Laboratory and Theoretical Studies Relative to the Design of Salt Caverns for the Storage of Natural Gas

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ABSTRACT

Although the mechanical behavior of salt has been investigated for many years, a review of the world literature indicates that criteria for the optimum design of engineering "structures" in salt are at present relatively limited. The present paper will deal mainly with basic problems associated with the design of salt caverns for the storage of natural gas, although the results and conclusions, for the most part, will also apply to the more general use of such storage facilities.

In 1975 an industry sponsored research project was initiated at The Pennsylvania State University involving the design and performance of salt caverns for natural gas storage. During the succeeding seven-year study, research has been undertaken relative to the development of a better understanding of how salt behaves under conditions of stress and temperature equivalent to those found around a typical pressurized salt cavern and the application of established mechanics principles to the development of design criteria for such caverns. The project was completed in 1981 and a detailed monograph on the study was published in late 1982.

The present paper will include a brief outline of the concept of salt cavern storage as it relates to the storage of natural gas and the current status of cavern design procedures. This will be followed by a review of a number of laboratory and analytical studies carried out by the writers in an effort to provide basic input for the development of meaningful salt cavern design techniques. In particular a number of aspects of these studies not presently available in the open literature will be considered in some detail.

INTRODUCTION

For some fifty or more years rock mechanics engineers and scientists have been investigating the mechanical behavior of a wide range of geologic materials, such as hard rocks and coal, utilizing a variety of laboratory, analytical and field techniques. In recent years such investigations have expanded into the area of soft rocks (Akai et al., 1981), and during the last ten years detailed studies have been underway in regard to the behavior of a specific class of soft rock, generally referred to as salt. Due to the complex properties of salt, and the unique procedures required for the design and construction of structures in this material, a specialized area of rock mechanics, known as "Salt Mechanics," has developed (Hardy, 1982A).

Limited basic and applied research in the area of salt mechanics has been underway for a number of years, mainly in relation to the design and operation of salt and potash mines. In recent years, however, salt, both bedded and domal, has been found to provide an excellent medium for the construction of underground facilities for the storage of a variety of materials, including crude oil and various refined petroleum products, natural gas, compressed air (energy storage) and radioactive and chemical wastes.

Due to the accelerated interest in the use of salt as a medium for underground storage, a wide range of research and engineering studies have been underway to optimize the design and mining techniques needed for the construction of salt caverns, and to develop suitable means for stability monitoring of such structures. During the last eight years, salt mechanics research relative to the design and performance of caverns for the storage of natural gas has been underway in the Geomechanics Section at The Pennsylvania State University.

This paper will include a brief outline of the concept of salt cavern storage as it relates to the storage of natural gas, and the current status of cavern design procedures. This will be followed by a review of a number of laboratory and analytical studies carried out by the writers in an effort to provide basic input for the development of meaningful salt cavern design techniques. In particular, a number of aspects of these studies not presently available in the open-literature will be considered in some detail.

SALT CAVERN STORAGE OF NATURAL GAS

Types of Underground Storage

As the demand for natural gas increases, the necessity of storing larger and larger volumes of gas underground during periods of low demand has increased markedly. At present three basic types of underground storage are utilized, namely, depleted gas and oil reservoirs, aquifers and man-made caverns. The use of man-made caverns for the underground storage of natural gas has increased rapidly in recent years. Such facilities include conventionally mined caverns and tunnels, solution mined caverns and modified mine workings. At present solution mined salt caverns are the most widely utilized of the man-made storage facilities.

One important advantage of salt cavern storage is that since the gas does not have to flow through porous rock into the wellbore, as it does in other types of underground gas storage (reservoirs and aquifers), it can be produced very quickly (high deliverability) when needed and the cavern can be refilled rapidly when demand is less. For such "peak shaving" applications, salt caverns are ideal since they need not be large to be extremely valuable. They can, however, be built to store large volumes if required and single caverns with volumes of 10×10^6 ft^3 have been constructed.

According to a recent American Gas Association survey (Anon., 1980A), as of 1980 there were eight salt cavern facilities in operation in North America utilized specifically for the storage of natural gas. These facilities involve a total of 19 separate storage caverns and some 27,500 MMscf of stored natural gas. A recent industrial report (Anon., 1980B) indicates that at present seven additional caverns are in the planning or construction stage. Similar storage facilities for natural gas and other fluids are in use in Great Britain, Germany, France and other foreign countries (Hardy, 1980). For example, Gaz de France has plans to construct a total of 45 salt caverns at two sites (Etrez and Tersanne) for the storage of natural gas; and one West German firm, Kavernen Bau- und Betriebs—GmbH (KBB), has in recent years constructed some 16 storage caverns for this purpose.

Salt Cavern Storage Concept

Salt caverns for the storage of pressurized natural gas are simply large containers created underground using solution mining (leaching) techniques. In use this container is loaded internally by the pressure of the stored gas and externally by in-situ ground stresses. The mechanical stability of such a container depends on a number of factors including the internal pressure, the in-situ stress field, the geometry of the container and the mechanical properties of the associated salt. It is important to note that in such a storage facility there is a critical minimum storage pressure as well as a maximum one. This critical minimum pressure level arises due to the fact that over a specific range the pressure exerted by the stored gas actually helps maintain cavern stability by partially balancing the effects of the in-situ ground stresses; however, below the minimum critical pressure the in-situ stress field may be sufficient to overcome the "strength" of the surrounding salt causing cavern closure and/or failure.

Cavern Instabilities

A major concern in salt cavern design is that of structural stability. In general there are a number of possible types of mechanical instabilities that may occur in solution mined salt caverns during and after their development. As illustrated in Figure 1, these include subsurface subsidence and subsequent surface subsidence, closure, local fracture and block flow, deep fracturing and various combinations of these factors. It should be emphasized

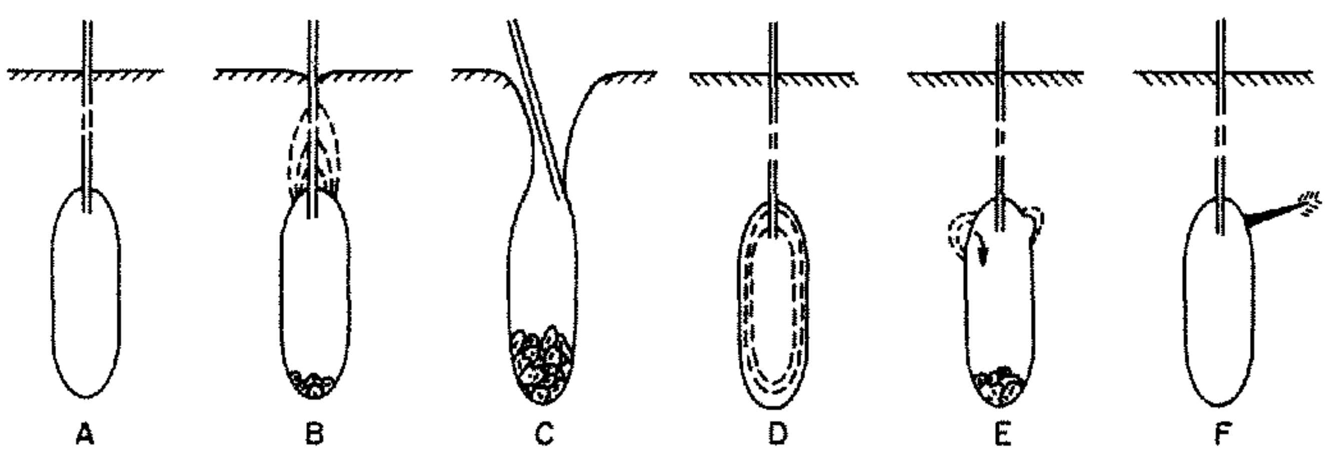


Figure 1. Various types of mechanical instability which may occur in solution mined caverns. (A—initially stable cavern, B—development of subsurface subsidence, C—piping subsidence and resulting surface subsidence, D—cavern closure, E—local fracture and block flow, F—deep fracture.)

that at present, with the exception of closure, which is the primary type of salt cavern instability considered to date, the occurrence of gross instabilities of the type noted are rare; although small scale instabilities of most types probably occur frequently.

Cavern Design

In general the development of a design procedure for a specific type of structure (e.g., a salt cavern storage facility) involves a number of components. These include physical property data for the material from which the proposed structure will be built; detailed information on the loads (mechanical and thermal) to which the proposed structure will be subjected; and analytical methods for predicting and/or evaluating the performance of the proposed structure.

Design approaches. The basic component of any design approach is the set of analytical tools necessary for calculation of the various unknown design factors and may involve closed-form solutions, numerical methods (e.g., finite element method) or a combination of both. In general the required design tools may be developed using three different techniques, namely:

1. *Laboratory Model Technique*—Here the behavior of scale models, subjected to equivalent loading conditions, are investigated and suitable empirical equations fitted to the laboratory data.
2. *Theoretical Technique*—Using this technique the assumed field situation is first reduced to a mathematically tractable form and then analyzed in terms of available mechanics techniques.
3. *Field Technique*—Here suitable data is collected from an actual field structure and suitable empirical equations fitted to the field data.

In many cases, two or even all of these techniques may be required to provide the information necessary to isolate the critical design factors and to develop a meaningful design approach.

Important design factors. Based on fundamental rock mechanics considerations and a review of the limited field case histories available for operating caverns, a number of factors appear to be of critical importance in the design of salt caverns, namely:

1. In-Situ Stress Field
   - Depth
   - Stress Ratio (k)
2. Cavern Dimensions
   - Shape (Geometry)
   - Size (Volume)
3. Cavern Spacing
4. Storage Pressure Limits
   - Maximum
   - Minimum
5. Injection-Withdrawal Cycle
   - Pressure Increment
   - Injection/Withdrawal Rate
6. Temperature
   - Ambient Salt Temperature (Geothermal Gradient)
   - Temperature Changes Due to Injection/Withdrawal
7. Mechanical Properties of Associated Media
   - Salt
   - Adjacent Rock

A number of these factors, such as in-situ stress field, temperature and mechanical properties, are dependent on the proposed cavern site and in general must be determined by field and/or laboratory studies. Factors such as cavern dimensions and spacing, storage pressure limits and the form of the injection/withdrawal cycle will, for the most part, be dependent on the eventual application of the storage facility.

Present status. It is clear, from the information obtained during recent studies (Hardy, 1982B) that a variety of empirical "guidelines" for the design of salt caverns exist today. However, although a number of important design factors have been isolated, comprehensive design procedures based on mechanics principles are not presently available. In North America this is primarily due to the fact that relatively few salt caverns have been developed for gas storage. Furthermore, since the majority of these have been "designed" on the basis of successful past experiences, rather than on the basis of an established design procedure based on fundamental rock mechanics principles, the necessary numerical data for such factors as in-situ stress field, mechanical properties, etc., are not available.

In order to develop the required design procedures, considerable basic and applied research has been underway during the last ten years. A detailed review of these activities are available in a recent A.G.A. monograph (Hardy, 1982B) and in the proceedings of the First Conference on the Mechanical Behavior of Salt (Hardy and Langer, 1984).

PENN STATE SALT CAVERN STUDY

Outline of Overall Study

Since 1975 the Pipeline Research Committee of the American Gas Association (A.G.A.) has supported a research project (PR-12-71), in the Geomechanics Section at The Pennsylvania State University, involving the design and performance of salt caverns for natural gas storage. As illustrated in Figure 2, the project has involved analytical studies to develop suitable methods for analysis of cavern behavior (component 5) and laboratory studies (component 3) in which the basic mechanical behavior of salt

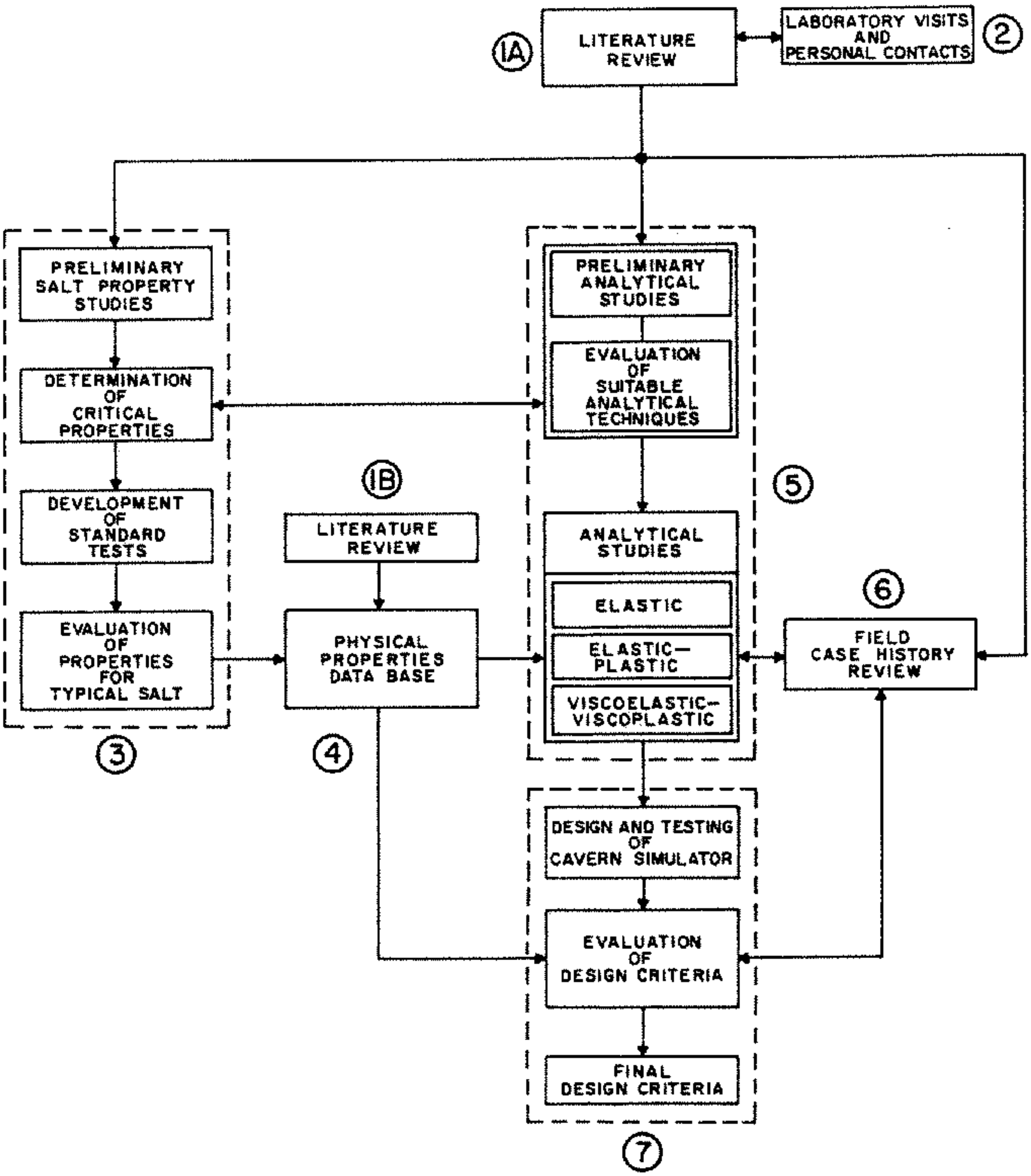


Figure 2. Block diagram illustrating the various components of the Penn State study. (Component 7 remains to be completed.)

was investigated in order to evaluate the necessary parameters for use in the analytical studies. These major studies have been supplemented by a detailed review of the associated literature and the development of extensive personal contacts with other researchers involved in the study of the mechanical behavior of salt and salt cavern design.

Although a review of the Penn State study has been presented in a number of recent papers (Hardy, 1980B, 1982C, 1982D), and a detailed description of the project is presented in an associated project monograph (Hardy, 1982B), a brief outline of the laboratory and analytical components of the study will be included here for completeness.

Laboratory Studies

Past experience has indicated that the rational design of an underground structure is contingent on a thorough knowledge of the critical properties of the construction medium. Salt is one of the more complex of the common geological materials in respect to its response to stress and is generally considered to be best described as a viscoelastic-viscoplastic material. As a result, a relatively large number of mechanical properties are required if a realistic design of a structure in salt is to be undertaken.

