27-80
9-22-80
240-19

SAND80-0467

UNLIMITED RELEASE

NUMERICAL SIMULATION OF CREEP CLOSURE OF
DEEP POTASH MINES (WITH APPLICATION TO
WASTE ISOLATION)

MASTER

D. E. MUNSON, P. R. DAWSON

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

JULY 1980

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

Sandia Laboratories
energy report

DISCLAIMER

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

DISCLAIMER

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

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

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

Printed in the United States of America

Available from

National Technical Information Service

U. S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$4.00; Microfiche \$3.00

SAND80-0467
Unlimited Release

Numerical Simulation of Creep Closure
of Deep Potash Mines
(with Application to Waste Isolation)

by

D. E. Munson
Geotechnical Research Divison 4732
Sandia Laboratories, Albuquerque, NM 87185

and

P. R. Dawson
Department of Mechanical and Aerospace Engineering
Cornell University, Ithaca, NY 14853

ABSTRACT

In this work, numerical simulation of the mechanical response of a deep mine opening in potash is shown to match measured room closures to within a factor of two. In this case, the calculated closure rates after eight years are within 25 to 75 percent of those measured. In making the calculations, a constitutive model for creep, as determined from laboratory triaxial tests of salt and short cylinder compressive tests of potash, was incorporated into a coupled thermal-mechanical fluid flow code, COUPLEFLO. The model is a multimechanism formulation of thermally-activated processes acting in parallel. Because the field tests were well-documented, two-dimensional configurations and because the constitutive model was uniquely determined by laboratory data, the agreement between calculations and field data for these significant time durations is a first step in verification of the simulation technique.

Application of the model and numerical methods presented here can be used to understand deformation in deep potash mines and, very importantly, to aid also in design of the waste isolation and petroleum storage facilities.

DISCLAIMER

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1

INTRODUCTION

Recent proposals to isolate radioactive waste in salt formations and to store strategic petroleum reserves in salt cavities, as well as many other potential storage uses, is adding impetus to establishing reliable numerical techniques and material constitutive models for making design calculations of underground opening stability. The constitutive modeling problem is complicated because salt undergoes a pronounced time-dependent deformation, even at room temperature. This behavior is markedly accelerated at the elevated temperatures. Some nuclear waste repositories, in fact, could possibly involve thermal inputs of appreciable magnitude, with salt temperatures up to 200°C.

Methods for evaluating stability of openings in deep salt and potash mines and in solution mined cavities have been of practical concern for many years. As an example, economic extraction of potash from the deep Saskatchewan evaporite beds was made possible through the improved mining practice developed with the aid of relevant theoretical and underground rock mechanics studies.¹⁻⁴ This concern has produced a relatively large body of literature on the mechanical response of salt, much of which is rather simple, practical evaluations of deep openings. Also, among these studies are sophisticated numerical analyses using rather elaborate material models. The work presented here addresses further the constitutive modeling of salt and simulation of field experience through numerical methods.

In previous reports,^{5,6} we have established a theoretical framework for the time-dependent deformation (creep) of salt, as well as a constitutive equation based on empirical data for the range of stresses and temperatures germane to the problem. What remains to be done is the verification of the numerical and constitutive models through simulation of underground experiments. The numerical analysis was accomplished through the code, COUPLEFLO,⁷⁻⁹ a finite element method for computing creeping viscous flow.

BACKGROUND

The necessary elements for the analysis of ground movements around underground openings are the relevant geometric and physical simulation, an appropriate constitutive model, and the proper material parameter values. Increasingly over the last decade, the agent for combining these elements to obtain an analysis has been numerical solution methods. In a relative sense, numerous testing programs have established the mechanical properties of salt, and potash minerals, over a wide range of stress and temperature. The area of major concern is, however, the

proper choice of a constitutive model. Basically, two types of models have been advanced, "plasticity" models and creep models, of either the decelerating or steady-state forms.

The plasticity models for geomaterials are perhaps best exemplified by those of Serata^{10,11} even though others have also been proposed.^{12,13} At the current stage of development, the Serata model incorporates elasticity, viscoelasticity, viscoplasticity and permanent volume deformation, and a failure envelope in principal stress space.¹¹ The three-dimensional formulation is in terms of octahedral shear stresses and strains. Laboratory evaluation of numerous parameters of the model has been done for salt by means of rather complicated multiaxial test methods.^{10,14} Although details are lacking, finite element calculations using this model have been made which agree substantially with field observations of the stress and strain around a deep potash mine opening as a function of time.² With the same model, Winkel *et al.*¹⁵ obtained calculational agreement with the closure of boreholes in potash mine pillars, but only after significant arbitrary modification of the material parameters.

A creep model or law of the decelerating type developed by Starfield and McClain¹⁶ is based on empirical fits to a strain-time deformation curve. The form of the law taken was the product of the separate variables of temperature, time, and stress all raised to some power. Material parameters were evaluated from the laboratory model pillar creep test results of Lomenick,¹⁷ even though separation of geometric and material effects in the model pillar experiments is difficult. With this model and the Lomenick parameters, Waki *et al.*¹⁸ used an explicit finite difference method to calculate the room surface displacements for a two-dimensional abstraction of the three-dimensional underground experiment of the Project Salt Vault.¹⁹ In this experiment, four dead-end rooms were cut in an inactive salt mine, and the instrumented rooms and pillars were heated either by electric heaters or radioactive waste for some period of time. The final displacements calculated for floor and wall locations were within a factor of two of those measured. Ratigan and Callahan²⁰ used a thermo/viscoelastic model for two-dimensional simulation of these same rooms with similar results.

