Thermomechanical Modeling and Salt Mining

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ABSTRACT

Significant advances have been made in the rock mechanics of salt over the past five to ten years, primarily through the support of nuclear waste disposal programs in the U.S.A. and other countries. Unfortunately, the practical application of this technology to the salt and potash mining industries has been slow in forthcoming. This paper provides a review of the state of the art in numerical analysis of salt behavior, as well as a brief review of the enormous growth in computer technology. The capabilities in rock mechanics have increased substantially in the past decade and are applicable to salt and potash mining, either by underground mining or solution mining techniques. The calculation of time-dependent room/cavern closure and pillar deformations is illustrated. Factors that can be incorporated include the effects of various in situ stress levels, the effects of sequential mining, the effects of heat, and other factors.

The purpose of this paper is to stimulate the broader use of recent advances in salt rock mechanics technology by the salt and potash mining industries.

INTRODUCTION

Although salt is one of the simplest and most common of all minerals, its rock mechanics behavior is inherently very complex. Salt is a viscoelastic material, and therefore has a time-dependent stress-strain relationship. Finding solutions to mathematical formulations that describe this nonlinear behavior is a formidable problem. In the laboratory it is a challenging problem to obtain constitutive equations describing the material behavior of salt, because tests need to be conducted over long periods of time under carefully controlled and monitored conditions. Nevertheless, significant advances have been made over the past five to ten years in understanding the rock mechanics of salt. Most of the progress has been a direct result of the large research program to investigate the potential disposal of nuclear wastes into salt formations sponsored by the U.S. government, which has been ongoing for over 20 years.

The salt and potash mining industries, in particular, stand to benefit from these technological advances. Their proper application can assist the mining engineer in designing mine layouts, choosing optimal pillar and cavity sizes, predicting closure rates and surface subsidence, etc. It is clear that sound decisions concerning these matters can be an important factor in the overall profitability of a mine—a matter of vital consequence in today's harsh economic climate.

This paper reviews the advances that have been made on the current state-of-the-art salt rock mechanics in an attempt to stimulate the broader use of these modern tools by the salt and potash industries. Significant technological progress has been made in three interrelated areas: numerical analysis methods for solving nonlinear problems, laboratory testing of salt, and computer hardware. This report describes the state of the art in each area and indicates how they are being applied to salt rock mechanics problems.

COMPUTER TECHNOLOGY

The modern computer and the dramatic improvements in computing power deserve a special mention since the computer is the basic tool of the rock mechanics analyst, as well as being of fundamental importance to the laboratory scientist. An enormous growth in computer efficiency has occurred in the past decade. For example, the cost of computer calculations has decreased by a factor of 20,000 from 1965 to 1979 (J. G. Doleman, CDC, personal communication); and the cost of computer processing on a per-unit basis continues to decrease even in these inflationary times. Thus, many applications—particularly the solving of large, complex, nonlinear rock mechanics problems which were not cost effective only a few years ago—can now be economically justified.

The last five years have seen the emergence of a new breed of systems, the so-called super mini-computers that have the capabilities of many of the main frame machines of the late 1960s and early 1970s, at a fraction of the price. These super-minis have multiuser, multiprocessing capabilities that enable them to handle large volumes of work on an interactive basis. The cost (approximately $150,000 to $300,000) is low enough that they are affordable by many mining companies and can be installed at the mine site.

In addition to performing rock mechanics analyses, an on-site computer can provide systems analysis and control of the overall mining and milling operation. For example, the National Coal Board of the United Kingdom increased the output of each man at the coalface by 4.8 percent during 1981 because of the installation of a computer system (Gunton, 1982).

NUMERICAL ANALYSIS

The dramatic growth in computer capability has resulted in a parallel growth in numerical techniques that can be used to solve complex engineering problems. Numerical modeling per se can be used for sensitivity calculations, parametric studies, as well as for detailed modeling and design. For the most part, the numerical methods that have been developed for the analysis of thermomechanical and hydrological behavior of underground openings have been developed for a continuum. A continuum is described by the partial differential equations governing heat transfer, fluid flow, and distribution of stresses. The numerical methods used to solve these partial differential equations are separated into two broad categories: those based on differential methods and those based on integral methods. The differential methods require that either a mathematical or a physical approximation be made for some region in space, while the integral methods require only that approximations be made on internal or external boundaries. The finite difference method and the finite element method (Zienkiewicz, 1977) are the two main differential methods; and the displacement discontinuity, boundary element (Brady, 1979), and boundary integral methods (Cruse and Rizzo, 1975) comprise the integral methods.

Finite element models exist that can simulate the large-scale thermomechanical behavior of rock salt during the excavation process and the operation of a salt mine. These models may include the sequential excavation associated with room-and-pillar or solution mining methods (Fossum, 1977). The models can incorporate relatively complex stratigraphy and may also include slip along clay seams. It is possible to include finite strains and large deformations coupled with fluid flow and heat transfer. There is a growing need, particularly in solution mining, for the numerical model to embrace all of the above physical processes.