Figure 2 (components 1B, 3 and 4) illustrates the various phases of the laboratory study, the ultimate aim of which was to develop a meaningful physical properties data base for salt. In general, four main laboratory studies were undertaken, namely:

1. *General Studies*—Uniaxial studies to evaluate the elastic properties (Young's modulus and Poisson's ratio) and strength properties (compressive and tensile strength) were carried out (Hardy and Roberts, 1977; Roberts, 1981). A number of accessory parameters, such as specific gravity, acoustic emission, ultrasonic velocity, etc., were also investigated.
2. *Creep Studies*—Creep studies were undertaken in order to evaluate a number of the viscoelastic-viscoplastic parameters for salt (Roberts, 1981; Bakhtar, 1979; Hardy et al., 1983; Mrugala, 1983B). A three-phase program was involved.
3. *Yield Strength Studies*—Here acoustic emission, microscopic and other techniques were investigated in an attempt to develop an objective means for evaluating the yield-point in salt (Richardson, 1978). Tests were carried out on both single crystal and polycrystalline specimens.
4. *Residual Stress Retention Studies*—Since residual stresses may be important in the analysis of salt cavern stability, particularly in salt domes, experiments were carried out to evaluate if and how residual stresses may be stored in salt (Mangolds, 1984; Hardy and Mangolds, 1980). Studies were conducted on artificial salt and on a number of types of natural salt.

A detailed description of the overall laboratory study and the resulting physical properties data base is available in the associated project monograph (Hardy, 1982B).

Analytical Studies

The original intention of the analytical phase of the salt cavern study was to develop a highly flexible, computer-based "cavern-behavior simulator" that could be programmed to investigate a wide range of conditions associated with the storage of natural gas in salt caverns. From the outset it was clear that such a simulator should involve the use of a suitable finite element program incorporating constitute relations based on the mechanical and thermal properties of salt. At an early stage in the analytical studies two finite element programs (BOPACE and BUMINES) were obtained and modified for use on the Penn State computer. As the project proceeded, however, it became increasingly clear that the development of a practical simulator would not be immediately possible due to the complexity of the problem and the time and financial restrictions of the project. Rather than proceeding with the development of an overly simplified simulator, with limited application to real field situations, it was, therefore, decided to utilize the available finite element programs to carry out a series of relevant analytical studies, the results of which could later be used as the basis for the development of the desired cavern behavior simulator.

The major studies undertaken in the analytical phase of the project included a series of three finite element studies and a study involving the closed-form analysis of two simple cavern shapes. In review, the major analytical studies were as follows:

1. *Elastic Studies*—In the first series the behavior of three cavern shapes, spherical, tapered cylindrical and teardrop were investigated assuming that the salt behaved elastically (Chabannes and Richardson, 1979). Although this assumption is somewhat unrealistic, particularly at high stress levels, the results did provide useful data on the elastic stress distributions existing around the three cavern shapes and the effects of in-situ stress (related to cavern depth) and cavern pressure.
2. *Elastic-Plastic Studies*—The behavior of a cavern with a circular cross-section was investigated assuming that the salt was an elastic-plastic material (Punwani, 1982). Such a material behaves elastically at low stresses and above a critical stress (yield stress) behaves as a time-independent plastic material. The BOPACE finite element program was utilized for these analyses which provided useful data on stress distribution and cavern closure as a function of such parameters as in-situ stress and cavern pressure. Since material behavior was considered to be time-independent, information on such charac-

teristics as the rate of cavern closure could not be evaluated.

3. *Viscoelastic-Viscoplastic Studies*—In the final series of analytical studies it was assumed that the salt behaved as a viscoelastic-viscoplastic material (Chabannes, 1983). Such materials, in general, exhibit elastic, viscoelastic, plastic and viscoplastic behavior. Two sets of studies were carried out in this series, namely, those based on closed-form and finite element techniques.

   Closed-Form Studies—In these studies the closed-form stress-strain-time relations were developed for a cylindrical and a spherical cavern assuming that salt behaved as a rigid-viscoplastic material. Using these relations the rate of cavern closure as well as other factors were evaluated for these two cavern shapes as a function of a number of parameters including cavern pressure and temperature.

   Finite Element Studies—In these studies the behavior of three cavern shapes—spherical, tapered cylindrical, and teardrop—were investigated using the BUMINES finite element program. Here the salt was assumed to be an elastic-viscoplastic material. In particular, the rate of cavern closure was investigated as a function of cavern pressure.

A detailed presentation of the overall analytical study is available in the associated project monograph (Hardy, 1982B), and a brief outline of the finite element studies have been presented in a number of recent papers (Hardy, 1982C, 1982D).

Discussion

As indicated earlier in this section various phases of the analytical and laboratory studies carried out during the Penn State salt cavern study have been presented in recent papers. The latter part of the current paper will consider a number of other aspects of these studies not presently available in the open-literature. These include details of the closed-form solutions developed for the calculation of time-dependent closure in cylindrical and spherical caverns, and various considerations relative to the evaluation of creep parameters for salt.

CALCULATION OF TIME-DEPENDENT CLOSURE

Introduction

An outline of the various analytical studies carried out during the recent Penn State salt cavern project has been presented earlier in this paper. These have included a variety of finite element analyses (elastic, elastic-plastic and elastic-viscoplastic) and a closed-form analysis assuming that salt behaves as a rigid-viscoplastic material. Further details of the latter analysis will be included here.

In general, only a limited number of closed-form solutions suitable for calculation of time-dependent salt cavern closure are available in the literature. A few such solutions have been obtained for cylindrical caverns assuming various linear viscoelastic models (Gnirk and Johnson, 1964; Berry, 1967). The general applicability of linear viscoelasticity to salt, however, is doubtful due to the highly non-linear behavior of this material. More recently Krenk (1978) presented non-linear elastic solutions for spherical and cylindrical caverns subjected to internal pressure. He derived formuli for stress distribution, the extent of the non-linear zone and the volume reduction. A method to estimate creep convergence was also outlined. Klein (1980) presented a closed-form solution for the steady state stress distribution and closure rate for a shaft subjected to a non-uniform temperature distribution due to artificially freezing the ground near the shaft. He assumed a power law model for secondary creep.

Rigid-Viscoplastic Analysis

During the Penn State salt cavern study one of the writers (Chabannes, 1983) developed closed-form solutions for the analysis of creep closure of cylindrical and spherical caverns located in an infinite medium and subjected to internal pressure. The solutions obtained are applicable when it can be reasonably assumed that the in-situ state of stress prior to the creation of the cavern is approximately hydrostatic. Details of these closed-form solutions will be discussed in this section.

Steady state power law. A commonly used relationship between creep strain rate, stress and temperature in the steady state region is a form of the power law (Norton, 1929) in which the strain rate increases exponentially with temperature, namely:

$$\dot{\epsilon}_e^c = A \exp(-Q/RT)(\sigma_e/\sigma_c)^n \qquad (1)$$

where

$\dot{\epsilon}_e^c$ = effective creep strain rate,
A = experimentally determined constant,
Q = activation energy,
R = universal gas constant,
T = absolute temperature,
σ_e = von Mises effective stress,
σ_c = constant used to normalize stress, and
n = experimentally determined constant.

The von Mises effective stress is equal to the difference between the axial stress (σ) and the confining pressure (P_0) in a triaxial creep test, namely, ($\sigma - P_0$). The effective strain is simply equal to the axial strain if the assumption of incompressibility, Poisson's ratio equal to 0.5, is valid.

Analysis of creep data available for salt from the Tatum salt dome in terms of Equation 1 (Chabannes, 1983) yielded the parameters listed in Table 1.

TABLE 1

Values for temperature-dependent secondary creep model parameters for salt from the Tatum Salt Dome

Parameter*	Value
A	8.372×10^{-15} in./in. per second
n	4.29
Q	11550 calories/mole
R	1.987 calories/mole/°K
σ_c	1 psi

*See Equation 1.

Analysis outline. The closed-form analysis described by Chabannes (1983) was based on the elastic analogy for stationary creep. Here a state of stationary creep is defined as one where the space distribution of stress in the body remains constant (Hult, 1966). Furthermore, it was assumed that the total strains and the strain rates were small, i.e., second-order terms in these quantities as functions of the displacements and their derivatives can be neglected.

In developing the closed-form solutions a number of simplifying assumptions were necessary in order to make the problem of stationary creep tractable. These assumptions, which pertain to the macro-behavior of the material and have in the past been incorporated in a number of laws of creep and creep rupture, are as follows:

1. Elastic deformation is neglected
2. Plastic deformation with strain hardening
3. Viscous flow under constant stress.

Elastic deformation, as determined by Hooke's law, usually involves strains of the order of less than 10^{-4} for most materials under the conditions of interest in this study. Since total strains of the order of 10^{-3} or larger are involved, it is possible to neglect elastic deformations, since they are small when compared with the associated plastic or creep deformations. This assumption allows considerable simplification in the development of the closed-form solutions.

Plastic deformation (slip) with strain hardening is given by the plastic strain $\epsilon^{i,p}$. The plastic strain neglects velocity effects and is by definition irrecoverable. In principle the Bauschinger effect is also neglected.

Viscous flow under constant uniaxial stress (σ) is characteristic of the secondary (steady state) stage of creep, and it is by nature irrecoverable. The creep rate $\dot{\epsilon}^c$ during this stage proves to be strongly dependent on the stress and also on the prevailing temperature. The stress dependence of $\dot{\epsilon}^c$ may be presented in the form of a power law, namely:

$$\dot{\epsilon}^c = \dot{\epsilon}_c\,(\sigma/\sigma_c)^n \tag{2}$$

where $\dot{\epsilon}_c$ is the creep rate for which $\sigma = \sigma_c$, σ_c is an arbitrarily chosen constant stress level to normalize stress in the equation, and n is the stress exponent. For brevity, Equation 2 will be termed Norton's law (Norton, 1929). Other functions such as the hyperbolic sine have been used by some workers, but the power law was retained in the current study for several reasons. First, it is in reasonable agreement with experimental results obtained for salt in the stress range of interest. Second, it is simple in use and offers good limiting possibilities for $n = 1$ and $n = \infty$.

In general the term $\dot{\epsilon}_c$ in Equation 2 will be a function of temperature. In the current studies this temperature dependence was assumed to be of the form

$$\dot{\epsilon}_c = A\exp(-Q/RT) \tag{3}$$

where

$\dot{\epsilon}_c$ = creep rate at an absolute temperature T for stress level $\sigma = \sigma_c$,
A = a constant,
Q = activation energy, and
R = universal gas constant.

Substituting Equation 3 into Equation 2 gives

$$\dot{\epsilon}^c = A\exp(-Q/RT)(\sigma/\sigma_c)^n. \tag{4}$$

The combination of assumptions 1, 2 and 3, noted earlier in this section, gives rise to a "theory of total deformation" (Odqvist, 1966) which is particularly suitable for describing the behavior of salt. In practice, however, it is difficult to separate elastic and plastic deformations of salt. Furthermore, since a transient creep response is also present, in this analysis, the "theory of total deformation" requires some modification. In this modified theory, the instantaneous elastic strain ($\epsilon^{i,e}$), instantaneous plastic strain ($\epsilon^{i,p}$) and the transient (primary) creep strain ($\epsilon^{c,p}$) are lumped together to give

$$\epsilon^0 = \epsilon^{i,e} + \epsilon^{i,p} + \epsilon^{c,p} \tag{5}$$

and the total strain is given by

$$\epsilon = \epsilon^0 + \epsilon^c. \tag{6}$$

As a further simplification, the contribution from ϵ^0 to the total strain is neglected in developing the closed-form solutions presented later in this section. The closed-form solutions developed will, therefore, provide only lower bounds on deformation. In general, a material which is based on the assumption just outlined and other assumptions noted earlier could be briefly described as a nonlinear rigid-viscoplastic material.

In the case of a three-dimensional state of stress, the generalized form of Norton's law, which is based on the following five assumptions:

1. the material is incompressible
2. the creep rate is independent of a superimposed hydrostatic pressure

3. the existence of a flow potential (or coaxiality of the stress and strain rate tensors)
4. the material is isotropic and
5. Norton's law holds in the special case of uniaxial stress,

will be as follows:

$$\dot{\epsilon}_{ij}^{c} = \dot{\epsilon}_c(\sigma_e/\sigma_c)^n \, 3/2 \, \sigma_{ij}'/\sigma_e. \quad (7)$$

Based on the so-called "elastic analog" (Odqvist, 1966) for problems of stationary creep, Equation 7 together with the equations of equilibrium and the boundary conditions associated with the specific problem are sufficient to determine the required solution.

Solutions for cylindrical and spherical caverns. The detailed development of the closed-form solutions for the cylindrical and spherical caverns are presented in detail elsewhere (Chabannes, 1983); therefore, only the results of particular interest to the current study are included here.

Cylindrical cavern. A solution-mined cylindrical cavern in salt used for the storage of pressurized natural gas may be approximated by a thick-walled cylinder with an internal pressure (P_i) equal to the gas pressure and an external pressure (P_0) equal to the in-situ hydrostatic stress field. This is a problem involving a non-homogeneous, three-dimensional stress distribution. Figure 3 illustrates the associated geometry and loading conditions.

Based on the theory developed by Chabannes (1983), the distribution of effective stress in a thick-walled cylinder located in an infinite medium is given by

$$\sigma_e = \frac{\sqrt{3}\, a^{2/n}(P_0 - P_i)}{nr^{2/n}} \quad (8)$$

and the associated radial displacement rate is given by

$$w = -\dot{\epsilon}_c \left(\frac{\sqrt{3}}{2}\right)^{n+1} \left(\frac{2a^{2/n}(P_0 - P_i)}{n\sigma_c r^{2/n}}\right)^n r. \quad (9)$$

Spherical cavern. A solution-mined spherical cavern in salt used for the storage of pressurized natural gas may be approximated by a thick-walled sphere with internal pressure (P_i) equal to the gas pressure and external pressure (P_0) equal to the in-situ hydrostatic stress field. This, as in the case of a cylindrical cavern, is a problem solving a non-homogeneous, three-dimensional stress distribution. Figure 4 illustrates the associated geometry and loading conditions.