The constitutive equation used in our work to simulate the creep of salt, and salt-like minerals, is based upon steady-state creep concepts. While the model is essentially empirical, it is extracted from a fundamental micromechanical framework. Initially, Munson⁵ used experimental creep data to construct a deformation-mechanism map of those thermally-activated processes acting in parallel which control the

steady-state creep of salt. The map indicates the existence of three mechanisms which govern the creep response in the range of stresses and temperatures relevant to mining, waste repository and petroleum storage operations (See Figure 1).

The deformation-mechanism map is constructed by considering the additive creep rate contributions of relevant thermally activated and thermally aided flow mechanisms. Because the contribution of a given mechanism normally dominates the creep process over certain ranges of the principal variables of stress and temperatures, the map consists of several regimes where the dominant mechanism in each regime is noted. Regime boundaries are the loci of equal strain rate contribution of two mechanisms. Customarily, the map is given in terms of a nondimensionalized stress (deviatoric stress over the shear modulus) and the homologous temperature (temperature over the melt temperature). As is done in Figure 1, the range of stress and temperature of a proposed facility, in this case a probable repository, can be placed on the mechanism map. Thus, the creep mechanisms relevant to the deformation of that facility are defined. An appropriate constitutive model must be couched in terms of the relevant mechanisms.

Using the triaxial creep data of Heard,²¹ Hansen and Mellegard,²² and Waversik and Hannum,²³ Munson and Dawson⁶ then evaluated the material parameters of the multi-mechanism model in the low stress and temperature range relevant to proposed storage facilities. The model which is based on steady-state creep also incorporates terms to account for primary creep. This physically well-motivated model was the basis for the numerical calculations of the stability of underground openings in potash reported here.

A more complete review and analysis of available constitutive models of salt deformation has been given by Dawson.²⁴ The brief discussion here is intended to characterize the distinguishing features of major constitutive modeling approaches.

CONSTITUTIVE EQUATION

A typical creep curve consists of 1) a transient (primary) creep stage of decreasing creep rate, followed by 2) a steady-state (secondary) creep stage of essentially a constant creep rate, and terminated by 3) a failure process which causes an accelerated (tertiary) creep stage and rupture. It is with the first two stages that the model development of Munson and Dawson⁶ deals. The creep curve can be decomposed into contributions from the transient and steady-state components. This decomposition is a matter of convenience and does not imply different controlling mechanisms for transient and steady-state creep. In generating the function

Figure 1. Deformation-mechanism Map for the Steady-State Creep of Salt.

which describes the creep response, steady-state creep behavior forms the foundation of the model. Then, transient response is incorporated as a modification of the steady-state behavior.

For the nuclear waste repository application, three regimes of behavior outlined by the deformation-mechanism map⁵ are involved: dislocation glide, dislocation climb by pipe diffusion, and an undefined mechanism (see Figure 1 for regimes). Since mining and petroleum storage applications are at room temperature, only the first and last of these three regimes are normally of concern. Although one of the regimes is controlled by an undefined mechanism, the recent experimental data by Waversik and Hannum²³ permit development of an empirical equation for this regime.

Steady-state creep response is modeled using multiple mechanisms through

$$\dot{\epsilon}_{II}^s = \sum_{i=1}^3 \dot{\epsilon}_{II_i}^s \left(S, \theta, \frac{\sigma_{II}'}{\mu} \right) \quad (1)$$

where $\sum$ denotes summation over i values of the effective steady-state deviatoric strain rates for each mechanism $\dot{\epsilon}_{II_i}^s$, $\frac{\sigma_{II}'}{\mu}$ is nondimensionalized stress (effective deviatoric stress divided by the shear modulus), θ is the temperature, and S the structure factor. Here, the deviatoric stress and strain rate are given by

$$\sigma_{II}' = \sqrt{\frac{3}{2} \sigma_{ij}' \sigma_{ij}'} \quad \text{and} \quad \dot{\epsilon}_{II} = \sqrt{\frac{2}{3} \dot{\epsilon}_{ij} \dot{\epsilon}_{ij}}; \quad \text{respectively.}$$

Theoretical and experimental knowledge of creep response peculiar to each regime permits writing of explicit equations. The low stress regimes are thermally activated with power law stress dependencies, and the high stress regime has an exponential stress dependence. Thus, the individual steady-state creep rates are

$$\dot{\epsilon}_{II}^s = A_1 e^{-Q_1/R\theta} \left(\frac{\sigma_{II}'}{\mu} \right)^{n_1}, \quad \text{for dislocation climb,} \quad (2a)$$

$$\dot{\epsilon}_{II}^s = A_2 e^{-Q_2/R\theta} \left(\frac{\sigma_{II}'}{\mu} \right)^{n_2}, \quad \text{for the undefined mechanism,} \quad (2b)$$

and

$$\dot{\epsilon}_{II_3}^s = 2 B_1 e^{-Q_1/R\theta} + B_2 e^{-Q_2/R\theta} \sinh \left[q \left(\frac{\sigma_{II}'}{\mu} - \sigma_0 \right) \right], \quad (2c)$$

$\sigma_{II}' > \sigma_0$ and inactive for $\sigma_{II}' < \sigma_0$, for glide,

where the A 's and B 's are structure factors, Q 's are activation energies, n 's are stress exponents, q an activation volume, σ_0 a cut-off stress and R the gas constant.