The parameters necessary in conducting analyses must be determined experimentally as is discussed in the next section. Thus, there must be some interaction between numerical modeling and laboratory testing and analysis. In addition, the mechanical behavior of openings in bedded and domal salt depends to a high degree on discontinuities or anomalous features in the salt. Without site-specific knowledge of the character and orientation of these discontinuities or anomalous features, properties obtained from core specimens alone are insufficient to enable numerical predictions to be made on potential instabilities resulting in part from the nonhomogeneities in the salt. It is therefore good engineering practice to include, along with laboratory testing and numerical modeling, and in situ testing program that involves a wide range of geotechnical and geophysical methods coordinated with the geologic structure of the area as determined by a continuing mapping program.

Although the state of the art in numerical analysis has reached a fairly high level of sophistication, it has been the authors' observation that few documented cases exist of its application to salt mine design. Developments have been instigated primarily in the nuclear waste disposal area. As an example of the capabilities and uses of numerical models for salt, a description and some results will be provided from Sandia's Waste Isolation Pilot Plant Benchmark II Study (Morgan et al., 1981) for evaluating the capabilities of structural computer codes to predict drift response in a creeping salt. The purpose is not to compare the capabilities of various thermal-structural computational codes, as was the purpose in the Benchmark II Study, but rather to demonstrate the existing capabilities for modeling salt behavior. The structural computer codes used for the drift response calculations were capable of handling simultaneously the viscoelastic behavior of halite layers, the elastic behavior of anhydrite and polyhalite layers that do not creep, and the slip behavior of layers separated by clay seams. One of the two boundary value problems used in the Benchmark II Study included a drift configuration designed to represent a hypothetical room for storing heat-producing high-level radioactive waste. In problems such as this, the analyst must decide on the extent of the medium to be modeled and on the proper boundary conditions. The initial in situ stresses must also be incorporated in the problem. The heated drift model is illustrated in Figure 1. The stratigraphy ranged from a depth of 598.02 m to a depth of 706.77 m. For the sake of simplicity, some of the stratigraphic details have been omitted from Figure 1. The single drift is meant to be part of a regular array of long drifts. Thus, a plane strain assumption is made and symmetry planes are assumed through the drift and pillar centerlines. The shear tractions and the horizontal displacements were specified to be zero along the vertical boundaries. A lithostatic (all normal stresses equal) ini-

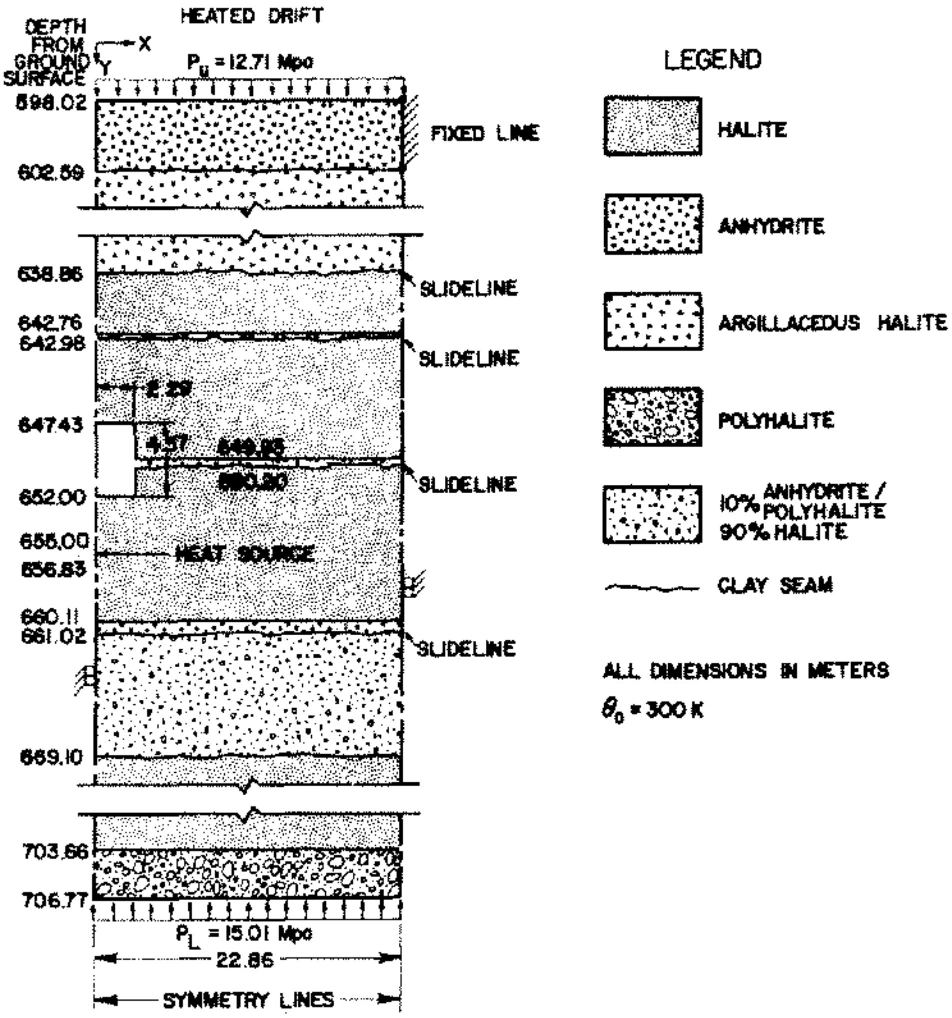

Figure 1. Heated drift configuration.

tial in situ stress state was assumed. The boundary conditions at the top and bottom were uniform pressures. The top anhydrite layer was fixed along the edge at the pillar centerline to preclude rigid body motion. The surfaces of the room were traction free, and the initial temperature was 300 K. Four clay seams were taken to be active slip planes as shown in Figure 1.