Based on the theory developed by Chabannes (1983) the distribution of effective stress in a thick-walled sphere located in an infinite medium is given by the following:

$$\sigma_e = \frac{3(P_0 - P_i)a^{3/n}}{2nr^{3/n}} \quad (10)$$

and the associated radial displacement rate is given by

$$w = -\frac{\dot{\epsilon}_c}{2}\left(\frac{3(P_0 - P_i)a^{3/n}}{2n\sigma_c r^{3/n}}\right)^n r. \quad (11)$$

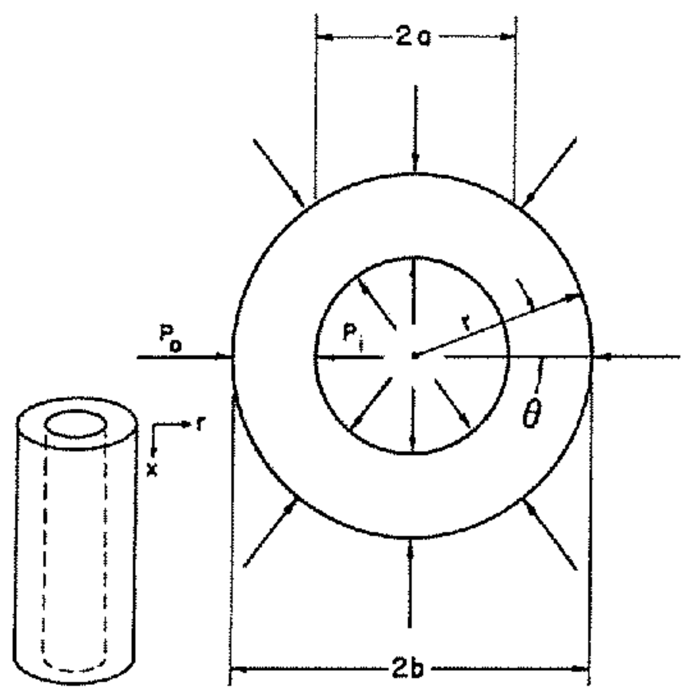
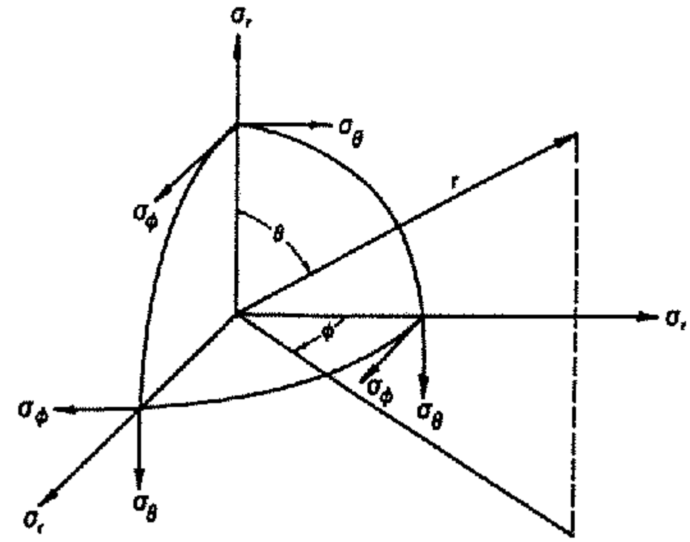
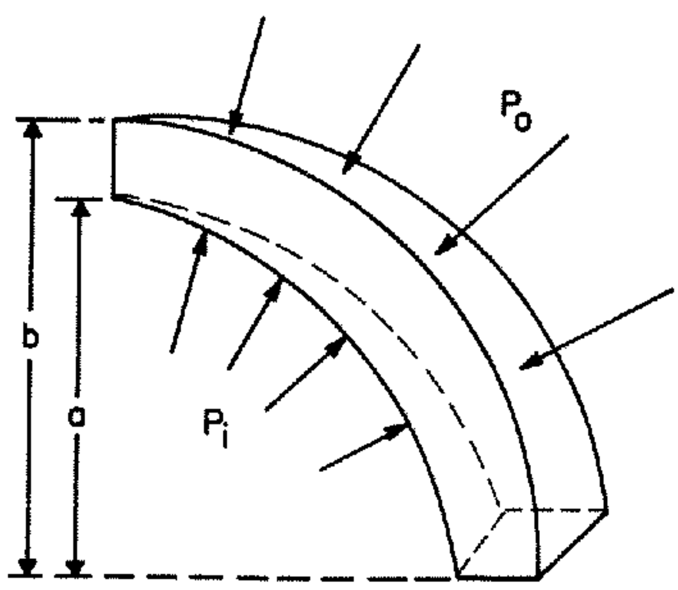


Figure 3. Geometry and loading conditions for a thick-walled cylinder subjected to internal and external pressure.



(A) Spherical coordinates



(B) Loading conditions

Figure 4. Geometry and loading conditions for a thick-walled sphere subjected to internal and external pressure.

Discussion. Closed-form solutions for evaluating the stationary stress and displacement-rate fields for cylindrical and spherical caverns subjected to internal pressure have been developed in this section. These solutions have been derived on the assumption that the caverns are located in an infinite media and that the in-situ far-field stress is hydrostatic.

In developing the closed-form solutions a large number of simplifying assumptions had to be made in order to make the solutions tractable. The applicability of the closed-form solutions is therefore limited. The primary shortcomings of these solutions include

1. The effects of transient creep on closure response cannot be studied
2. The evaluation of arbitrary cavern shapes cannot be undertaken
3. The influence of gravity loading cannot be treated for caverns having large dimensions
4. The influence of cavern spacing cannot be studied since the principal of superposition is not valid for non-linear problems
5. The effects of cyclic variations in cavern pressure cannot be investigated since the closed-form solutions are based on a total deformation theory. A method, such as the finite element technique, which is based on an incremental deformation theory, is required to provide more realistic predictions of behavior under these conditions.

In order to address the types of problems for which the closed-form solutions are not applicable, numerical techniques such as the finite element method must be utilized.

Application of Closed-Form Solutions

General. When a solution mined cavern is created in salt, a stress field is induced around the cavern which results in elastic and inelastic displacements as well as a time-dependent redistribution of stresses around the opening. A redistribution of stresses will occur every time there is a change in the internal pressure within the cavern. The extent of the time-dependent redistribution of stress, from the initial instantaneous stress distribution, will be dependent on a number of factors, namely:

1. the constitutive relation used to characterize the instantaneous response of the salt
2. the constitutive relation used to characterize the time-dependent response of the salt
3. the cavern shape and
4. the time period between changes in the internal pressure in the cavern as well as the rate of change of the internal pressure.

As discussed earlier a material that obeys a power law creep relation will always approach an asymptotic state of stress.

The distribution of stresses around an underground opening is an important means of evaluating stability. However, when dealing with a highly creep sensitive material such as salt, which can undergo very large strains without failing in a brittle manner, a more useful measure of stability is the total volume closure at a given time, or the volume closure rate experienced under a given set of conditions.

For simplicity, in the following discussions it is assumed that

1. For closed-form solutions a stationary state of stress exists around the cavern.
2. A hydrostatic state of stress exists sufficiently far away from the cavern.
3. The internal gas pressure in the cavern remains constant. This is equivalent to allowing the cavern pressure to bleed-off at the well head as the cavern experiences closure.
4. The temperature in the salt is assumed to be constant. This will not be the case during periods of injection or withdrawal of gas from the cavern.
5. Cavern closure prior to reaching a stationary state of stress is neglected in the closed-form solutions.

In this section use will be made of the closed-form relations developed for cylindrical and spherical caverns to investigate the mechanical behavior of such caverns under a variety of conditions. In particular, two aspects of cavern behavior, namely, volume closure and the final stationary distribution of effective stress, will be considered.

Influence of power law parameters. In this section it will be assumed that the creep strain rate is given by setting $\sigma_c = 1$ in Equation 1 (presented earlier), resulting in the following expression:

$$\dot{\epsilon}_e^c = A \exp(-Q/RT)\sigma_e^n \tag{12}$$

where

$\dot{\epsilon}_e^c$ = effective creep strain rate,
A, n = experimentally determined parameters,
Q = activation energy,
R = universal gas constant,
T = absolute temperature and
σ_e = von Mises effective stress.

The radial closure rate for cylindrical and spherical caverns may be readily obtained from Equations 9 and 11 by setting r = a and substituting for $\dot{\epsilon}_c$ in terms of Equation 3, giving, respectively,

$$(\dot{w}_a)_c = -A \exp\left(-\frac{Q}{RT}\right)\left(\frac{\sqrt{3}}{2}\right)^{n+1} \times \left(\frac{2(P_0 - P_i)}{n\sigma_c}\right)^n a \tag{13}$$

$$(w_a)_s = -\frac{A}{2}\exp\left(-\frac{Q}{RT}\right) \times \left(\frac{3(P_0 - P_i)}{2n\sigma_c}\right)^n a. \quad (14)$$

Now it may be easily shown that the percentage volume closure after a time t for a cylindrical and spherical cavern are as follows:

$$(\Delta V/V)_c = \left[\frac{200(w_a)_c}{a}\right] t \quad (15)$$

and

$$(\Delta V/V)_s = \left[\frac{300(w_a)_s}{a}\right] t. \quad (16)$$

Finally, substituting in Equations 15 and 16 for $(w_a)_c$ and $(w_a)_s$ from Equations 13 and 14, the following equations are obtained:

$$(\Delta V/V)_c = -200A\exp\left(-\frac{Q}{RT}\right)\left(\frac{\sqrt{3}}{2}\right)^{n+1} \times \left(\frac{2(P_0 - P_i)}{n\sigma_c}\right)^n t \quad (17)$$

and

$$(\Delta V/V)_s = -150A\exp\left(-\frac{Q}{RT}\right) \times \left(\frac{3(P_0 - P_i)}{2n\sigma_c}\right)^n t \quad (18)$$

where

- A, Q, n = parameters associated with the creep law used in the current study,
- T = absolute temperature of the cavern structure (salt) in degrees Kelvin,
- P_0 = in-situ hydrostatic stress field in psi (equivalent to approximately 1.0 psi/foot of depth),
- P_i = internal cavern pressure in psi,
- t = total duration of time for which the closure estimate is required in seconds, and
- R and σ_c = constants (normally equal to 1.0).

The expressions for the final stationary distribution of effective stress for cylindrical and spherical caverns, given earlier, are respectively:

$$(\sigma_e)_c = \frac{\sqrt{3}\, a^{2/n}(P_0 - P_i)}{n r^{2/n}} \quad (19)$$

$$(\sigma_e)_s = \frac{3(P_0 - P_i)a^{3/n}}{2n r^{3/n}} \quad (20)$$

Using the preceding equations it was possible to study the influence of the various power law parameters (i.e., A, Q, and n) on both the cavern closure and the final stationary distribution of effective stress closure and to study the influence of temperature and cavern shape on cavern closure.

Influence of Leading Constant (A). It is noted in Equations 13 and 14 that the constant A simply acts as a multiplier for the cavern displacement rate for both the cylindrical and spherical caverns. A two-fold increase in A will therefore result in a two-fold increase in the displacement rate and thus in the volume closure rate. Considering Equations 19 and 20, it is noted that there is no influence of A on the final stationary stress distribution around either cavern shape.

Influence of the Activation Energy (Q). The activation energy Q for a given salt type will generally be the parameter that is based on the least amount of data. This is primarily because most laboratory creep tests are run at room temperature with only a few being performed at evaluated temperatures. The activation energy plays an important role in the assessment of cavern closure, since it is used to either extrapolate or interpolate laboratory creep data at room temperature to the operating temperatures of the cavern under consideration.

An indication of the sensitivity of cavern closure to variations in the value of activation energy is shown in Figure 5. As would be expected, the volume closure is relatively sensitive to variations in this factor, since it is included in the exponential term of the creep relation (see Equation 12). As noted from Equations 19 and 20 the activation energy, however, has no influence on the final stationary stress distribution around a cavern.

Influence of Stress Exponent (n). A survey of the literature indicates that the value of the creep parameter n for salt may typically range from 2.7 to 5.5 (Hedley, 1967; Obert, 1964; Thompson and Ripperger, 1964; Heard, 1972). In this current study values of n ranging from 1 to 6 have been considered. It is possible that the value of n for a specific salt could be outside this range; however, the results of the present study are considered sufficient to bring out the influence of this factor.

Figure 6 shows the influence of n on the maximum final stationary effective stress at the surface of both a cylindrical and a spherical cavern. It is noted that as n increases, the final value of the maximum effective stress acting at the cavern surface decreases. Furthermore, a spherical cavern will have a lower value of maximum effective stress than a cylindrical cavern for a given value of n. This is to be expected because of the greater three-dimensional "arching" existing around a spherical cavern (Aiyer, 1969).

Figure 7 shows the influence of n on the distribution of the effective stress for a cylindrical and spherical cavern. In this figure, n = 1 corresponds to the distribution for an incompressible elastic material. It is interesting to note that the higher the value of n the lower the maxi-

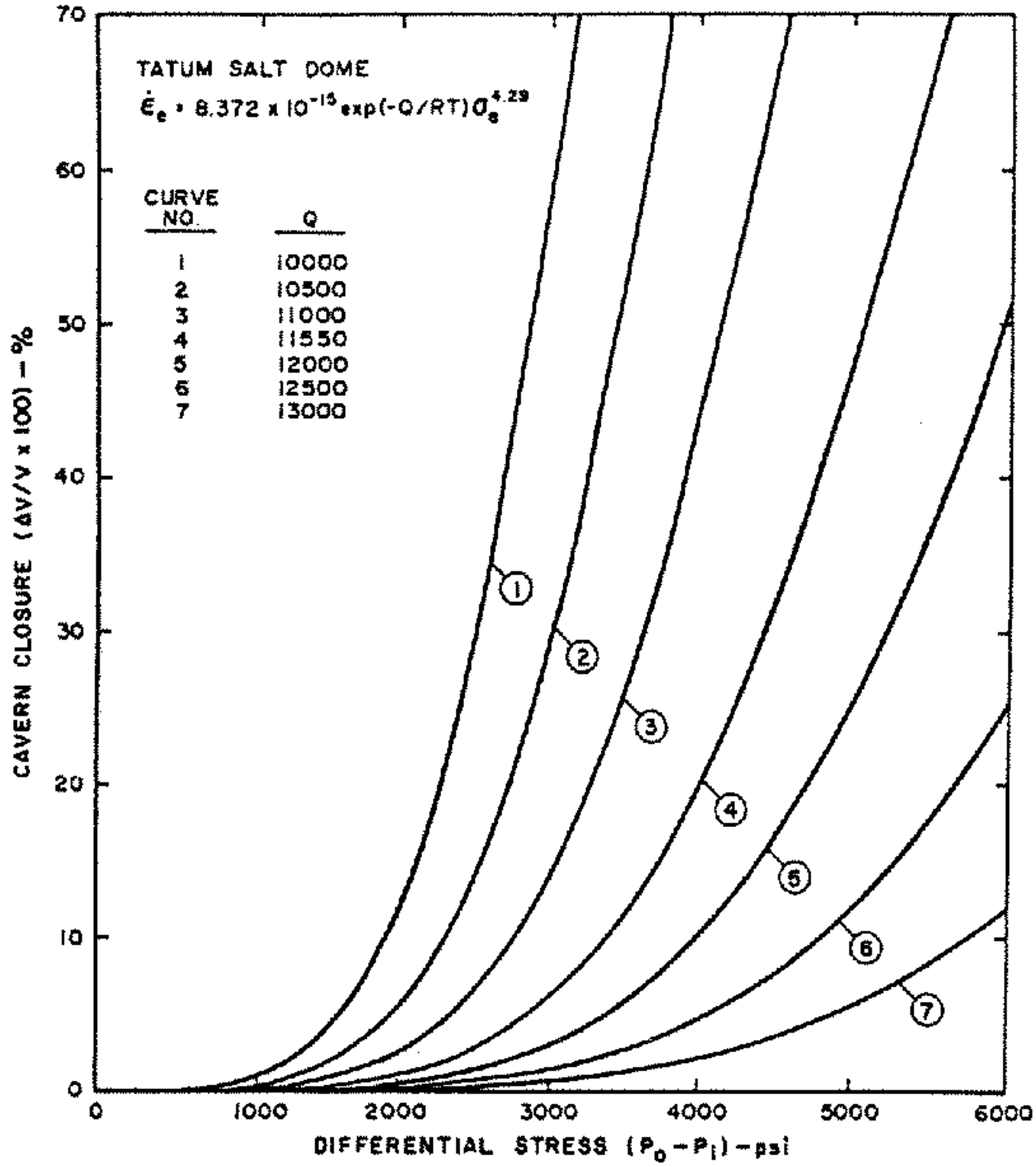


Figure 5. Influence of activation energy (Q) on volume closure versus differential stress for a cylindrical cavern after 200 days at a temperature of 120°F. (Based on closed-form solution; the associated strain rate equation is shown in the top lefthand corner of the figure.)

mum effective stress at the cavern surface. However, away from the cavern the effective stress appears to increase with increasing values of n. In other words, the higher the value of n the more load is transferred farther out from the cavern. Figure 7 also shows that for a given value of n the effective stress is not only lower for a spherical cavern at the cavern surface but it drops off with distance much faster and to a lower level at a given point than for a cylindrical cavern. Therefore, not only is the effective stress lower but the zone of salt which experiences a significant amount of creep is smaller for a spherical cavern. It should be noted, however, that even though the effective stress decreases as n increases, this does not necessarily indicate that the associated volume closure will be less.

Figure 8 shows the influence of n on the volume closure of a cylindrical and spherical cavern using values for the leading coefficient A and activation energy Q given earlier in Table 1 for domal salt from the Tatum Salt Dome. It is evident that an increase in the stress exponent n will result in an increase in volume closure, assuming the values for the other material power law parameters remain constant.