In treating the transient or primary creep response, it was assumed that the mechanism controlling transient creep has the same activation energy as that of steady-state creep. Transient deviatoric strain is assumed to exhaust itself at a transient strain limit, ϵ_t^* , which is a function of mechanism and stress. The increased strain rate due to the transient strain also exhausts itself; i.e., the total strain rate becomes equal to the steady-state rate at ϵ_t^* .

All of these contributions have been folded into the constitutive equation through a transient strain rate parameter, F , which modifies the steady-state creep rate. The total strain rate is therefore given by

$$\dot{\epsilon}_{II}^T = F \dot{\epsilon}_{II}^S . \quad (3)$$

The form chosen for F is as follows:

$$F = \begin{cases} \Delta \left(1 - \frac{\epsilon_{II}^P}{\epsilon_t^*} \right) & , \epsilon_{II}^P \leq \epsilon_t^* \\ 1 & , \epsilon_{II}^P > \epsilon_t^* \end{cases} \quad (4)$$

where $\Delta = \Delta(\sigma)$ is the transient strain rate change, ϵ_{II}^P is the effective transient strain accumulated regardless of strain path and ϵ_t^* is the transient strain limit. A necessary restriction of the transient strain requires it to accumulate regardless of the sense of the strain or the stress history. This restriction causes no problems for the monotonically increasing, deviatoric stress loading considered here.

Transient strain limits for each regime are assumed to be functions of stress alone, as given by

$$\epsilon_t^* = K \left(\frac{\sigma_{II}}{\mu} \right)^m \quad (5)$$

where K and m are empirical constants. While the basis of this functional form is empirical, there is considerable evidence that the equilibrium substructure developed in the dislocation climb dominated regime depends only upon the applied deviatoric stress. Transitions in response occur at regime boundaries; these manifest themselves in what appears to be a temperature dependent K .

NUMERICAL CALCULATIONS

Mathematically, the creep constitutive model given above resembles those used to describe temperature-dependent, non-Newtonian fluids. By assuming that elastic strain increments are small in relation to the inelastic creep strain increments and that inertia effects are negligible, a creeping, incompressible, fluid flow formulation can be applied to the analyses of salt deformation in the manner described by Munson and Dawson.⁶ Thus, Lamb's functional describes such a system in terms of the rate of virtual work as

$$J = \int_V \frac{1}{2} \sigma'_{ij} d_{ij} dv - \int_V X_i u_i dv - \int_S T_i u_i dS \quad (6)$$

where σ'_{ij} is the deviatoric Cauchy stress, d_{ij} is the deformation rate, X_i is the body force vector, T_i is the surface traction vector, u_i is a velocity vector, V is the volume, and S is the surface area. The deformation rate and velocity are related through the kinematic equation

$$d_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \quad (7)$$

The additional constraint of material incompressibility is enforced by appending it as an auxiliary condition to the variational statement in which the Lagrange multiplier has the physical interpretation of pressure. Equation 6 then becomes

$$J = \int_V \sigma'_{ij} d_{ij} dv - \int_V p d_{ii} dv - \int_V X_i u_i dv - \int_S T_i u_i dS \quad (8)$$

where p is the Lagrange multiplier. A stationary value of the functional is found by equating variations with respect to the velocity and pressure to zero.

The Euler's equations resulting from Lamb's variational statement are

$$\sigma_{ij,j} + X_i = 0, \text{ for equilibrium,} \quad (9)$$

$$d_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}), \text{ for deformation-rate velocity,} \quad (10)$$

and

$$d_{ii} = 0, \text{ for incompressibility.} \quad (11)$$

Also required are the boundary conditions

$$u_i = \bar{u}_i \text{ on } S_u \quad (12)$$

$$\sigma_{ij} n_j = \bar{T}_i \text{ on } S_\sigma \quad (13)$$

where u_i is the imposed velocity over the surface S_u , and T_i is the applied traction vector on S_σ and v_j is the unit normal to the surface S_σ .

The final information required for solving problems involving the creep deformation of salt is the constitutive model that mathematically describes the behavior of rock salt. This relationship is presented in previous sections of this paper as a function relating the effective deviatoric strain-rate to the applied effective deviatoric stresses, temperature, and strain. It is important to point out that the strain-rate measure used to report the data and to fit parameters in the creep model is a small strain-rate measure depending linearly on the deformation gradient. The deformation rate, d , used in Lamb's formulation differs from this small strain-rate measure by a factor involving the deformation gradient. Corrections made to account for this difference produced only minor changes in the parameters of the creep model.⁶ Generally, these changes were less than the uncertainty involved with selecting the parameters regardless of the strain-rate measure used.