The heat source was designed to simulate hot canisters placed at regular intervals beneath the floor. The model of this heat source assumes a continuous distribution along the drift length. The waste is idealized as a plane source with no x-direction dimension. As the material characterization, material properties, and thermal properties have no significance in principle to our discussion, they will be omitted in favor of presenting some of the results to show the type of information that can be produced in an analysis such as this.

The fundamental output of most thermomechanical computer codes includes temperature, stresses, and displacements. The Benchmark II Study called for (1) displacement time histories in the form of relative vertical and horizontal closures of the room as a function of time, the relative horizontal and vertical displacements across each slide line as a function of position for selected times; (2) stress profiles at selected times including contour plots; and (3) temperature time histories. Some of these results are presented in Figures 2 through 5.

The finite element method is the main numerical method used to analyze underground structural problems. For example, seven of the eight different computer programs used in the Benchmark II Study (Morgan et al., 1981) were based on the finite element method. The sole exception was a finite-difference computer code. Some work, which is based on the displacement discon-

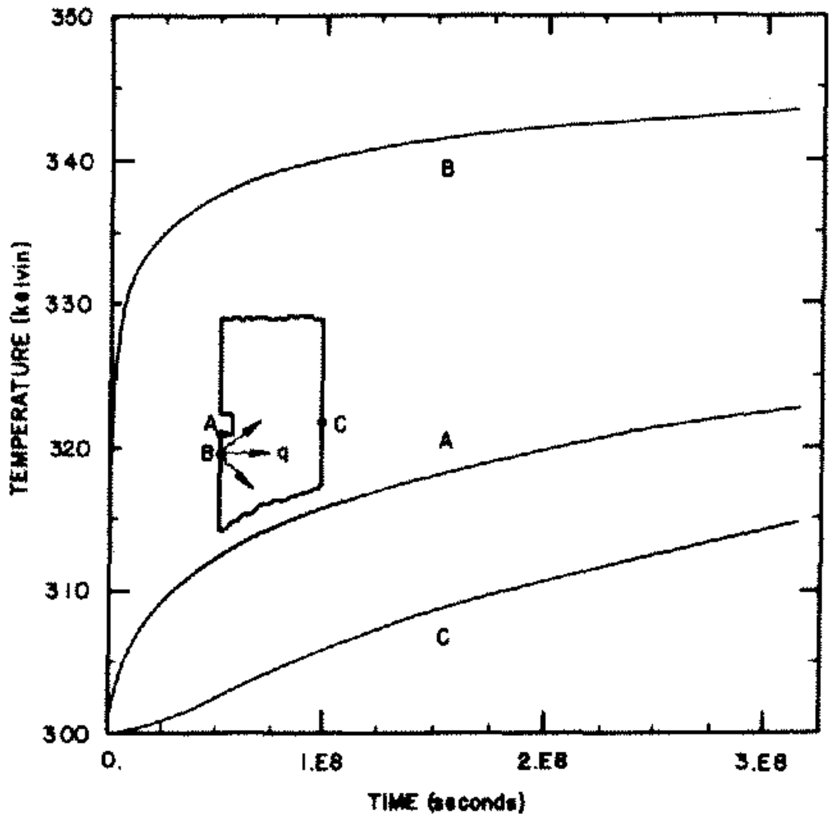

Figure 2. Temperature histories of the heated room at (A) the center of the room floor, (B) the heat source, and (C) the pillar center point.

tinuity method with applications to a nuclear waste repository in bedded salt, has been published by Crouch and McClain (1978).

LABORATORY TESTING

Testing machines. The role of laboratory testing is to allow the deformation and strength of salt to be studied under controlled stress and temperature. Measurements of strength and deformation are used to construct constitutive laws that relate strength and deformation to the stress and temperature. These constitutive laws are then used in numerical analyses to predict the behavior of structures in salt.

Test machines which can squeeze rock have evolved continuously since their introduction in the beginning of this century. However, it was not until the early 1970s that machines came into use with temperature and triaxial capabilities and which were designed and dedicated primarily for the testing of salt (Wawersik, 1979). Even today, the number of laboratories having such machines is very limited.

Current laboratory testing machines allow specimens to be tested in triaxial compression and elevated temperatures for extended periods of time. Figure 6 shows a common testing machine design (Wawersik, 1979; Mellegard et al., 1981). These machines use a pressure vessel that accommodates a cylindrical jacketed specimen. A hydraulic cylinder bolted to the base of the load frame drives the loading piston which applies axial compressive force to the specimen. Confining pressure is applied to the specimen by pressurizing the sealed vessel chamber with silicone oil. A dilatometer system maintains constant confining pressure and provides volumetric measurement for making lateral strain calculations.

The testing machines can apply compressive axial loads up to 1.5 MN and confining pressures up to 70 MPa. The heating system can maintain constant test temperatures up to 200°C.