Influence of Temperature (T). The temperature in the salt surrounding a gas storage cavern is primarily a function of the natural geothermal gradient plus any induced

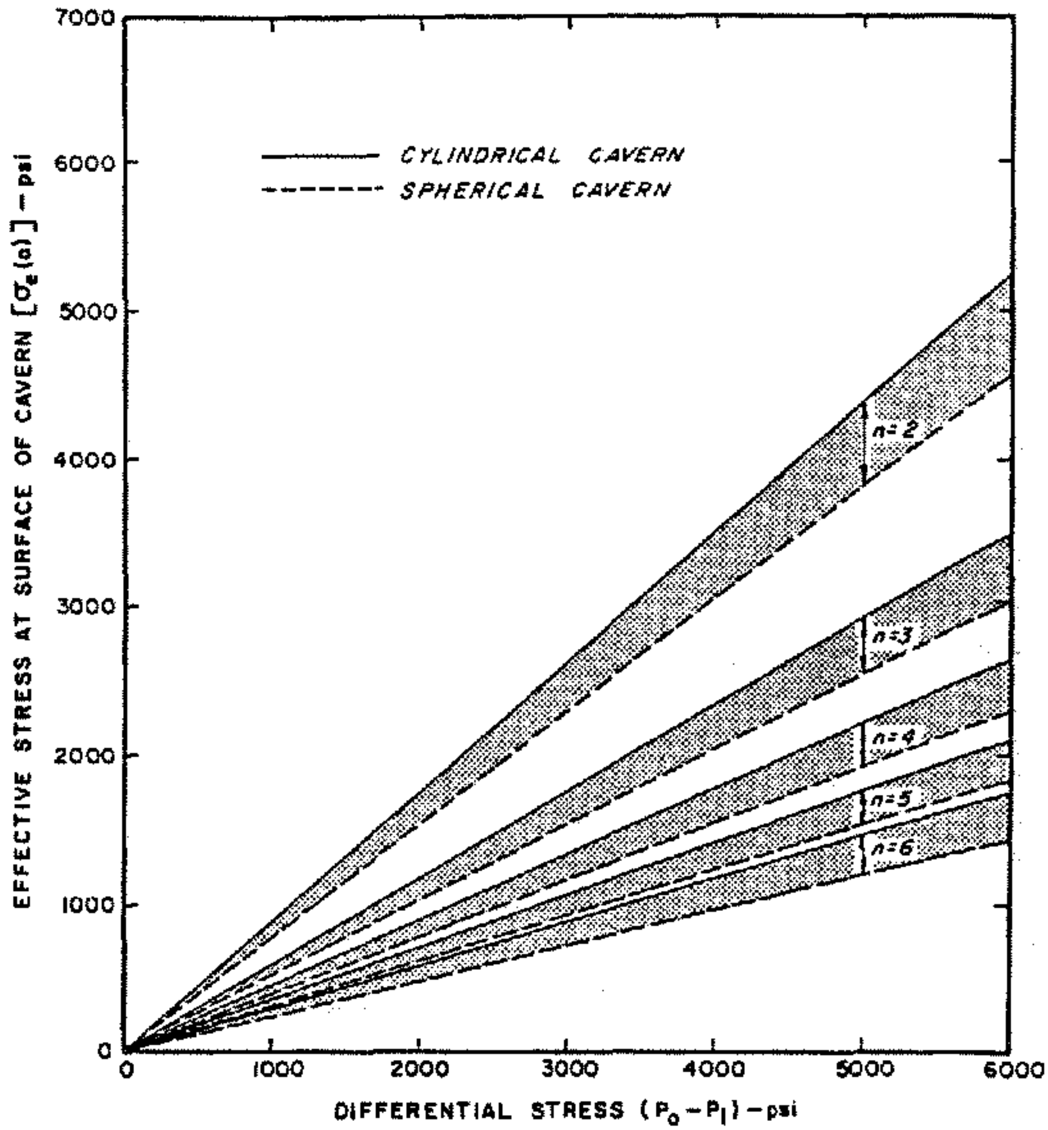


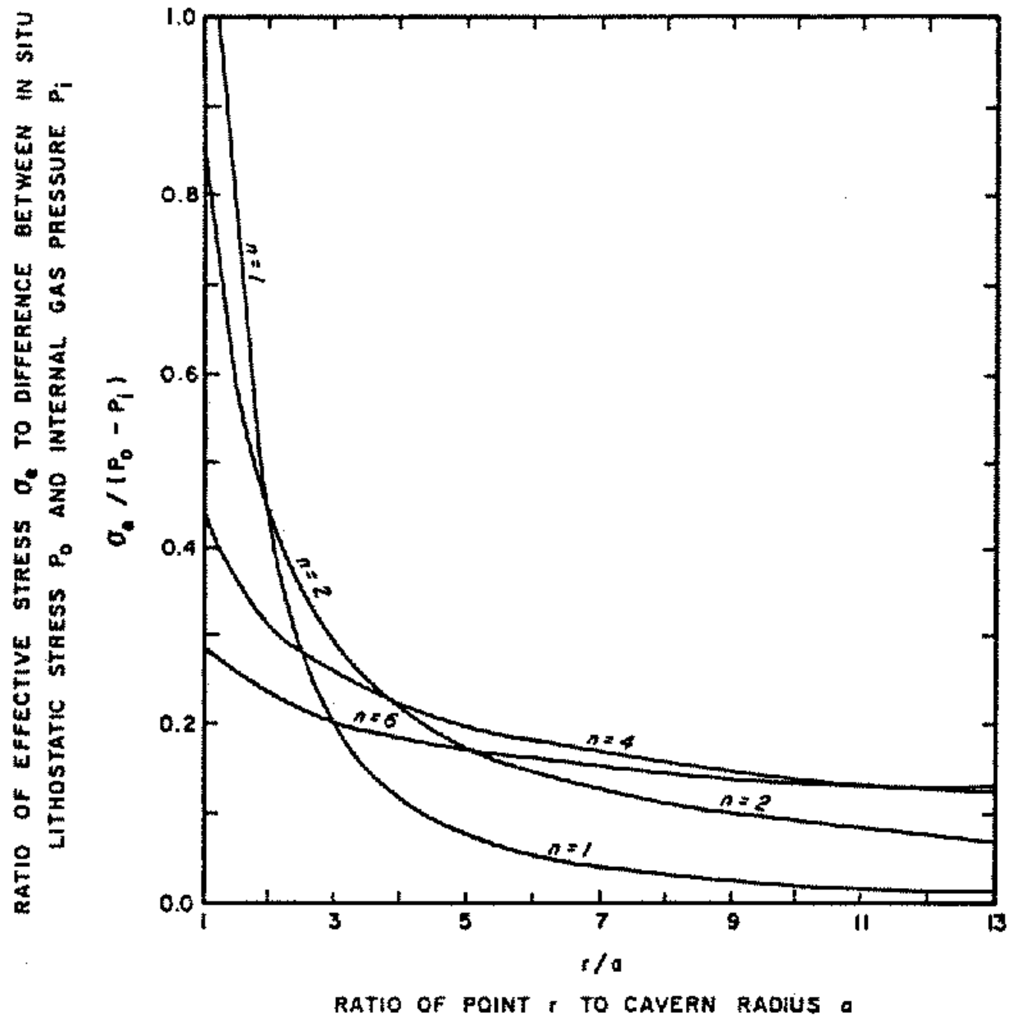
Figure 6. Influence of stress exponent (n) on the maximum final stationary effective stress at the surface of a cylindrical and spherical cavern over a range of differential stress. (Based on closed-form solutions.)

changes in temperature due to the injection or withdrawal of gas from the cavern. Based on a specified form of the power law (Tatum Salt Dome data), Figure 9 shows the influence of temperature on the volume closure of a cylindrical and spherical cavern assuming a constant temperature exists throughout the salt. This figure illustrates that temperature has a very significant influence on cavern volume closure and that for a given temperature a spherical cavern has superior closure characteristics.

A temperature of 160°F would not be unusual for the salt surrounding a cavern located at 6000 feet below the surface. This fact clearly points out the advantage of locating gas storage caverns at as shallow a depth as possible to avoid excessive amounts of volume closure caused by a high in-situ salt temperature and the associated accelerated creep strains. Furthermore, the importance in design calculations of using a creep law based on data appropriate to the range of temperatures anticipated is clearly shown.

Influence of cavern shape. In order to evaluate the influence of cavern shape on the distribution of effective stress, data presented earlier in Figure 7 were replotted. Figure 10 shows the influence of cavern shape on the distribution of effective stress for stress exponents of 2, 4 and 6, respectively. As pointed out earlier, for a specific value of n not only is the peak effective stress lower for the spherical cavern but the effective stress also drops off faster and to a lower value with increasing distance from the cavern.

Based on the creep data from the Tatum Dome (Table



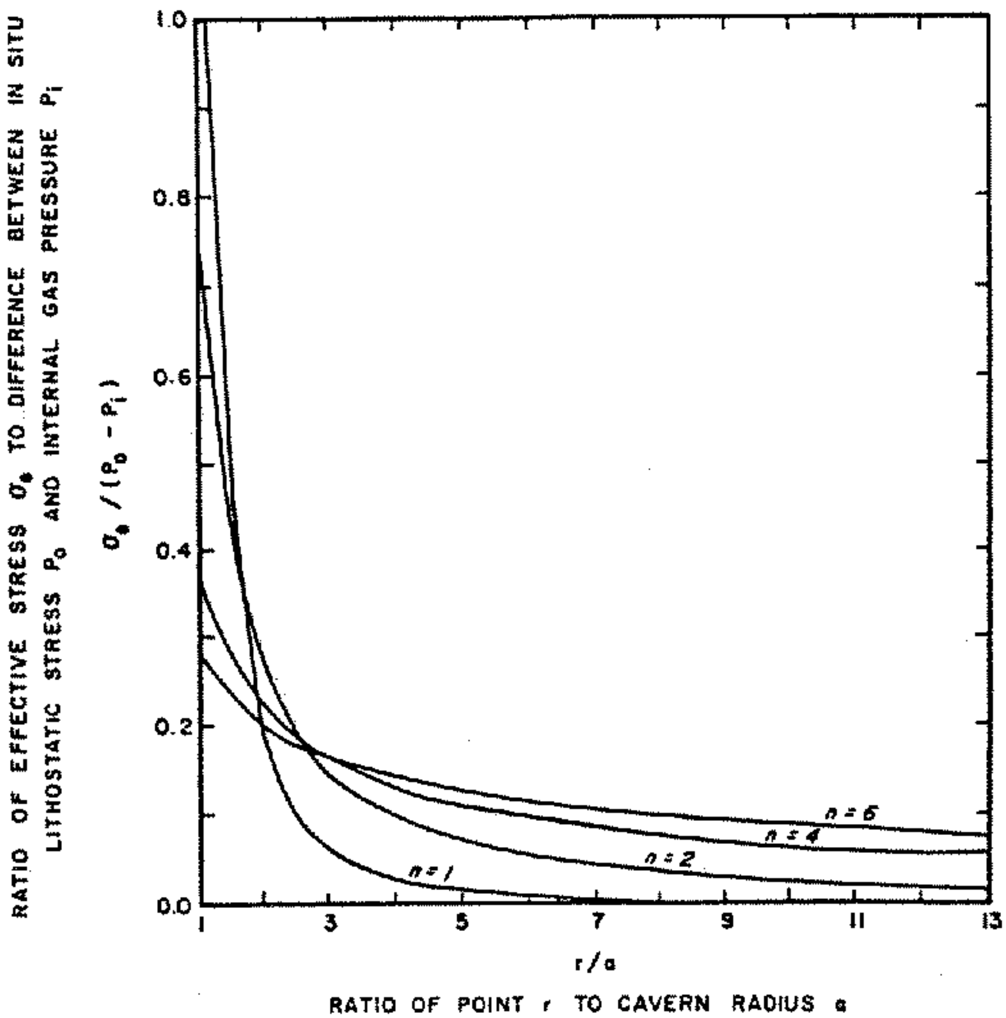
(A) Cylindrical cavern

Figure 7. Influence of the stress exponent (n) on the final stationary distribution of effective stress for cylindrical and spherical caverns. (Based on closed-form solutions.)

1) and the closed-form solutions (Equations 17 and 18), Figure 11 illustrates the influence of cavern shape on volume closure. The figure clearly illustrates the superior closure characteristics of a spherical cavern as compared to a cylindrical one.

Figure 12 illustrates the variation of cavern closure with time for the cylindrical and spherical closed-form solutions. The data presented is based on a cavern depth of 3000 feet, internal pressure of 1000 psi, in-situ temperature of 110°F and creep characteristics of the salt as listed earlier in Table 1. It is important to note that the closed-form data presented in Figure 12 differ from that presented earlier in this section. Firstly, they are associated with a temperature of 110°F rather than 120°F. Secondly, the caverns are not assumed to be located in an infinite medium but rather are considered as a thick-walled cylinder and a thick-walled sphere. In both cases the ratio of outer radius to inner radius (b/a) were selected to correspond to those of the equivalent finite element model, as noted in the top lefthand corner of Figure 12. Further details in regard to the calculation of closed-form response under the above conditions are presented elsewhere (Chabannes, 1983).

Figure 12 also includes data for a tapered cylindrical cavern (TCC) and a spherical cavern (SC) computed using the finite element method. Further details in regard to the finite element techniques employed and a detailed description of the models used for these cavern shapes are given elsewhere (Chabannes, 1983; Hardy, 1982B). Figure 12 clearly indicates that the closed-form solutions provide a lower bound to the results obtained by the finite element method when the cavern shape and boundary conditions are similar. This is to be expected, since the closed-form solutions do not account for the transient



(B) Spherical cavern

Figure 7. *(continued)*

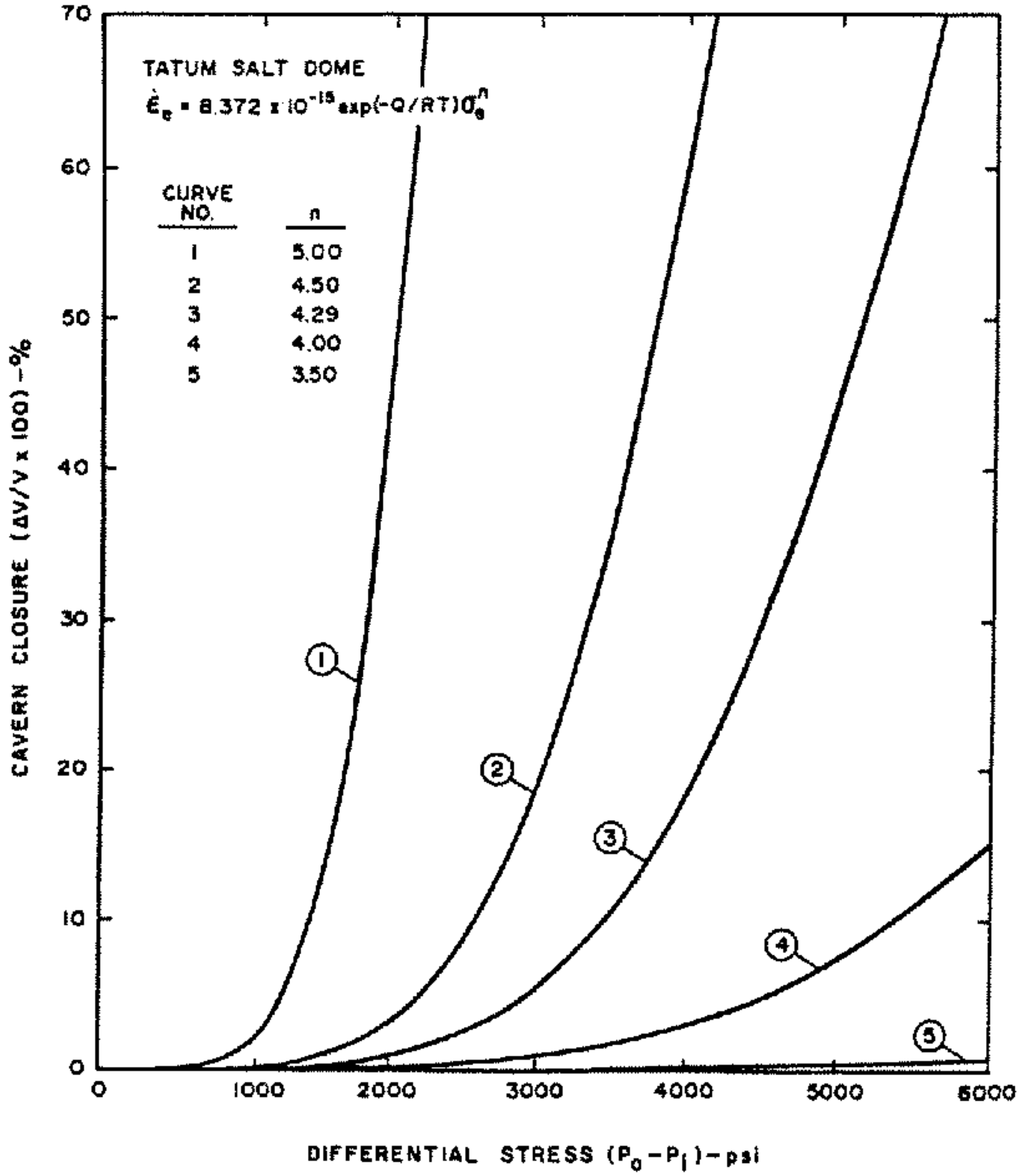
structural response that occurs during the time period when the stresses are relaxing from the initial elastic distribution to the final stationary distribution.