A flow rule defines the components of strain-rate for a specific deviatoric stress tensor. It was assumed that components of strain-rate are proportional to the deviatoric stress such that

$$d_{ij} = \beta (\sigma'_{ij} / \sigma'_{II}) \quad (14)$$

where

$$\beta = \frac{3}{2} (d^T_{II}) . \quad (15)$$

The incremental solution procedure (COUPLEFLO) uses a quasi-Lagrangian reference frame in following the material deformations.⁷ At each step in time the velocity field is determined from the field equations. An Euler method is used to integrate the geometry (based on the velocity field) and the strains (based on the deformation rates) ahead in time. Conditions of stress, strain, and temperature at the end of one time increment are used as the initial conditions for the following increment.

Field Experiments

There are certain features that are optimal for the selection of a field experiment. These are 1) well-controlled two-dimensional geometry, 2) well-characterized geologic setting, 3) established material properties, and 4) significant time intervals and displacement magnitudes. The first of these features is of major importance because accurate numerical simulation of the two-dimensional geometry is feasible, with a clean separation between constitutive and geometric effects. While abstractions of a complicated three-dimensional geometry can be made, as was done for Salt Vault;

it is not always certain that a separation between constitutive and geometric effects is accomplished. Typically, however, discrepancies in the calculational results, in many of these cases, is assigned, properly or not, to failure of the constitutive model rather than the abstraction. Pragmatically, because of the difficulty and cost of underground testing, one compromises to the best available data. Although quite a large number of field experiments have been performed in salt, most are for short durations, often under three-dimensional conditions, with marginally small displacements. The best field experiments for matching these requirements were found to have been made in the deep potash mines of Saskatchewan.^{3,4,26}

In the deep potash mines, Mraz³ reports measurements of room closure, as well as displacements of the "ground" (material adjacent to the opening) taken over a period of eight years for a long, isolated room (virgin ground opening). The room is cut in the shaft pillar of the International Minerals and Chemical Corporation's Esterhazy Mine in Saskatchewan at a depth of about 958 m. A simplified geologic cross-section for the mine location is given in Table I. The opening, which is in the ore zone, is overlain by 30.5 m of competent evaporite deposits consisting of halite with potash zones and distributed clay stringers.* The ore zone, which is distinguished only by grade and lack of clay content, is composed of halite, sylvite and some carnallite with some disseminated clay (<2%). Underlying the ore zone is nearly 92 m of competent rock salt with anhydrite bands, some of which are quite thick. On the basis of a more detailed geologic section of the

Table I - Geologic Section at Esterhazy (After Mraz³)

Depth (m)	Strata	Remarks
91.4	Glacial Till	Incompetent
377.9	Shale (Montana and Colorado Groups)	Incompetent in zones
438.9	Sandstone and Shale (Blairmore Formation)	Incompetent
757.4	Limestone, Dolomite, Anhydrite and Shale	Competent to very weak
865.3	Limestone and Anhydrite	Competent
915.9	Limestone and Dolomite	Competent
925.1	Shale	Competent
955.5	Halite w/Potash Zones (Prairie Evaporites)	Competent
958.0	Potash Ore Zone (Room location)	Competent
1046.0	Halite w/Anhydrite Bands (Prairie Evaporites)	Competent

*In some mines the clay stringers are in the immediate roof; however, this is not the situation in the Esterhazy Mine where the immediate roof is relatively free of clay.²⁷

Prairie Evaporites,⁴ one concludes that the major constituent above and below the opening is halite.

The opening was mined in two passes of a continuous boring machine. As-mined cross-section of the opening is shown in Figure 2. The initial opening was nominally 6.02 m wide by 2.33 m high. Instrumentation³ consisted of arrays of bolts anchored at various depths up to 6.10 m in the ground around the opening, in the horizontal direction at pillar (rib) mid-height and the vertical direction at roof mid-span. Ground displacements were measured periodically between symmetrical bolt arrays in the horizontal direction and between the roof bolt array and a floor surface plate in the vertical direction. Measurements were continued for eight years, except for the vertical surface displacements which were precluded by slabbing of the immediate roof shortly after mining. The slab was about 0.5 m at the thickest dimension.

In this same opening, pressure measurements were obtained using hydraulic pressure cells emplaced horizontally at various depths into the pillar. The measurements were obtained eight years after the excavation.

Material Properties

A complete constitutive model for potash is not available. As can be appreciated from just the low temperature region of salt creep shown in Figure 3, quite a few data are required to define the stress and temperature dependence of steady-state creep. We are fortunate, however, to have the time-dependent deformation of short cylindrical (disks) specimens of Saskatchewan potash from the work of King.²⁸ These data when corrected to crudely approximate the conditions of a uniaxial, uniform stress test can be related to the creep response of salt. Some reasonable assumptions then permit the use of a form of the constitutive equation determined for salt creep.

