity results in more rapid closure. A similar trend is also noted in Figure 6 for the results obtained with Cases A and C. For the baseline case the pressure and deviatoric stress distributions within the pillar are plotted in Figure 7 for the initial time ($t = 0$) and for a time of 3 years after the waste is emplaced. The deviatoric stress in this region varies from about 8-12 MPa (1100-1700 psi) while the pressure component increases substantially with depth into the pillar. Hence the deviatoric stress in the pillar is higher than the values shown in Table 2. The position of the points is different after 3 years from the position of the same material points at the beginning of the simulation due to the compression of the pillar that causes lateral expansion.

Activation energy effects on the room closure rates may be observed in Figure 8. As the activation energy increases (from the baseline, to Case F, to Heard's data represented as Case E), the closure of the room decreases significantly. Between Case F and the baseline case there is less than a 25% change in the activation energy and yet the closure of the room is significantly effected. This indicates that in obtaining an improved constitutive model for salt, it is important to establish firmly the value of the activation energy for the material within the region of stress and temperature space under consideration.

The closure rate predicted using a secondary creep law based on Heard's data (Case E) is relatively slow (Figure 8) in comparison with the baseline case. For times less than about 5 years after emplacement, very little salt has experienced significant temperature rise. However, the closure rate begins to accelerate after seven years due to larger amounts of salt reaching elevated temperatures.

Figure 7. Stress Variation at Pillar Midheight

Figure 3. Activation Energy Effect on Room Closure

To aid the reader in simultaneously viewing the effects of the previously described parameter variations, the results are superimposed onto a single plot presented as Figure 4.

The effect of higher thermal conductivity of the salt has also been examined. A simulation was performed in which the baseline conductivity (5 W/mK at 300 K to 3 W/mK at 500 K) was changed to vary from 8 W/mK at 300 K to 5 W/mK at 500 K. Although the temperature distributions were modified, the overall closure rates were not influenced to a significant degree. After six years, the room height was less than 5% larger than the room height at the end of 6 years predicted using baseline parameters.

The magnitude of the heat load is initially 18.5 W/m^2 (75 kW/acre) in the baseline case. The effect of storing wastes generating 30 kW/acre (initially) with a half life (for the first ten years following emplacement) of ten years has been simulated. The thermal response of the 30 kW/acre heat load is compared to the baseline case (75 kW/acre) in Figure 9. The temperature rise at the floor centerline is approximately 16 K after 4.4 years compared with 40 K for the baseline case. The lower salt temperature results in slower deformations and, thus, slower room closure rates. After four years, the room having 30 kW/acre heating rate has a height in excess of 3.9 m; whereas, the room subjected to 75 kW/acre thermal load is less than 3.5 m in height (see Figure 10).

Deformations predicted using the baseline creep equation are shown in Figure 11 for a period exceeding 25 years for ambient temperature conditions. The predicted room closure is in excess of 2 m during this period. The response predicted using Case D is also shown on this figure. It demonstrates relatively little deformation for the 30 year

Figure 9. Temperature Profiles for Two Heat Loads

Figure 10. Room Closure for Baseline and 30 kW/Acre Simulations

period analyzed. However, the creep rates predicted by Case D are less than measured values reported as upper bounds by Wawersik for the same conditions of stress and temperature (Table 3). The last curve appearing on Figure 11 was obtained by simulating the isothermal closure using Case F. The higher activation energy in Case F in comparison to the baseline equations results in much lower closure rates at 313 K. For the baseline case the ambient temperature room closure rates are higher than would be anticipated in a mine at this depth. An explanation of part of the reason for this lies in the assumption of an ambient temperature of 313 K. Measurements made in salt at 825 m depth, subsequent to these calculations, indicate that the ambient temperature should be about 300 K. For the baseline case, reducing the ambient temperature from 313 K to 300 K would reduce the creep rates by a factor of 2.

Mesh resolution and region size were varied as part of the parameter study. The mesh designated for thermal analyses (see Figure 2) was used for both the thermal and creep analyses. This moved both the upper and lower boundaries an additional 50 m from the room in the creep analyses. For the baseline parameters, the room height was less than 1% different than the height predicted using the two meshes depicted in Figure 2. Similarly, analyses performed using a much more coarse mesh (144 elements instead of 288 elements for the viscous analyses) resulted in less than 2% difference from the baseline case after approximately 5.9 years.

The effects of the detailed shape of the room on the predicted closure rate were evaluated. In Figure 12 the mesh for the baseline case is shown with square corners along with a mesh in which the

Figure 11. Room Closure for Ambient Temperature Condition

Figure 12. Meshes for Room Geometry Effects Evaluation

boundaries of the room are curved. The results presented in Figure 13 show that while the use of the curved boundaries does decrease the room closure rates, the amount of this decrease is small compared to the changes induced by variations in the material model.

The magnitude of the time step used to advance the solution ahead in time was also studied. Values of 0.5 year, 0.10 year, and 0.01 year used in the ambient temperature analyses with baseline creep constitutive equation produced only small variations in predicted closure rates. Similarly, for the heated case the use of a 0.10 year time step has a small effect on the room closure rate (see Figure 13) when compared with the computations for the baseline case made using a 0.5 year time increment.

Figure 13. Room Geometry and Time Step Effects

CONCLUSIONS

The simulations of mine room and pillar configurations demonstrate a strong sensitivity to variations in parameters appearing in the secondary creep equation. Several of the creep equations considered predict realistic creep rates in comparison to measured laboratory data but when used in pillar simulations gave large differences in room closure rates. Only minor changes in room closure rates were noted for mesh changes, time step variations, and for changes in the conductivity of the salt. Current efforts are being directed toward improving the constitutive model used to represent the behavior of the salt. Careful consideration is being given to assessing the activation energy and stress nonlinearity of salt over the range of temperatures and stresses of interest in radioactive waste disposal as well as to incorporating all regimes of creep behavior.

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