Discussion

Closed-form solutions, based on the assumption that salt behaves as a rigid-viscoplastic material, were developed for the analysis of the creep closure of cylindrical and spherical caverns subjected to internal gas pressure and an in-situ hydrostatic state of stress. These solutions may be used to evaluate the long-term closure characteristics of an underground cavern once a stationary state of stress has been reached. In the current study the closed-form solutions were used to investigate the influence of various factors on cavern closure and the stress state around the cavern, including the following:

1. the material properties (i.e., creep law parameters)
2. cavern shape
3. temperature
4. the difference between the internal gas pressure and the in-situ hydrostatic stress ($P_0 - P_i$).

The primary limitation of the closed-form solutions described in this paper is the fact that they do not account for the instantaneous and transient structural response of the salt. The cavern closure due to these responses can be significant, as was shown by the results of the finite element analyses presented in Figure 12. Nevertheless, such solutions, regardless of their innate limitations, do provide extremely useful data, and efforts should be continued toward the development of more realistic closed-form solutions.



(A) Cylindrical cavern

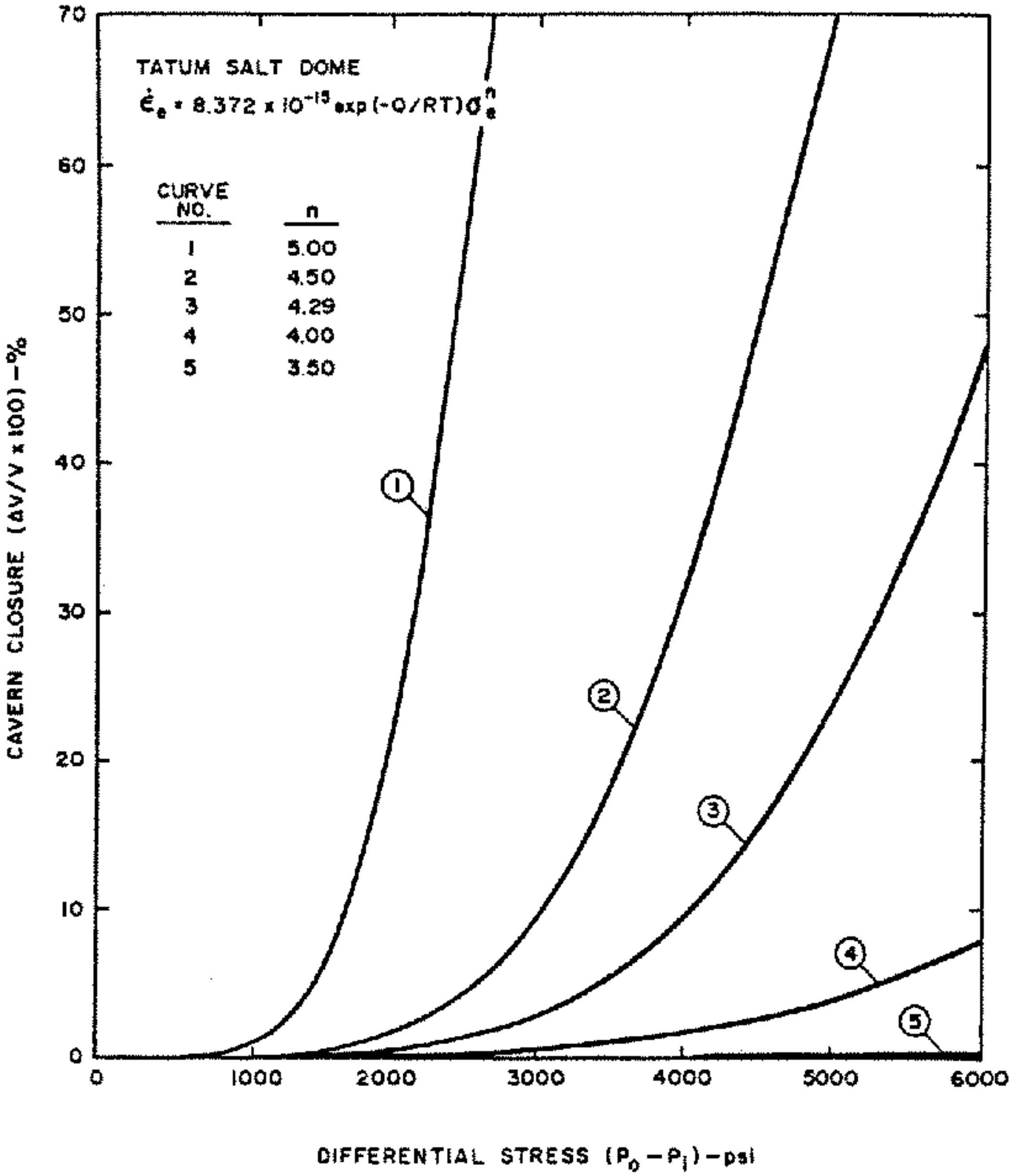
Figure 8. Influence of stress exponent (n) on volume closure versus differential stress for cylindrical and spherical caverns after 200 days at a temperature of 120°F. (Based on closed-form solutions; the associated strain rate equation is shown in the top lefthand corner of the figures.)

LABORATORY DETERMINATION OF CREEP PARAMETERS

Introduction

An outline of the various laboratory studies carried out during the recent Penn State salt cavern project has been presented earlier in this paper. Although a wide range of studies including those related to creep, yield strength, ultimate compressive and tensile strength, elastic moduli and acoustic emission have been carried out, the major effort has been associated with investigation of creep.

In recent years there have been many different creep laws formulated to predict the time-dependent response of salt. Even when using the same law, a wide range of values for the associated parameters have been determined for salt from different field sites. For example, Table 2 gives an indication of the range of values for such parameters for salt from different sites, and Figure 13 il-



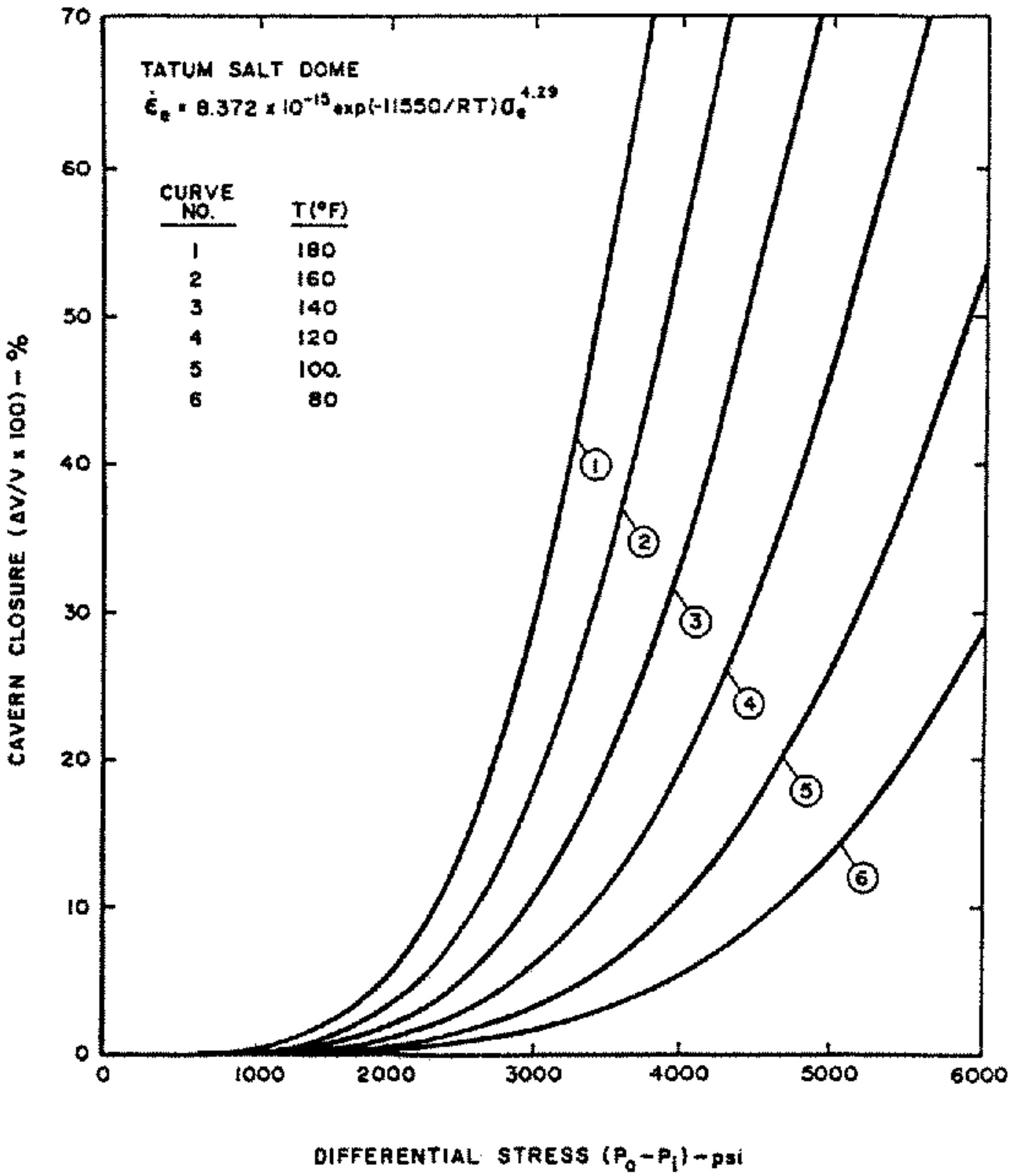
(B) Spherical cavern

Figure 8. *(continued)*

lustrates the extreme sensitivity of the cavern volume closure to variations in these parameters.

In the fall of 1981 the First Conference on the Mechanical Behavior of Salt was held at The Pennsylvania State University (Hardy and Langer, 1984). The objective of the conference was to bring together the expertise of various workers involved in the laboratory and field investigation of the mechanical behavior of salt and in the application of the results of such investigations to basic and applied problems in the general area of salt mechanics. A large proportion of the conference program was devoted to the topic of laboratory testing of salt, including a review of current testing methods and the development of models for describing the mechanical behavior of salt. Time was also provided for the discussion of various aspects of storage cavern design and stability monitoring. On the basis of the presented papers and the associated discussions it was clear that considerable additional research will be necessary before a thorough understanding of the creep behavior of salt is achieved.

The following sections will include a brief outline of the creep studies carried out as part of the Penn State salt



(A) Cylindrical cavern

Figure 9. Influence of temperature (T) on volume closure versus differential stress for cylindrical and spherical caverns after 200 days. (Based on closed-form solutions: the associated strain rate equation is shown in the top lefthand corner of the figures.)

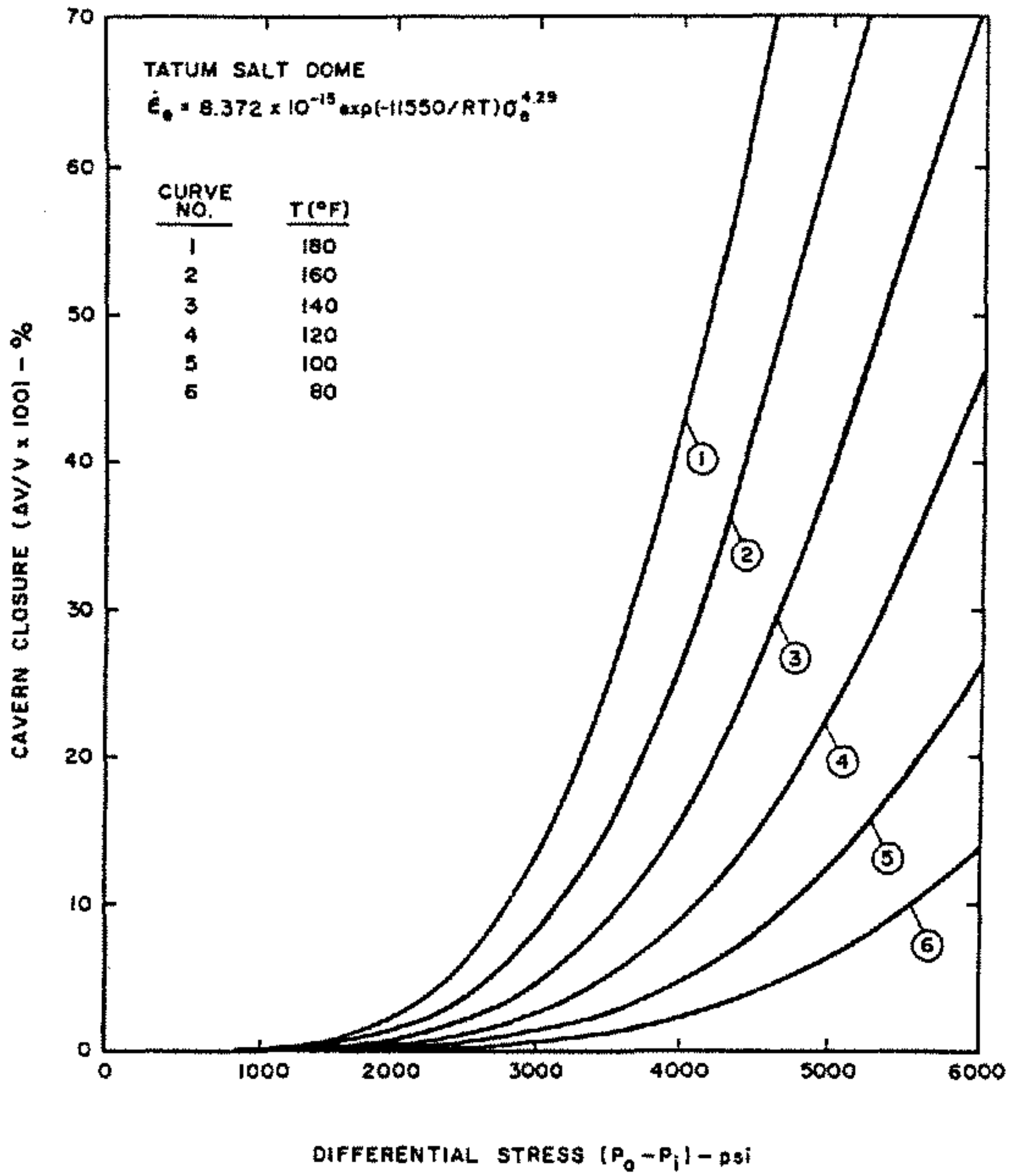
cavern project as well as a number of additional studies presently underway.

Outline of Creep Studies

In general, laboratory studies associated with the creep behavior of salt have involved a three-phase program, namely:

Phase I—This phase involved the evaluation of various methods of specimen preparation and strain instrumentation, modification of existing testing facilities and the completion of a series of short-term creep and acoustic emission studies on specimens of artificial salt. These studies were completed in 1977 and a detailed description of this phase is presented in a recent M.S. thesis (Roberts, 1981).