King tested unconfined short cylinders of potash with diameters of 165.1 mm and heights of 20.6 mm ($d/h = 8.0$) at 27 and 43°C for 1500 hours under various constant loads. The potash samples were of fine grained material. In order to minimize the end constraint, greased polythene sheets were placed between the specimen ends and the press platens. Deformation was monitored between platens by two linear potentiometers. King states that the 27°C test temperature is equivalent to a mine depth of 1036 m, only slightly deeper than the mine we are considering.

Analysis of constant load, short cylinder tests to obtain the deviatoric stress component that drives the creep process is difficult. The short cylinder

Figure 2. Cross-section of Virgin Room and Instrumentation at the Esterhazy Mine.

Figure 3. Experimental Stress Dependence of Creep of New Mexico Salt.

has a stress field which contains a spherical component that varies as a function of both the radial and axial position;²⁹ as a result, no unique value of deviatoric stress can be found. Proper analysis to obtain a constitutive response from such a test requires an iterative numerical analysis procedure. However, with this understanding of the nature of the stress field, we can make a crude correction to the data of King²⁸ to give an effective deviatoric stress by using the empirical results of Obert.³⁰ Obert tested salt for various d/h ratios for specimens with lubricated ends. Comparison of compressive strengths, as extrapolated from these tests, suggest that the apparent strength at $d/h = 8.0$ is about 1.35 times the strength at $d/h = 0.5$. In some way, this strength ratio describes the relative amounts of deviatoric and spherical stress components in the two stress fields.* Since $d/h = 0.5$ describes normal laboratory test specimens used to assure a nearly uniform deviatoric stress field,³¹ the stresses reported by King²⁸ can be reduced by this amount, 1.35, to give an effective deviatoric stress. A correction based upon the compressive strengths is expected to give an upper bound to the correction since the ratio of the relaxed strengths, actually the relaxed stress fields, of the creep tests would be undoubtedly less. This correction amounts to an offset toward lower stresses.

The constant load tests must also be corrected to constant stress by calculating the effect of strain on the cross-sectional area of the specimen. This correction is applied at the final strain. This also causes an offset to lower stresses.

The data over the time interval from 1000 to 1500 hours were assumed to be representative of actual steady state creep rates. These rates are plotted against both uncorrected and corrected stress in Figure 4. Here it was assumed that potash has the same shear modulus, μ , as salt, or 9.62 GPa. Also shown in Figure 4 is the best fit line to the creep of upper level New Mexico salt at 23°C. The potash data and corrections are given also in Table II.

As is apparent in Figure 4, the corrected potash creep results at 27°C fall essentially on the salt data at 23°C. The 43°C potash data, although less well behaved, fall correctly above the 27°C data as they should. The 43°C tests are somewhat suspect, especially the test at 41.4 MPa, because the very large final strains suggest that these specimens may be in some stage of failure.

Despite the limited amount of data and the rather severe assumptions required for the analysis of these data, we can conclude that the creep of potash at 27°C, for a limited stress range, appears to be equivalent to that of salt. If it is

*One would prefer to have the effective stress field in the relaxed state of the creep tests; however, such information is not available.

Figure 4. Creep of Saskatchewan Potash as Obtained from Model Pillar Tests.

further assumed that potash creep has the same stress dependence as salt, then the following values for the upper level salt of Southeastern New Mexico⁶ are appropriate for use in Equations 2-5 to describe the creep of Saskatchewan potash:

$$\begin{aligned}
 A_1 &= 2.88 \times 10^{21}/s & A_2 &= 1.58 \times 10^{12}/s \\
 Q_1 &= 0.105 \text{ MJ/mol (25 kcal/mol)} & Q_2 &= 0.042 \text{ MJ/mol (10 kcal/mol)} \\
 n_1 &= 5.5 & n_2 &= 5.0 \\
 B_1 &= 3.53 \times 10^6/s & B_2 &= 3.57 \times 10^{-2}/s \\
 q &= 4.39 \times 10^3 \\
 \mu &= 9.26 \text{ GPa} \\
 \sigma' &= 0.0207 \text{ GPa} \\
 \Delta &= 1.0 \\
 m &= 3.0 \\
 K &= \begin{aligned} &8.88 \times 10^5 \text{ (23 to 100°C)} \\ &2.29 \times 10^7 \text{ (200°C)} \end{aligned}
 \end{aligned}$$

Values of K are interpolated between 100 and 200°C.

Table II - Potash Deformation Data of King²⁸

Specimen	Temperature (°C)	Stress (MPa)		Engineering Strain Final	Strain rate (x10 ³ /s) Final
		Reported	Corrected		
I Ib-1	27	48.1	27.8	0.22	7.71
2	27	41.4	26.4	0.14	5.74
3	27	34.5	23.0	0.10	4.88
4	43	41.4	14.4	0.53*	1.43
5	43	34.5	15.8	0.38	7.05

*At this strain, this test had probably already failed, and the results may be questionable.

Calculational Results

In the calculations, the actual cross-section shape of the opening was simplified and a region around the opening was meshed. The meshes and boundary conditions for the isolated opening or room in virgin ground are shown in Figure 5. The position of the boundaries of the calculational meshes were chosen after several calculations to demonstrate that the boundaries did not affect the solution. Massive stratigraphic layers other than salt or related minerals occur only at distances several (~10) radii from the room.