Data collected during the tests are time, temperature, axial load, confining pressure, axial displacement, and volumetric displacement. A computer, an integral part of the system, records the data in digital form and computes axial stress difference, axial strain, and lateral strain. The computer also controls the axial load on the specimen to within 0.75 kN. Separate controllers maintain the confining pressure and temperature at their selected values within 35 kPa and 0.2°C, respectively.

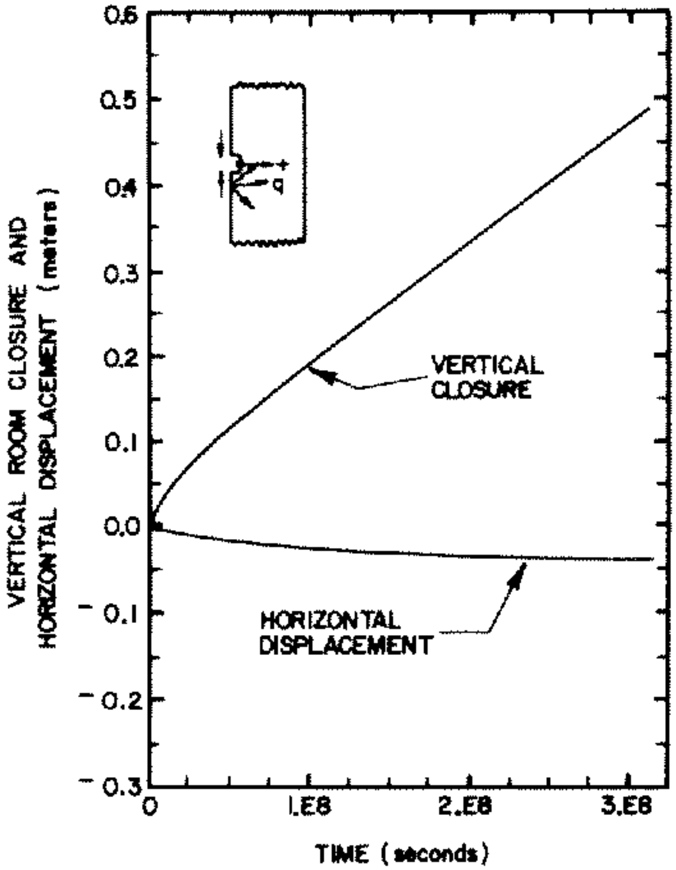

Figure 3. Vertical closure and pillar horizontal displacement with time.

Axial load data are provided by a load cell placed between the loading piston and hydraulic cylinder. Back-up readings are available from a mechanical gage connected directly into the hydraulic pressure system.

Confining pressure data are provided by a pressure transducer connected to the triaxial pressure vessel. This transducer also provides the feedback signal required by the dilatometer for constant pressure control.

Two Linear Variable Differential Transformers (LVDT) provide indirect axial displacement data by measuring piston displacement relative to the vessel baseplate. During data reduction, calibration factors are used to remove the machine softness component to give actual specimen displacements. The computer uses the axial and volumetric displacements to calculate lateral displacement.

Temperature data are collected from a thermocouple mounted in the wall of the triaxial test vessel. This thermocouple also provides the feedback signal for constant temperature control.

Typical accuracies and resolutions for the measurements are given in Table 1. The accuracies reported include linearity, hysteresis, and repeatability as determined in the laboratory using standards traceable to the U.S. National Bureau of Standards.

Test procedures. Generally, two types of tests are performed. The first is one in which the stress rate or strain rate is constant. Results of these tests give strength and elastic moduli. Appropriate values for the elastic moduli are obtained by unloading and reloading the specimen. Moduli values obtained from initial loading are about an order of magnitude lower than the unload-reload values because of inelastic deformation occurring during initial loading, as shown in Figure 7.

The second type of test is a constant stress or creep test. In these tests, the stress on the specimen is held constant, and deformation is measured as a function of time. Figure 8 shows the results of typical creep tests. The specimen is rapidly loaded at time $t = 0$ and allowed to deform under constant true stress. Initially, the deformation rate is very high. The deformation rate decreases steadily from this initial value to some lower value at which time deformation continues at a steady rate. The axial-strain-versus-time curve shown in the figure is divided into two parts. The first part is the transient regime in which the creep rate is decreasing, and the second is the steady-state regime in which creep deformation occurs at a constant rate. The duration of the transient regime, the magnitude of the transient creep strain, and the steady-state creep rate are all functions of stress and temperature.

If the confining pressure and temperature are low enough, a third regime, called tertiary creep, is observed. During tertiary creep, the rate of deformation increases, and ultimately, the specimen fails. This creep rupture phenomenon is currently being investigated (Langer, 1982).

Interpretation. The plastic deformation of crystalline solids such as salt is a thermally-activated process in which deformation occurs by the motions of point defects, individual atoms, and dislocations. Unfortunately, these processes are not sufficiently well understood to allow a theoretically-based creep law for salt to be derived. For this reason, the constitutive laws which have been developed to date are largely empirical.