Phase II—The second phase of the creep study involved the development, construction, and calibration of creep testing facilities specifically designed for carrying out long-term creep experiments on salt. This included apparatus for conducting both uniaxial and triaxial creep



(B) Spherical cavern

Figure 9. *(continued)*

tests over periods of time up to three months or more. Following completion of the facilities a series of uniaxial creep tests were carried out on specimens of artificial salt and a number of types of natural salt. These studies were completed in early 1979 and a recent M.S. thesis (Bakhtar, 1979) presents a detailed description of this phase of the study.

Phase III—The final phase of the study was initiated early in 1979. It involved initially some redesign of the apparatus developed earlier in Phase II and the relocation of the overall creep testing facility. This was followed by the development of facilities for carrying out tests at elevated temperatures and the improvement of strain, load and temperature monitoring facilities. Subsequently, an extensive series of calibration studies were completed and creep tests under uniaxial and triaxial stress were carried out on a range of types of natural salt at room and elevated temperatures. Further details of these studies are presented in a recent Ph.D. thesis (Mrugala, 1984B).

During the Phase III creep studies a considerable number of very detailed creep tests were carried out on a vari-

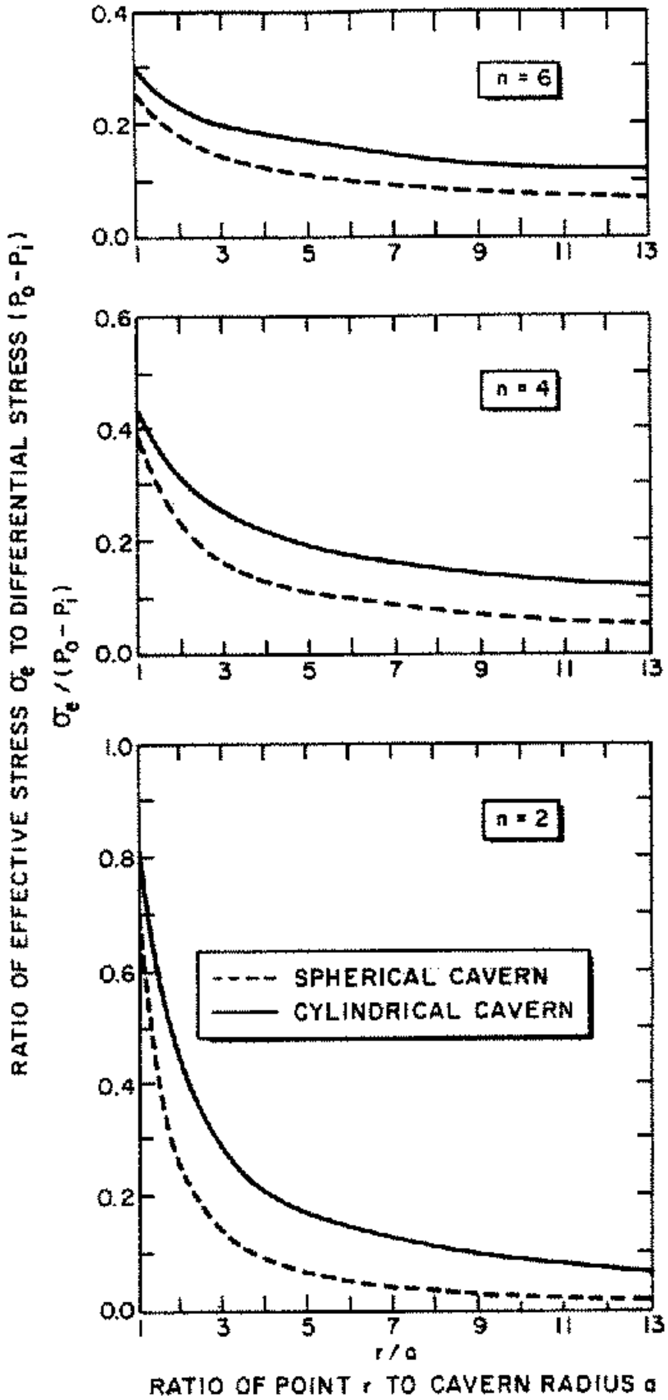


Figure 10. Influence of cavern shape on the stationary effective stress distribution for stress exponents n = 2, 4, and 6.

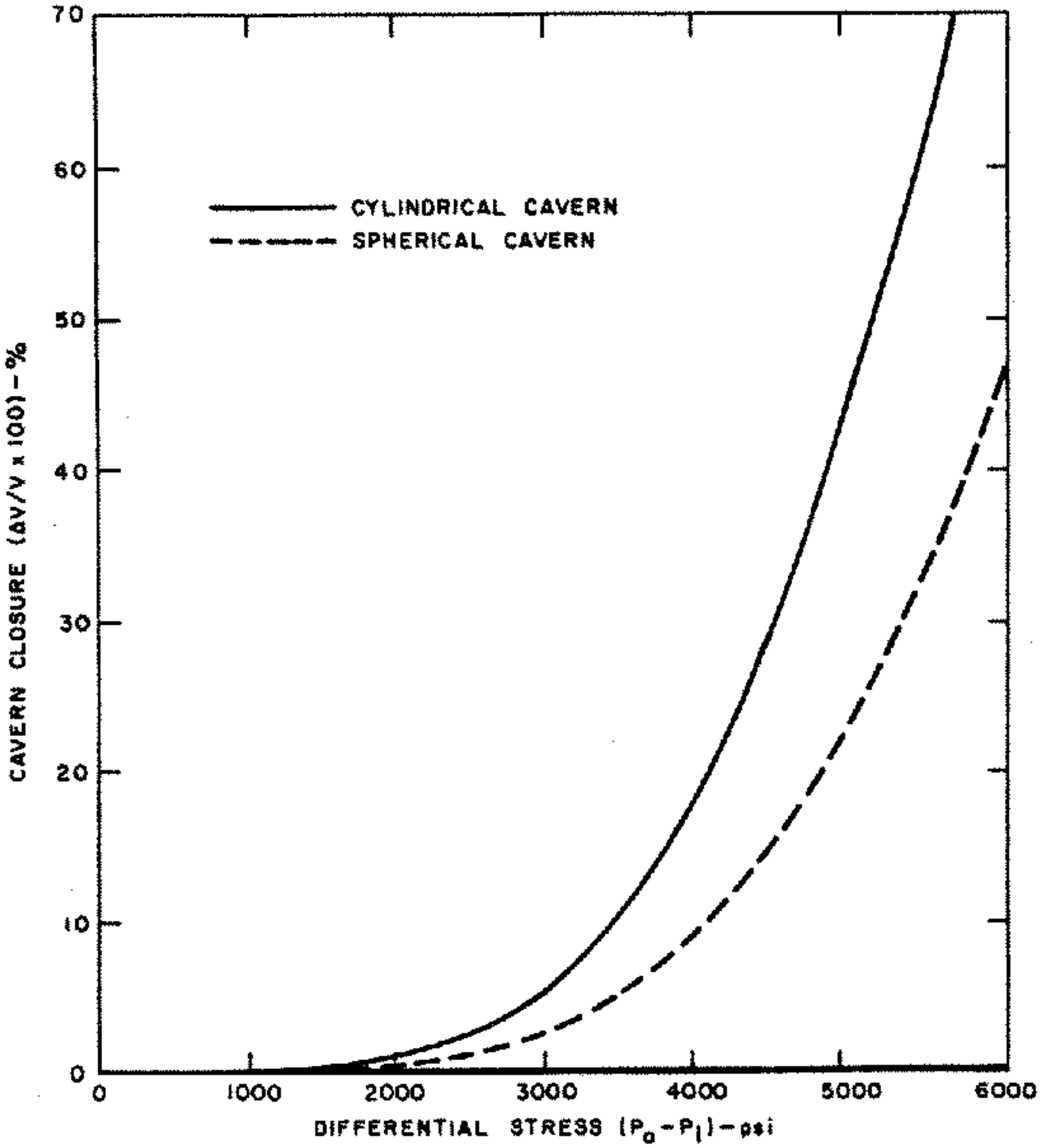


Figure 11. Influence of cavern shape on volume closure versus differential stress after 200 days at a temperature of 120°F. (Based on closed-form solutions and creep parameters for Tatum salt shown in Table 1.)

ety of types of natural salt. These tests were conducted in order to optimize experimental techniques and associated data processing techniques and to generate various creep parameters for use in later analytical studies. A block diagram of the deformation, strain and load monitoring facilities utilized during the Phase III uniaxial studies is shown in Figure 14. Similar facilities were developed for triaxial creep tests.

Eight major groups of creep tests were undertaken, including incremental and load-unload tests, long-term tests under room and elevated temperature conditions and a series of short-term comparative tests on six different types of salt. Data from these tests were fitted to a temperature-dependent secondary creep model (Equation 1) or to various forms of the generalized Burgers model. This model, shown in Figure 15, has the following mathematical form:

$$e_j = \frac{\Delta\sigma_j}{E_{n+1}} + \Delta\sigma_j \sum_{i=1}^{n} \frac{1}{E_i} \times [1 - \exp(-E_i t/N_i)] + \frac{\sigma_j t}{N_{n+1}} \qquad (19)$$

where

e_j = overall observed axial strain due to a stress increment $\Delta\sigma_j$,

t = time,
σ_j = new total stress,
n = the number of Kelvin-Voigt units in the model,

and the other factors are the various Burgers model parameters.

Figure 16 illustrates the axial creep strain versus time data for the first 58 days of a long-term (148 day) creep test on a specimen of type S12 salt (specimen S12L-01) tested at a uniaxial stress of 1450 psi and a temperature of 117°F. The solid curve is an n = 3 Burgers model fit to the data.

Detailed results of the various creep tests have been presented elsewhere (Hardy, 1982B); however, a brief outline of short-term comparative test series conducted on six different types of salt are presented in the next section.

Short-Term Comparative Tests

An unfortunate misconception amongst many researchers not directly involved in the evaluation of salt properties is that salt from various locations exhibits similar mechanical properties. The data presented earlier in Table 2 indicate that this is certainly not the case. To investigate this situation further a study was carried out to provide room temperature creep data for a wide range of different types of salt. During the study a series of short-term creep tests were carried out on small specimens of six different types of natural salt under uniaxial stress and room temperature conditions. All tests were of the incremental-type and involved two stress levels, each of which were maintained for a period of approximately seven days. Axial strain data was monitored using LVDT's.

Table 3 includes details on the origin, grain size and

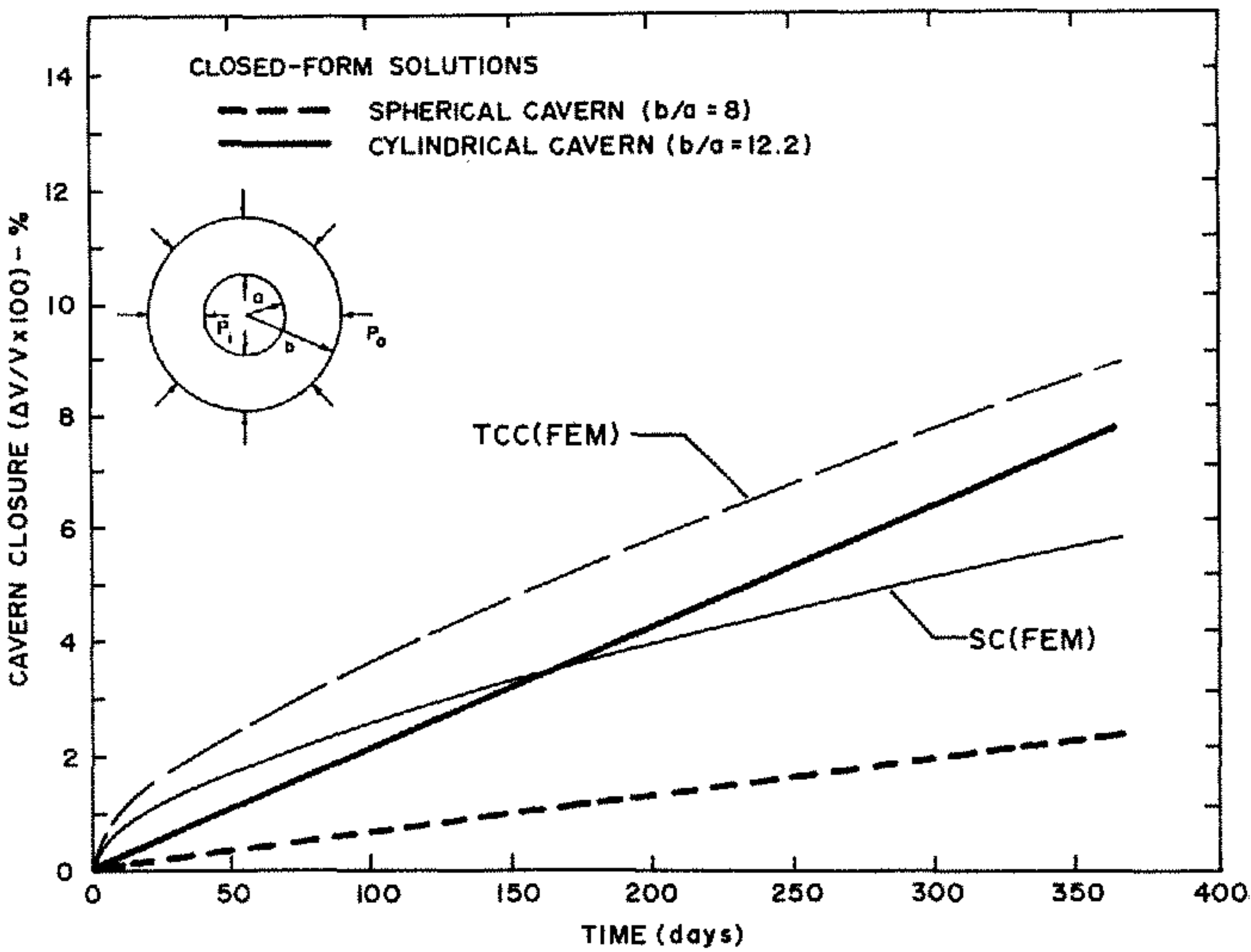


Figure 12. Influence of cavern shape on volume closure as a function of time for an internal gas pressure of 1000 psi, a depth of 3000 feet, and an in-situ temperature of 110°F. (Based on creep parameters for Tatum salt shown in Table 1. TCC (FEM) and SC (FEM) denote data for tapered cylindrical and spherical caverns computed using the finite element method).

TABLE 2

Range of values for parameters in temperature-dependent secondary creep model

Salt Type	Creep Model Parameters* A	Q	n	Location	Reference
1	3.72×10^{-17}	12000	4.90	S.E. New Mexico (2000 ft level)	Herrmann et al., 1980
2	9.98×10^{-17}	12000	4.90	S.E. New Mexico (2600 ft level)	Herrmann et al., 1980
3	3.27×10^{-17}	12900	5.00	Asse Anticline, West Germany	Herrmann et al., 1980
4	8.372×10^{-15}	11550	4.29	Tatum Salt Dome, Mississippi	(See Table 1)

*Parameters in temperature-dependent secondary creep model assuming $\sigma_c = 1$ psi. (See Equation 1 for further details.)