In Figure 6, the ground motion measurements (displacement of material around the opening) and calculations for the isolated opening are compared. We should note

Figure 5. Finite Element Meshes for Calculation of Virgin Room and Closure.

Figure 6. Comparison of Calculated and Field Results for Virgin Room Closure.

Data of Mraz³

that the vertical surface closure measurement was not included because of the immediate roof spall. While there are differences, both the closure magnitudes and rates are basically in agreement. In general, the calculations underpredict the closure magnitudes at early times and overpredict the closure magnitudes at late times. However, the discrepancies are less than a factor of two. Perhaps of more significance, the closure rates at eight years are predicted to within 25% in the vertical direction and to within 75% in the horizontal direction. In all cases, the calculations overpredict the measured closure rates. Perhaps the most important observation that can be made is that the predicted and measured final closure rates are within the scatter found in well-controlled laboratory creep tests.

In Figure 7, the calculated effective deviatoric stress, σ'_{II} , and mean pressure after eight years of creep are shown for the horizontal section at pillar midheight. As would be expected, the pressure increases into the wall, and the deviatoric stress decreases into the wall. The limit of the pressure is the lithostatic pressure; while the limit of the deviatoric stress is zero. The mean pressure is not zero at the wall since the stress components in the plane of the wall are non-zero even though the stress component normal to the wall is zero. The field measurements of pressure show the same trend as the calculations; however, the pressure magnitudes measured in the immediate wall are much less than the calculated values. Since the measured and calculated pressures agree at depth, we suspect that the discrepancy is caused by problems in making the field measurements or in establishing the correct gauge condition in the immediate wall.

The pressure at 27.2 m horizontally into the wall is calculated to be about 24.8 MPa, the effective deviatoric stress at the same location is less than 2.5 MPa. Since this distance is essentially the horizontal extent of the meshed problem, the small value of deviatoric stress indicates the horizontal dimension was perhaps adequate. The pressure at this location should be nearly the lithostatic pressure. At 24.8 MPa, the lithostatic pressure of the calculations corresponds to a mine depth slightly greater than the 958 m of the actual mine, assuming the typical pressure gradient of 0.0226 MPa/m. This occurred because the average overburden density of 2.454 Mg/m³ as used to calculate the overburden pressure was somewhat too large; had the correct overburden pressure been used, the calculated and observed rates would be in better agreement.

Except for the immediate wall region, the deviatoric stress magnitude is not large; but it does involve an appreciable volume of material. This is evident from

Figure 7. Comparison of Calculated Stress and Pressure Magnitudes with Measured Pressures after Eight Years.

Data of Mraz³

a comparison to the elastic solution for an elliptical opening where the deviatoric stress has virtually vanished at three semi-major axis dimensions into the wall.³¹ It must be realized, however, that the 2.5 MPa deviatoric stress level at 27.2 m into the wall generates uniaxial creep rates of less than 10^{-13} /s ($\log \sigma'_{II}/\mu = -3.59$), according to our constitutive model.

CONCLUSIONS

In the simulation of closure of a cavity in virgin ground, the numerical calculations have produced detailed salt (ground) motion and room closure results that agree with extended time, two-dimensional field measurements. Agreement is within the experimental uncertainty of the laboratory and field data, i.e., the calculated and measured rates are within a factor of two. The success of these calculations for a single, but significant field case, is encouraging because the constitutive equations were determined entirely from laboratory creep tests and used without modification for the calculations. Thus, the calculations close the loop between laboratory and field data.

Since the geometrical aspects of the two-dimensional field case considered is decoupled from the constitutive response of the material, these calculations serve as an important first step in verification of the constitutive model used to represent the potash and salt. Adequate verification of the constitutive model to support its general use will, of course, require further detailed comparisons with field data. While a need for much more of the type of analysis performed in this work is apparent, detailed field studies suitable for analysis are rare. This suggests the need for coordinated numerical analysis and field measurement programs.

ACKNOWLEDGEMENTS

The authors express their appreciation for the continued support of T. O. Hunter in this work. We are especially grateful to P. F. Chavez for his aid in completing the numerical calculations and to W. R. Wawersik for helpful discussions of the deeper meaning of creep in salt. J. Tillerson initially called our attention to the Esterhazy data. We are also grateful to G. Lacroix and E. Seidler of the Esterhazy Mine staff for discussions of the field conditions and measurements.