TABLE 1

Calibration results*

Measurement System	Working Range	Accuracy*	Resolution
Axial Strain (Percent)	0–12.5	0.006	0.0015
Lateral Strain (Percent)	0–8	0.004	0.001
Axial Load (MN)	0–1.5	.01	0.0002
Confining Pressure (MPa)	0–70	0.035	0.008
Temperature (°C)	25–200	2.0	0.025

*Includes linearity, hysteresis, and repeatability.

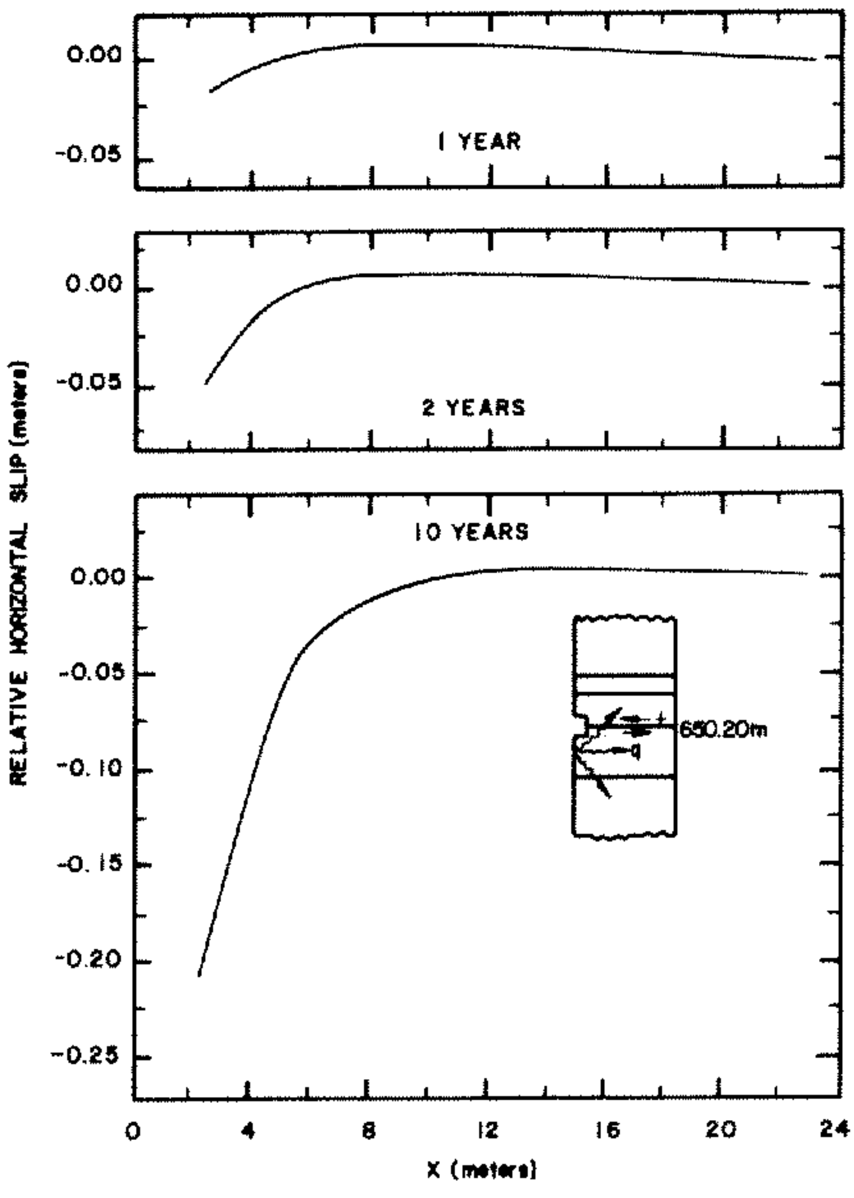

Figure 4. Relative slip across the slide line at 650.20 m at 1, 2, and 10 years.