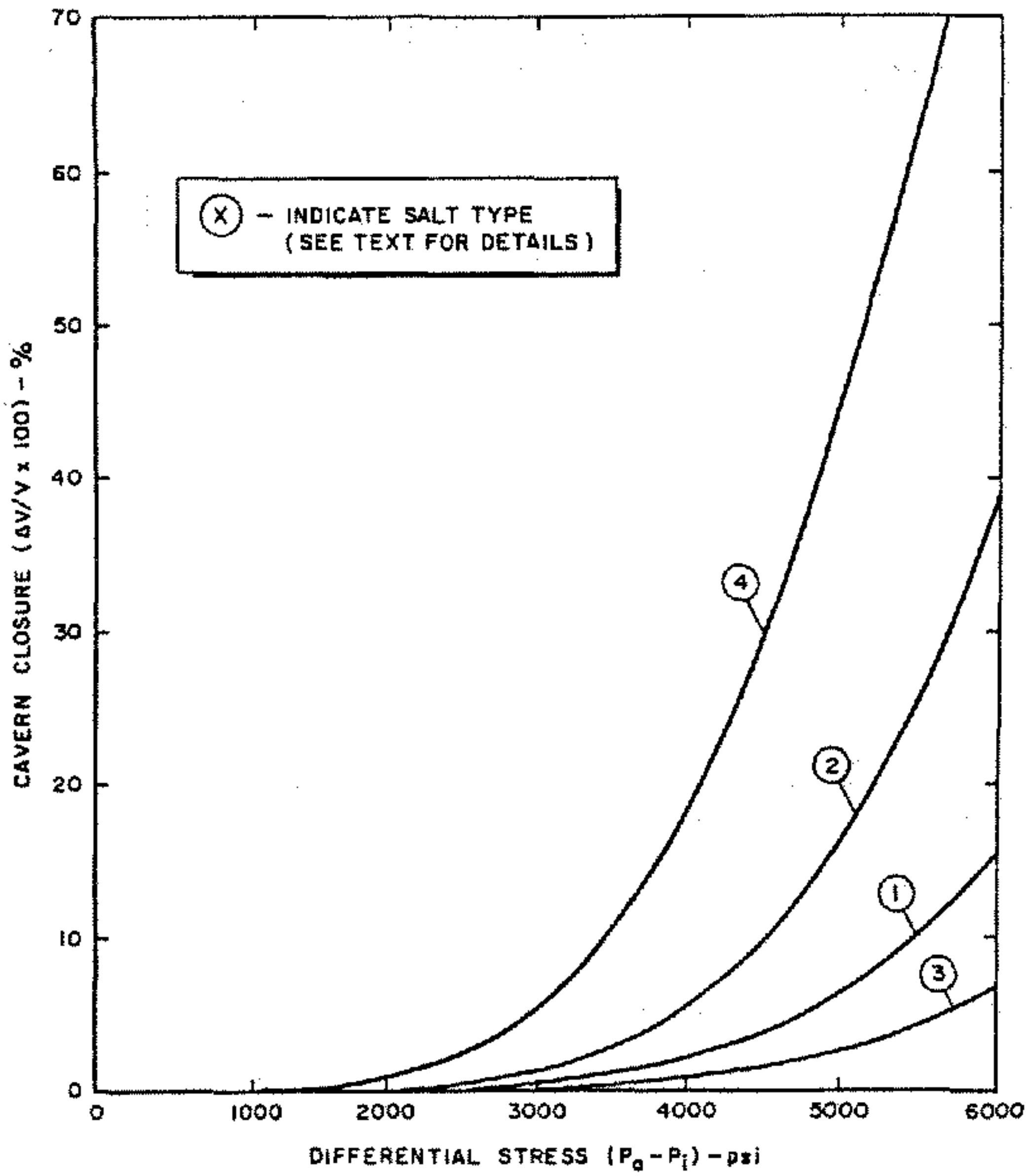


Figure 13. Influence of constitutive relation on volume closure versus differential stress for a cylindrical cavern after 200 days at a temperature of 120°F. (Based on closed-form solution given earlier in Equation 17 and parameters listed in Table 2.)

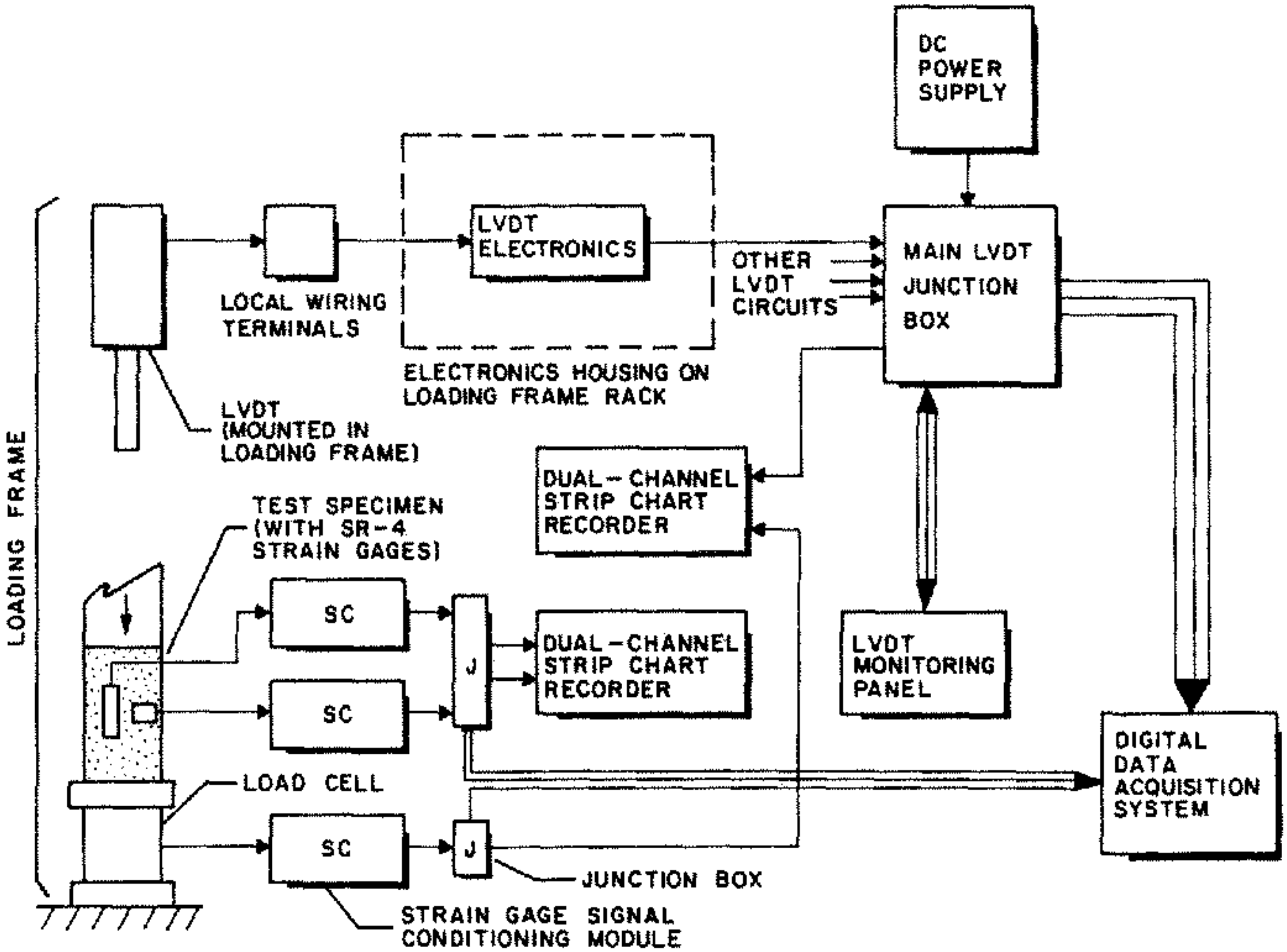


Figure 14. Block diagram of the monitoring system utilized in the phase III uniaxial creep studies.

bulk specific gravity of the six salt types tested in the study. Figure 17 shows the creep strain versus time curves obtained during the short-term comparative tests. These curves represent Burgers model fits to the experimental data, and with the exception of three cases, the curves shown are based on an $n = 3$ model.

The experimental data for the six different types of salt were analyzed in terms of the generalized Burgers model and the parameters (E's and N's) computed for models with $n = 1, 2,$ and 3. In all cases the $n = 1$ model was found to be unsatisfactory; however, in most cases an acceptable fit was obtained for either an $n = 2$ or $n = 3$ model. The model parameters associated with the latter fits are presented in Table 4, and in those cases where an acceptable fit was obtained for both $n = 2$ and $n = 3$ models, the parameters associated with both models are included and the most suitable indicated.

Based on a comparison of the data, there appears to be a considerable difference in the behavior of the six salt types investigated. Although a more detailed series of tests would be necessary in order to establish these differences in a quantitative manner, it is readily apparent (at least in terms of the test conditions utilized) that the creep characteristics of salt are highly site specific.

Current Research

The laboratory phase of the original American Gas Association sponsored salt cavern project was completed in 1981. A number of related laboratory studies, however, have continued and a brief outline of these are included here.

Mechanical Model Optimization. During the recent creep studies on salt, data for the most part was analyzed using equations based on various forms of the generalized Burgers mechanical model. In these cases the most suitable Burgers model and the associated model parameters were determined using a statistical program developed earlier (Hardy and Wang, 1969). More recently it was realized that in order to optimize the form of the Burgers model, or other appropriate model, a more objective data

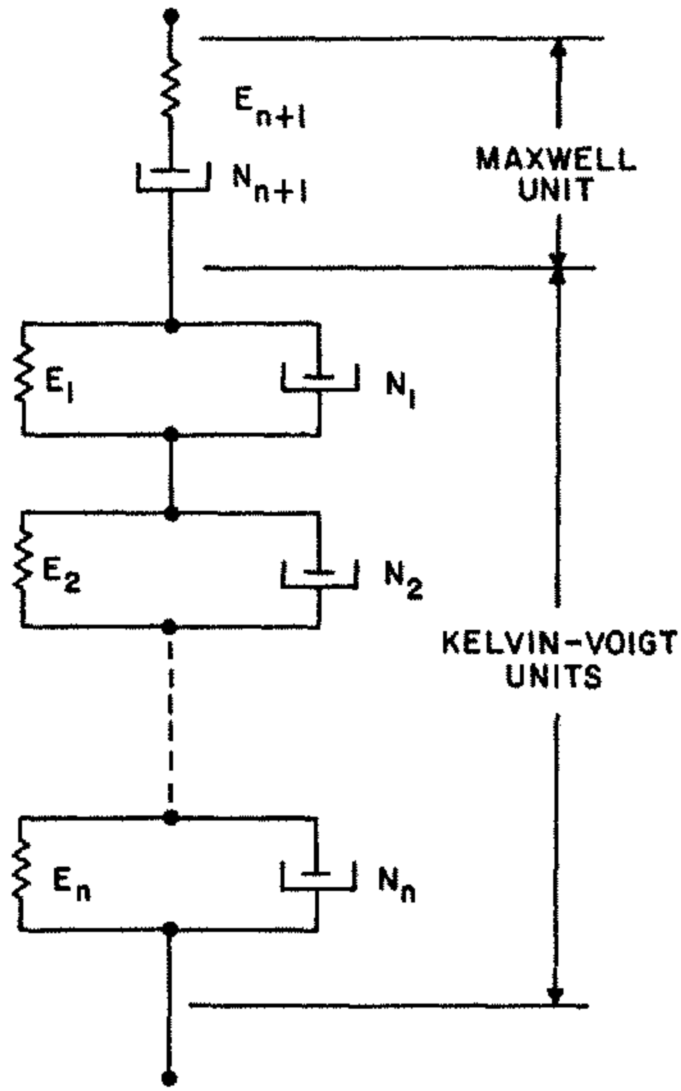


Figure 15. Generalized Burgers model.

analysis approach would be beneficial and that where possible, transverse as well as axial creep strain data should be utilized. On the basis of this need, studies were initiated early in 1981 to investigate suitable methods for Burgers model optimization. Preliminary studies in this regard were completed late in 1981 (Mrugala, 1984).

In these studies it was decided to consider the observed specimen behavior in terms of the associated shear (distortion) and dilatation (volume change) components. Figure 18 illustrates the most general form of the distortion and dilatation models utilized in the preliminary studies. It should be noted, however, that for the analysis of a specific set of creep data, various components of these models may be deleted.

During the analysis a suitable least-squares code known as NLIN2, based on an algorithm developed by Marquardt (1964), was used to fit the observed laboratory values of axial and transverse creep strain to equations developed on the basis of the distortion and dilation models shown in Figure 18. The computer program utilized in these studies was such that a relatively complex overall model could be assumed (e.g., the model shown in Figure 18); however, the analysis could be accomplished in a step-wise fashion utilizing only a limited number of the available model components. For one thing, the initial analysis could be carried out on the basis of a single elastic element (e.g., $2G_1$). The value computed for this parameter would then be used as an initial estimate for this parameter in the next step which would involve a more complex model. Using this procedure the model complexity (i.e., the number of parameters) used may be increased to the point that the fit of the model to the data does not improve, indicating that the model has become unnecessarily complicated.

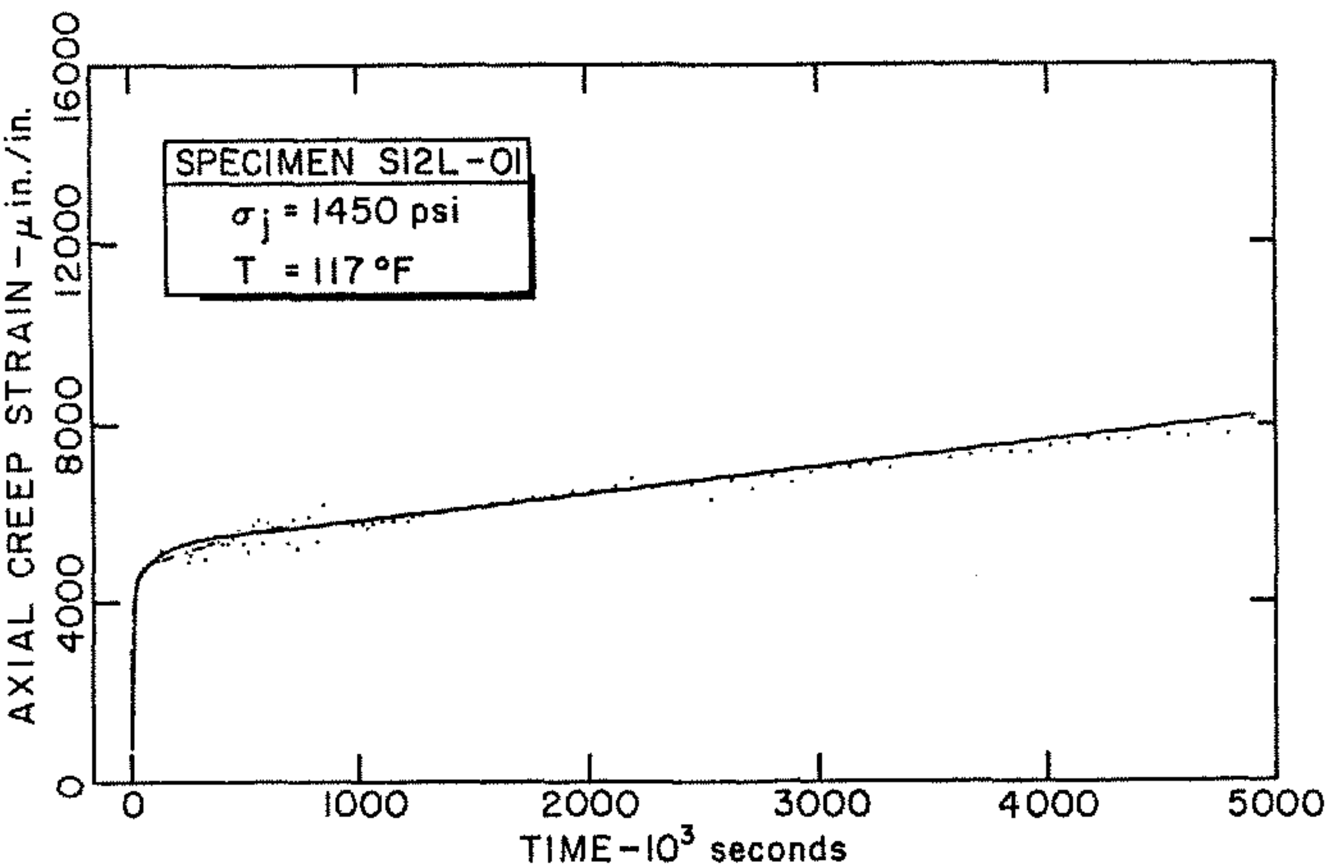


Figure 16. Axial creep strain versus time curve for the first 58 days of a 148 day long-term elevated temperature creep test on specimen S12L-01. (Natural salt type S12; test conducted at a uniaxial compressive stress of 1450 psi and a temperature of 117°F; curve is an n = 3 Burgers model fit to the data.)