REFERENCES

1. C. A. Baar, Applied Salt Rock Mechanics I, (Elsevier Scientific Publishing Co., New York, 1977).
2. S. Serata, "Stress Control Technology - An Alternative to Roof Bolting," Mining Eng., 42, 53, (May, 1976).
3. D. Mraz, "Theoretical Predictions Confirmed by In Situ Rock Behavior in Deep Potash Mine," Proc. 19th U. S. Rock Mechanics Symposium, compiled by Y. S. Kim (University of Nevada, Reno, NV, 1978), p. 468.
4. G. B. Lopez, "The Rock Mechanics Program at the Rocanville Division of P. C. S.," Proc. Ann. Western Can. Inst. Mines Meeting, Saskatoon, Saskatchewan, Nov. 1977 (private communication - Rocanville Division of P. C. S., Rocanville, Saskatchewan).
5. D. E. Munson, "Preliminary Deformation-Mechanism Map for Salt (with Application to WIP)," SAND79-0076, Sandia Laboratories, Albuquerque, NM (1979).
6. D. E. Munson and P. R. Dawson, "Constitutive Model for the Low Temperature Creep of Salt (with Application to WIPP)," SAND79-1853, Sandia Laboratories, Albuquerque, NM (1979).
7. P. R. Dawson and P. F. Chavez, "COUPLEFLO - A Computer Code for Coupled Creeping Viscous Flow and Conductive-Convective Heat Transfer, Part I. Theoretical Background," SAND78-1406, Sandia Laboratories, Albuquerque, NM (1978).
8. S. Sato and E. G. Thompson, "Finite Element Models for Creeping Convection," J. Comp. Phys., 22, (1976).
9. E. G. Thompson, "Average and Complete Incompressibility in the Finite Element Method," Int. J. Num. Meth. Eng., 9, 925, (1975).
10. S. Serata, "Application of Continuum Mechanics to Design of Deep Potash Mines in Canada," Int. J. Rock Mech. Min. Sci., 5, 293 (1968).
11. S. Serata, "Instrumentation for Stress Control Design of Deep Mine Entries," Proc. 19th U. S. Rock Mechanics Symposium, compiled by Y. S. Kim (University of Nevada, Reno, NV, 1978), p. 495.
12. S. Krenk, "Internally Pressurized Spherical and Cylindrical Cavities in Rock Salt," Int. J. Rock Mech. Min. Sci., 5, 219 (1978).
13. A. F. Fossum, "Visco-plastic Behavior during the Excavation Phase of a Salt Cavity," Int. J. Num. Anal. Meth. Geomech., 1, 45 (1977).
14. S. Serata, "Prerequisites for Application of Finite Element Method to Solution Cavities and Conventional Mines," Third Symposium on Salt, Vol. 2 eds. J. L. Rau and L. F. Dellwig, (Northern Ohio Geological Society, Inc., Cleveland, OH, 1969), p. 249.
15. B. V. Winkel, K. H. Gerstle, and H. Y. Ko, "Analysis of Time-dependent Deformations of Openings in Salt Media," Int. J. Rock Mech. Min. Sci., 9 249 (1972).
16. A. M. Starfield and W. C. McClain, "Project Salt Vault: A Case Study in Rock Mechanics," Int. J. Rock Mech. Min. Sci., 10, 641 (1973).
17. T. F. Lomenick, "Chapter 12 - Laboratory Pillar Model Experiments," Project Salt Vault: Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines, eds. R. L. Bradshaw and W. C. McClain, ORNL-4555 UC-70, Union Carbide, Oak Ridge, TN, (1971).
18. K. K. Waki, D. E. Maxwell, and R. Hofmann, "A Two-Dimensional Simulation of the Thermomechanical Response of Project Salt Vault Including the Excavation Sequence," SAI-FR-821-2, Science Applications, Inc., San Leandro, CA (1977).
19. Project Salt Vault: Demonstration of the Disposal of High-Activity Solidified Wastes in Underground Salt Mines, eds. R. L. Bradshaw and W. C. McClain, ORNL-4555 UC-70, Union Carbide, Oak Ridge, TN (1971).

20. J. L. Ratigan and G. D. Callahan, "Evaluation of the Predictive Capability of the Finite Element Method; II. Project Salt Vault - Thermo/viscoelastic Simulation," RI-0065, Re/Spec, Inc., Rapid City, SD (1978).
22. F. D. Hansen and K. D. Mellegard, "Creep Behavior of Bedded Salt from Southeastern New Mexico at Elevated Temperatures," RSI-0062, Re/Spec, Inc., Rapid City, SD, (1977)
21. H. C. Heard, "Steady-State Flow in Polycrystalline Halite at Pressures of 2 Kilobars," Flow and Fracture of Rocks, eds. H. C. Heard, I. Y. Borh, N. L. Carter and C. B. Raleigh, (Am. Geophys. Union, Washington, DC, 1974) p. 191.
23. W. R. Waversik and D. W. Hannum, "Interim Summary of Sandia Creep Experiments on Rock Salt from the WIPP Study Area, Southeastern New Mexico," SAND79-0115, Sandia Laboratories, Albuquerque, NM (1979).
24. P. R. Dawson, "Constitutive Models Applied in the Analysis of Creep of Salt," SAND79-0137, Sandia Laboratories, Albuquerque, NM (1979).
25. J. P. Poirier, "High-Temperature Creep of Single Crystalline Sodium Chloride I. Creep-Controlling Mechanism," Phil. Mag., 26, 701 (1972).
26. K. Barron and N. A. Toews, "Deformation around a Mine Shaft in Salt, Proc. Second Canadian Symp. Rock Mech., (Queen's University, Ottawa, Canada, 1964) p. 115.
27. G. Lacroix and E. Seidler, International Minerals and Chemicals Corporation (Canada) Limited; Esterhazy, Saskatchewan (private communication).
28. M. S. King, "Creep in Model Pillars of Saskatchewan Potash," Int. J. Rock Mecha. Min. Sci., 10, 363 (1973).
29. M. M. Baligh, "Numerical Study of Uniaxial and Triaxial Rock Compression Tests," Report SSS-R-73-1658, Systems, Science and Software, La Jolla, CA (1973).
30. L. Obert, "Deformational Behavior of Model Pillars made from Salt, Trona, and Potash Ores," Proc. Sixth Symp. on Rock Mechanics, eds. E. M. Spokes and C. R. Christianson (University of Missouri, Rolla, MO, 1964), p. 539.
31. H. G. Poulos and E. H. Davis, Elastic Solutions for Soil and Rock Mechanics, (John Wiley & Sons, New York, 1974), p. 237.