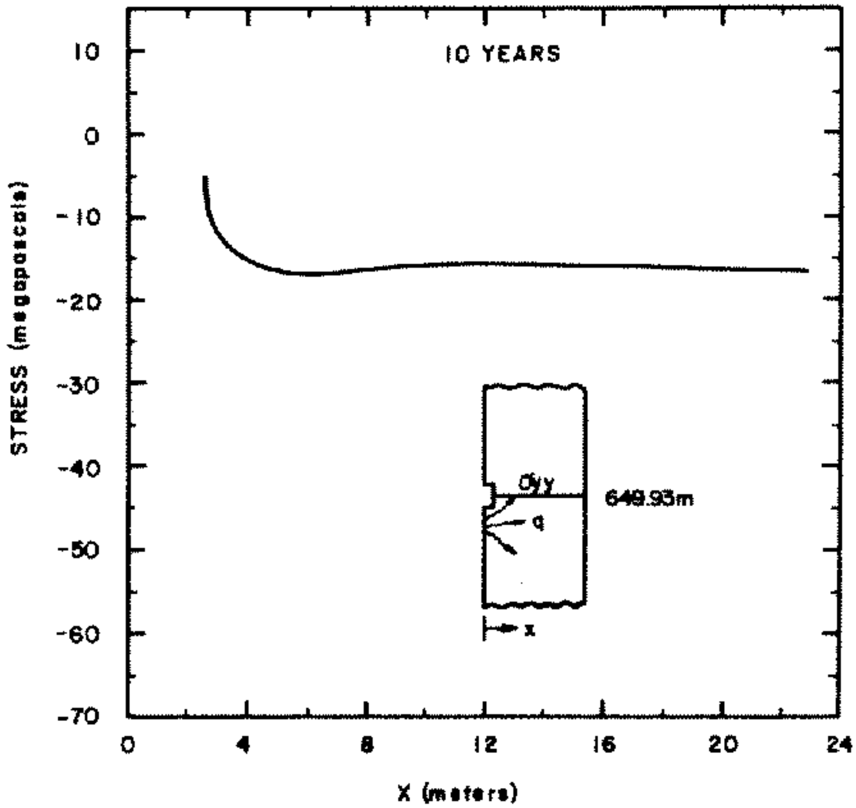

Figure 5. Vertical stress profile through the pillar at 10 years.

A number of these constitutive laws have been proposed (Senseny, 1981), and the particular constitutive law form that is used can substantially influence predictions of structural behavior (Wagner et al., 1982). The constitutive law that is currently used in the U.S. Nuclear Waste Program is the exponential-time law. This law models both transient and steady-state creep and accounts for stress and temperature history with a strain-hardening algorithm. When written in tensorial form, the total strain rate can be related to stress and temperature by

$$\dot{\epsilon}_{ij} = \frac{1}{E}\left[(1+\nu)\dot{\sigma}_{ij} - \nu\dot{\sigma}_{kk}\delta_{ij}\right] + A(3J_2')^{n+1/2}\exp(-Q/RT) \times \left\{1 + B\epsilon_a - \frac{B\epsilon_a\xi}{(J_2')^{n/2}\exp(-Q/RT)} \times \int_0^t (J_2')^{n/2}\exp(-Q/RT) \times \exp\left[-\int_{t'}^{t} \xi\, dt'\right] dt''\right\} \frac{\sigma_{ij}'}{2J_2'}$$

$$\xi = \begin{cases} BA(3J_2')^{n/2}\exp(-Q/RT) & \dot{\epsilon}_{ss} \geq \dot{\epsilon}^* \\ B\dot{\epsilon}^* & \dot{\epsilon}_{ss} \leq \dot{\epsilon}^*. \end{cases}$$

where

$\dot{\epsilon}_{ij}$ = total strain rate
$\dot{\sigma}_{ij}$ = stress rate
$\dot{\sigma}_{ij}'$ = stress deviator
δ_{ij} = Kronecker delta
J_2' = second invariant of the stress deviator
T = absolute temperature
E, ν = Young's modulus and Poisson's ratio, determined from unload-reload portion of constant stress or strain rate tests
A, n, Q/R, B, ϵ_a, $\dot{\epsilon}^*$ = parameters whose values are determined by analyzing data from creep tests.

It is important to characterize the thermomechanical behavior of salt in the ranges of stress and temperature expected in the particular application of the constitutive law. The wider these ranges, the greater the number of tests required. For example, in a nuclear waste repository application, a minimum of twelve tests are required to obtain approximate parameter values over the temperature range 20°C to 200°C and stress difference range 2.5 MPa to 15 MPa. About 50 tests are required for a more complete characterization. For mining applications, however, where the temperature is nearly constant, a