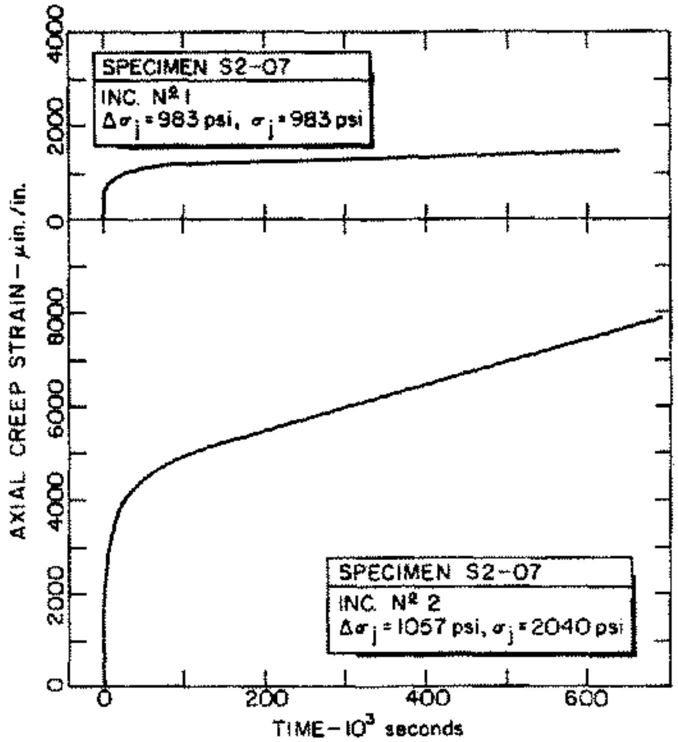
TABLE 3

Details of the origin, grain size and bulk specific gravity for the salt types studied during the short-term comparative tests

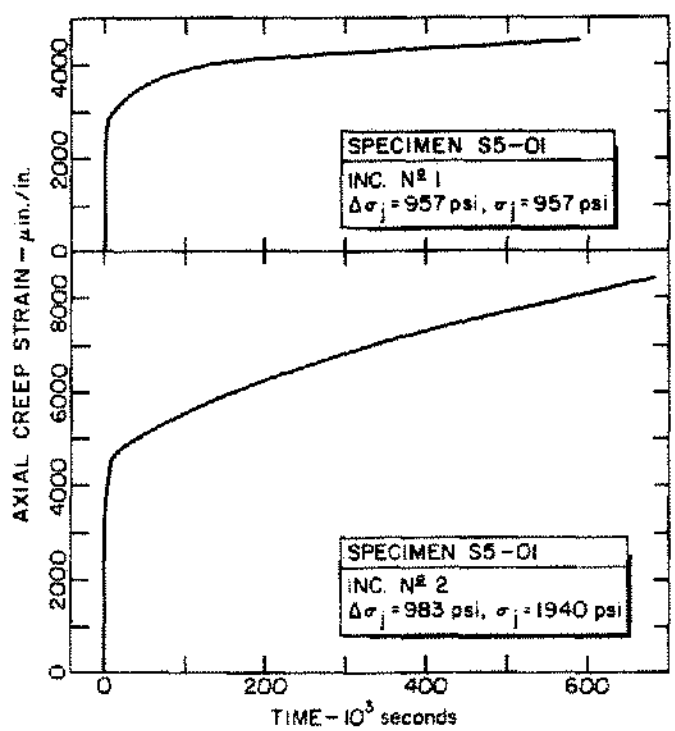
Salt Type	Origin	Grain Size—in. Range	Grain Size—in. Average	Mean Bulk Specific Gravity	Comments
S2	Bedded deposit	0.5–1.0	0.6	2.13	Clay impurities
S5	Dome	0.1–0.5	0.2	2.13	Very white High purity
S8	Unknown	0.1–0.3	0.1	2.15	Dark color
S10	Dome	0.1–0.2	0.2	2.14	—
S11	Bedded deposit	0.2–0.6	0.4	2.13	Grey to white impurity layers
S13	Dome	1.5–2.8	2.4	2.17	Large colorless grains Very pure

The results of the preliminary mechanical model optimization studies carried out during the latter part of 1981 clearly indicated that such optimization can greatly assist the researcher in selecting the most suitable model for analysis of laboratory creep data. In particular, these studies have indicated that more complex mechanical models do not necessarily lead to more precise values of the associated model parameters. Further studies in this area are planned for the future.

Effects of Cyclic Loading. A research study is presently underway to investigate the creep behavior of salt subjected to a variety of cyclic stress conditions. Salt caverns utilized for the storage of natural gas are subjected to pressures that vary over a wide range during a typical

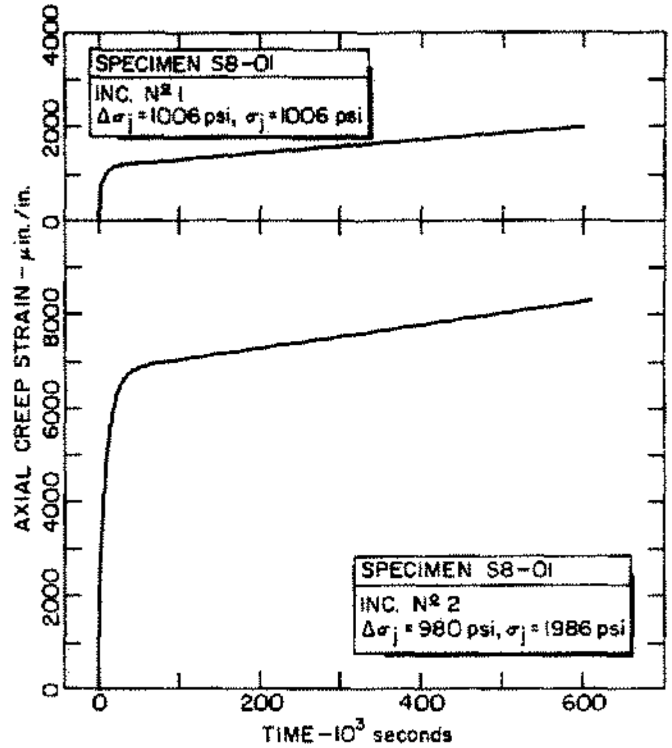


(A) Specimen S2-07

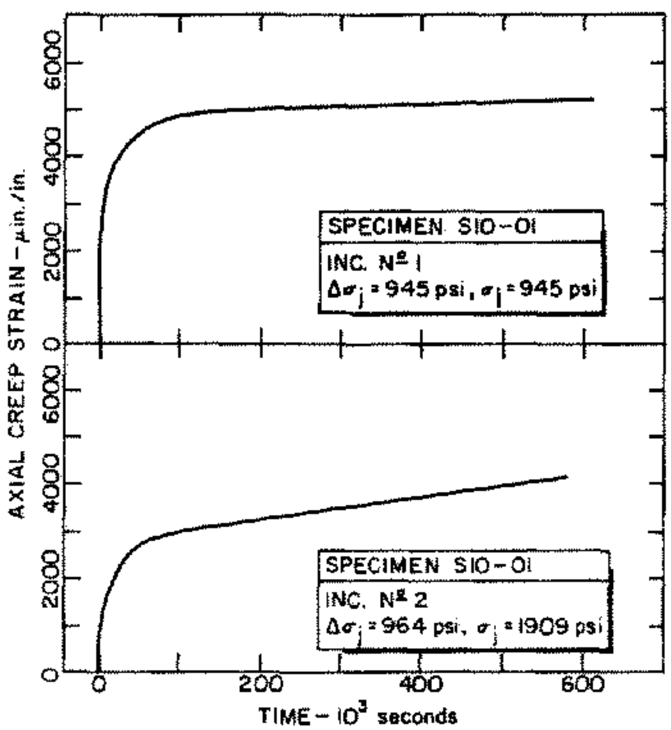


(B) Specimen S5-01

Figure 17. Axial creep strain versus time curves for specimens of natural salt tested during short-term comparative tests. (Curves shown are based on Burgers model fits to the experimental data, see Table 4 in regard to models utilized.)

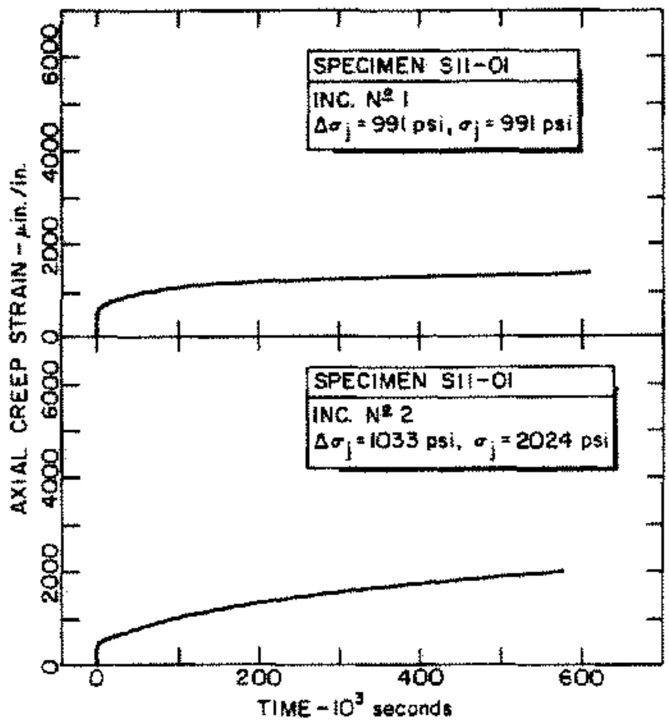


(C) Specimen S8-01

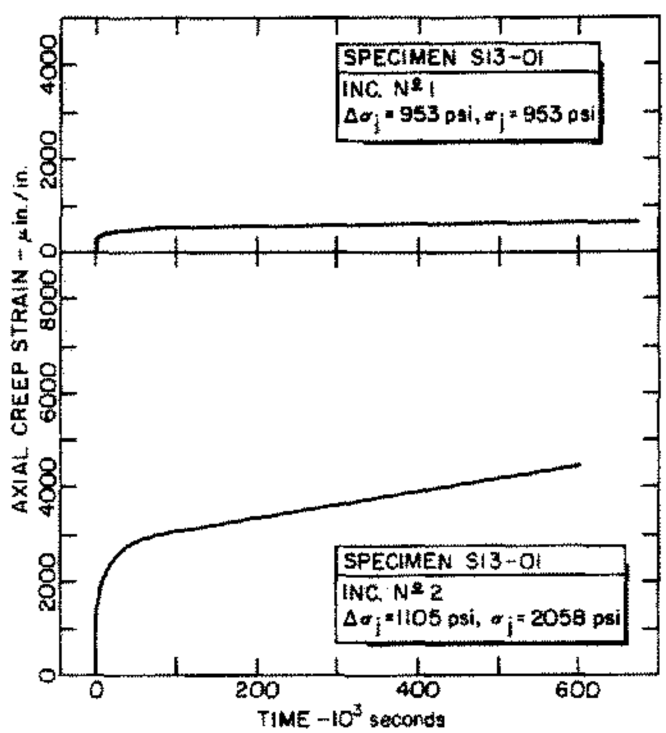


(D) Specimen S10-01

Figure 17. *(continued)*



(E) Specimen S11-01



(F) Specimen S13-01

Figure 17. *(continued)*

TABLE 4

Burgers model ($n = 2$ & 3) parameters for specimens of six different types of natural salt based on data obtained during short-term comparative tests under conditions of uniaxial compressive stress and room temperature

Specimen Number	Inc. No.*	$\Delta\sigma_1$† psi	σ_1 psi	n —	E_1 10^6 psi	N_1 10^9 psi-sec	E_2 10^6 psi	N_2 10^9 psi-sec	E_3 10^6 psi	N_3 10^9 psi-sec	E_4 10^6 psi	N_4 10^9 psi-sec
S2-07	1	983	983	2	1.65	0.21	1.53	25.25	0.41	1933.4	—	—
				3‡	2.69	0.15	2.87	2.77	1.80	41.5	0.41	2094
	2	1057	2040	3	0.62	0.06	0.60	3.68	0.74	25.0	1.22	401
S5-01	1	957	957	2	0.38	0.08	0.48	10.07	0.37	673.2	—	—
				3‡	0.60	0.05	0.59	1.20	0.67	33.8	0.37	968
	2	983	1940	3	0.37	0.05	0.41	1.63	0.60	110.0	0.64	544
S8-01	1	1006	1006	2‡	1.39	0.10	1.46	9.98	0.06	619.1	—	—
				3	3.43	1.68	1.05	0.68	2.87	102.4	0.06	850
	2	980	1986	3§	0.51	0.20	0.19	1.66	5.96	202.6	1.02	774
S10-01	1	945	945	3	0.52	0.12	0.68	2.66	0.51	17.3	0.13	1729
	2	964	1909	3§	1.33	0.54	0.49	9.71	9.15	317.3	1.63	766
S11-01	1	991	991	3	2.03	0.36	4.73	13.27	2.12	125.5	0.13	1960
	2	1033	2024	2	3.19	1.75	1.17	9.44	119.90	4208.8	1.11	1388
S13-01	1	953	953	2	2.93	0.42	3.27	203.15	1.24	4380.6	—	—
				3‡	3.96	0.27	5.80	18.88	4.79	162.2	1.25	3932
	2	1105	2058	2	0.56	0.15	0.58	10.21	2.11	640.0	—	—

*Load increment number.
†Parameters are those associated with Equation 19.
‡Most suitable Burgers model.
§Data validity suspect due to poor quality Burgers model fit.

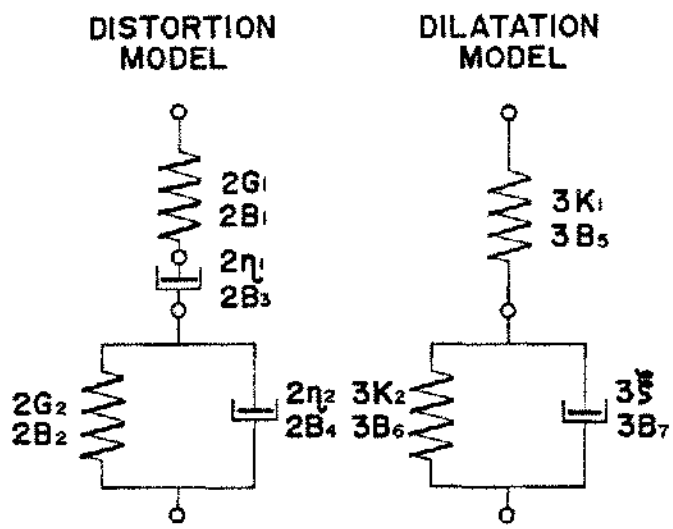


Figure 18. General form of the distortion and dilatation models used in preliminary studies. (G, K, and ξ terms represent the mechanical model parameters, and B terms represent the equivalent forms of the model parameters used in the associated statistical analysis.)

injection-withdrawal cycle. As a result, a theory is required to describe the mechanical behavior of salt subjected to similar conditions. No suitable theory at present exists, and until the necessary laboratory studies are conducted and the required theory developed, realistic analysis of cyclic cavern behavior will not be possible.

Effects of Specimen Size. In general it has been observed that under the same stress conditions larger test specimens exhibit a lower creep rate than smaller ones. At present the form of the associated "size effect" relationship is unknown, and caution must be exercised in comparing creep data obtained from different sized test specimens. Preliminary studies, utilizing acoustic emission techniques, are underway to investigate the role of dilatation and the effect of confinement on "size effect."

Discussion

As noted earlier in this section a variety of creep studies were undertaken during the recent salt cavern design project. Similar studies have also been underway at a number of major research organizations throughout the world. Salt is a complex time-dependent material and it is apparent that considerable research remains to be done before its behavior is well understood. At present a number of specialized studies are continuing at Penn State, including those associated with cyclic loading, specimen "size-effect" and model optimization.

GENERAL COMMENTS

The purpose of the preceding paper has been to briefly outline the recent salt cavern design project and to discuss a number of aspects of the associated laboratory and analytical studies not presently available in the open literature. It is important to note that in recent years extensive research on the mechanical properties of salt and the design of structures in this material has been underway relative to the underground storage of nuclear wastes. Unfortunately, although some of the results obtained from these studies are directly applicable to the design of salt caverns for the storage of liquids and gases, many of the problems associated with such storage are somewhat unique and still remain unsolved.

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