UNLIMITED RELEASE

DISTRIBUTION: ,

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

Attn: Eugene F. Beckett,
Project Coordinator (WIPP) (1)
Colin A. Heath, Director,
Division of Waste Isolation (2)
Sheldon Meyers
Raymond G. Romatowski
R. Stein
C. L. Cooley
D. Vieth

U. S. Department of Energy
Division of Engineering, Mathematical
and Geosciences
Office of Basic Energy Research
Washington, DC 20545
Attn: George A. Kolstad

U. S. Department of Energy, Albuquerque
Operations
P. O. Box 5400
Albuquerque, NM 87185
Attn: D. T. Schueler, Manager,
WIPP Project Office (2)
G. Dennis, Director,
Public Affairs Division
S. C. Taylor, C&TI Division
(for public reading rooms)

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

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

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

Westinghouse Electric Corporation
P. O. Box 40039
Albuquerque, NM 87196
Attn: R. C. Mairson
D. Hulbert

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

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

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

Frank L. Parker
Department of Environmental and Water
Resources Engineering
Vanderbilt University
Nashville, TN 37235

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

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

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

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

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

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

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

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

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

Distribution (cont)

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

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

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

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

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

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

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

Bruno Giletti
Department of Geological Sciences
Brown University
Providence, RI 02912

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

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

John Lyons
Department of Earth Sciences
Dartmouth College
Hanover, NH 03755

George Pinder
Department of Civil Engineering
Princeton University
Princeton, NJ 08540

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

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

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

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

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

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

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

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

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

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

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

Dr. Paul R. Dawson
254 Upson Hall
Department of Mechanical and Aerospace
Engineering
Cornell University
Ithaca, NY 14853

Distribution (cont)

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

Oak Ridge National Laboratory
Box Y
Oak Ridge, TN 37830
Attn: C. Claiborne
G. H. Jenks

RE/SPEC Inc.
P. O. Box 725
Rapid City, SD 57701
Attn: Dr. P. Gnirk
L. Van Sambeek
R. Stickney
W. C. McLain

Rockwell International
Atomics International Division
Rockwell Hanford Operations
P. O. Box 800
Ricland, WA 99352
Attn: M. J. Smith

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

U. S. Geological Survey
Special Projects
MS 954, Box 25046
Denver Federal Center
Denver, CO 80255
Attn: C. Jonco

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

Los Alamos Scientific Laboratory
Los Alamos, NM 87545
Attn: R. Brownlee, MS 570
W. J. Carter, MS 320
P. Smith, MS 329

Lawrence Livermore Laboratory
P. O. Box 800
Livermore, CA 94550
Attn: R. N. Schock, L-437
H. Heard, L-437

Center for Tectonophysics
Texas A&M University
College Station, TX 77843
Attn: J. E. Russel
N. Carter

1100 C. D. Broyles
1110 J. D. Plimpton
1112 C. R. Mehl
1116 S. R. Dolce
1120 T. L. Pace
1125 G. L. Ogle
1130 H. E. Viney

2645 L. D. Bertholf
3141 T. L. Werner (5)
3151 W. L. Garner
For DOE/TIC (Unlimited Release) (3)
3154-3 R. P. Campbell
For DOE/TIC (25)
3310 W. D. Burnett
4413 N. R. Ortiz
4500 E. H. Beckner
4510 W. D. Weart
4511 D. W. Powers
4512 T. O. Hunter (5)
4512 D. E. Munson (25)
4512 C. L. Christensen
4512 D. R. Fortney
4512 M. A. Molecke
4514 M. L. Merritt
4530 R. W. Lynch
4537 L. D. Tyler
4538 R. C. Lincoln
4540 M. L. Kramm
4541 L. W. Scully
4542 Sandia WIPP Central Files (2) (TEI)
4543 R. R. Beasley
4700 J. H. Scott
4730 H. M. Stoller
4732 D. A. Northrop
4732 A. R. Sattler
4745 J. R. Tillerson
4738 J. R. Wayland
5500 O. E. Jones
5510 D. B. Hayes
5520 T. B. Lane
5511 J. W. Nunziato
5511 G. R. Hadley
5521 R. D. Krieg
5521 C. M. Stone
5530 W. Herrmann
5531 S. W. Key
5531 W. T. Brown
5532 B. M. Butcher
5532 L. W. Teufel
5532 W. R. Wawersik
5541 W. C. Luth
5800 R. S. Claasen
5810 R. G. Kepler
5824 J. N. Sweet
8266 E. A. Aas (2)