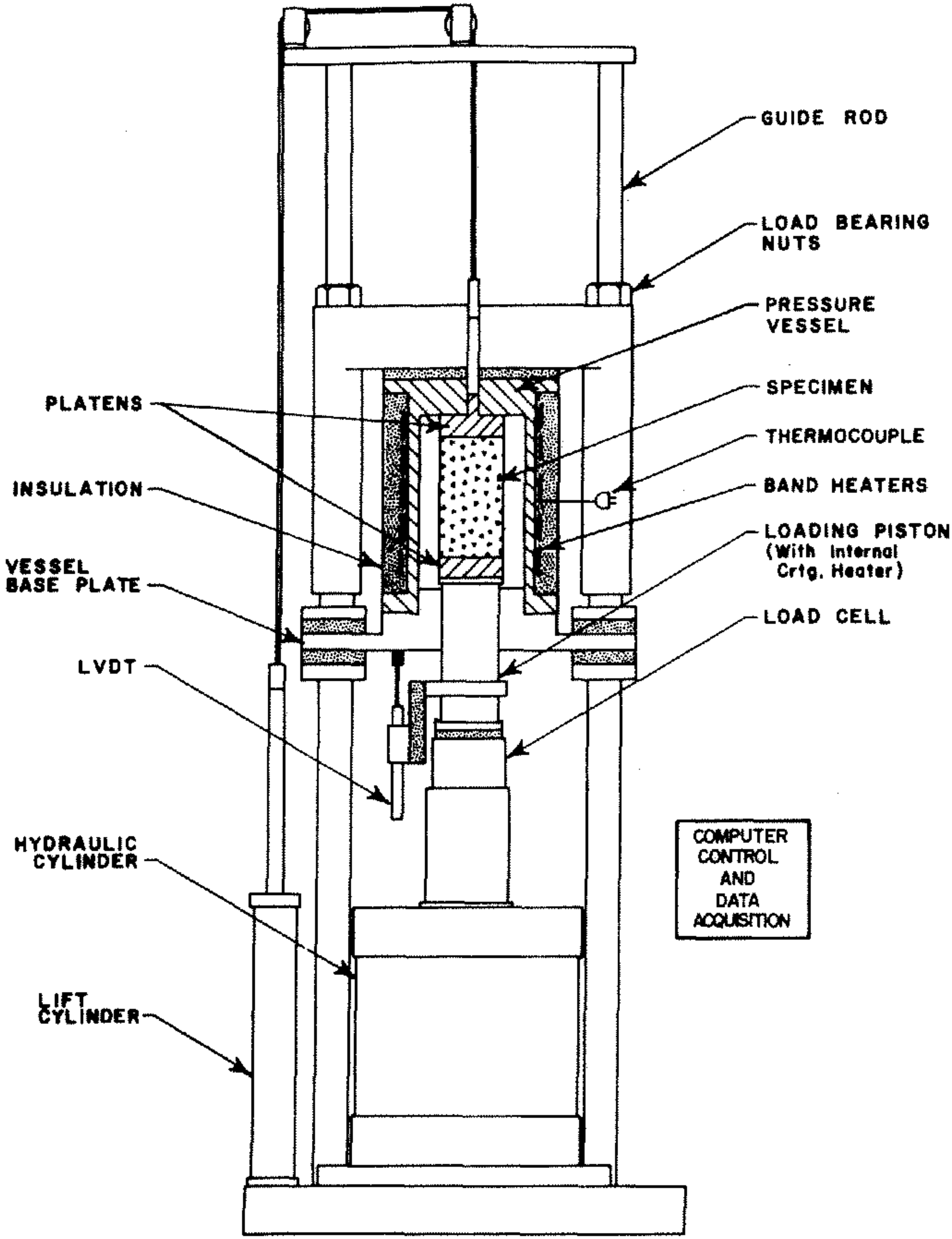

Figure 6. Schematic diagram of the apparatus for creep testing salt.

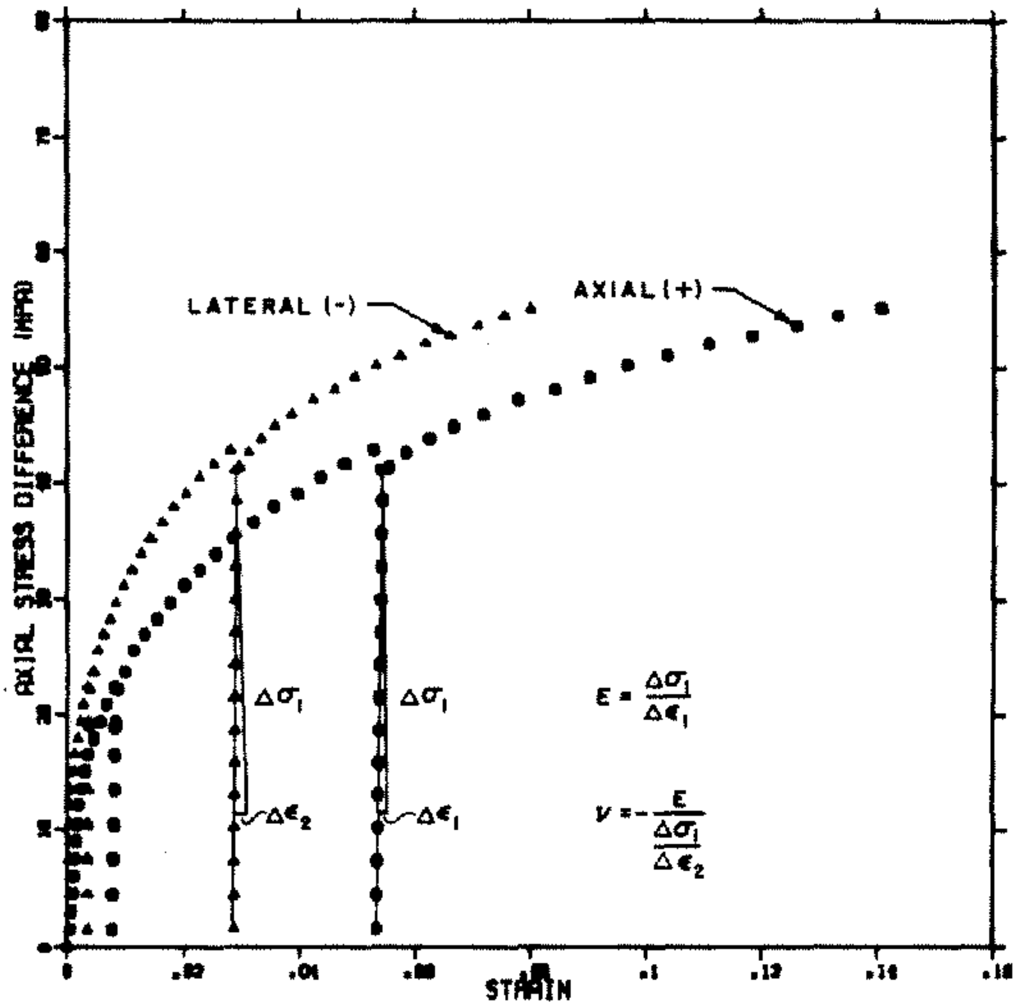

Figure 7. Typical plot of axial stress difference versus strain.

minimum of five or six tests is sufficient to cover the range of stress difference. For a more complete characterization, perhaps twice this number is required.

Results. The elastic parameters do not vary much from salt to salt (Hansen et al., 1982). Young's modulus is equal to about 30 GPa, and Poisson's ratio is equal to about 0.35. The remaining parameters in the law, however, depend on the specific salt. Figure 9 shows this graphically by plotting the results of creep tests performed on salt from four different sites. All tests were performed at a temperature of 100°C, a confining pressure of 15 MPa, and a stress difference of 10 MPa (Pfeifle et al., 1981). The widely divergent results shown on this figure illustrate the importance of having site-specific parameter values when predicting the behavior of underground structures in salt.

SUMMARY

This paper presents a brief review of the state of the art in three areas (computers, numerical analysis, and laboratory testing) which have evolved rapidly over the last decade and which are critical to an understanding of the rock mechanics of salt. It is seen that a fairly high level of sophistication has been reached and that an integrated rock mechanics program can make an important contribution to the salt and potash mining industry, for both solution mining and shaft mining concepts. In general, the mining industry has been rather conservative and has used the tried and proven methods in their rock mechanics programs. It is urged that the mining industry embrace the modern technological tools that are available today. Let's live in the computer age.

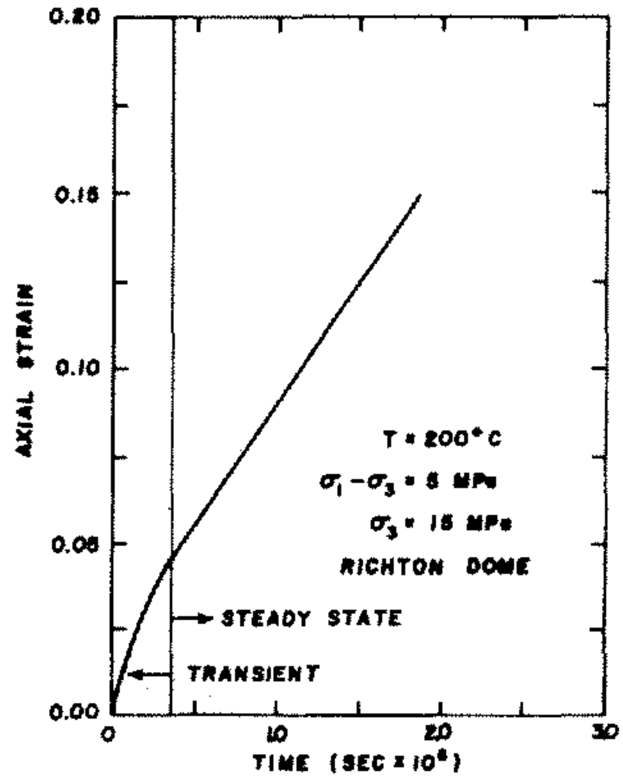

Figure 8. Axial strain as a function of time for salt at constant stress and temperature.

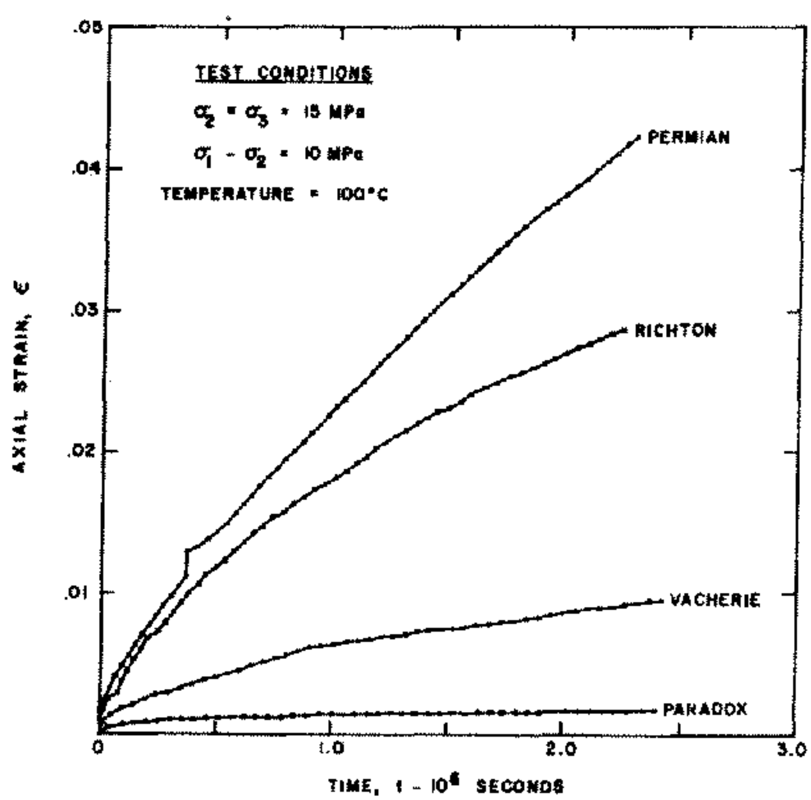

Figure 9. Axial creep strain as a function of time at a stress difference of 10 MPa and a temperature of 100°C.

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