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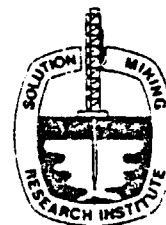
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DESIGN AND STABILITY MONITORING OF SALT CAVERNS*

by

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INTRODUCTION

For some 50 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, 1981), and during the last 10
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 wide range of
materials, including, crude oil and various refined petroleum products,
natural gas, compressed air (energy storage), and radioactive and chemical
wastes. As a result extensive research and industrial development in the
general area of salt cavern storage is presently underway in the U.S.A. and
elsewhere. At present such activities represent a major area of interest to
those involved in salt mechanics research.

Worldwide interest in the field of salt mechanics was clearly illus-
trated by the overwhelming success of the First Conference on the Mechanical
Behavior of Salt held at Penn State in early November of 1981 (Hardy and
Langer, 1982). This three day conference was attended by some 45 scientists

and engineers including participants from Canada, France, West Germany, The Netherlands, The United Kingdom, and the U.S.A.

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 seven 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. The present paper will include an outline of a number of the analytical and laboratory studies associated with this research, and a brief discussion of the application of microseismic techniques to the evaluation of salt cavern stability. It should be emphasized that, although the present paper deals specifically with the storage of natural gas, the majority of the material presented may be equally well applied to salt caverns used for the storage of pressurized fluids in general.

UNDERGROUND STORAGE OF NATURAL GAS

1. 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, depeleted gas and oil reservoirs, aquifers, and man-made caverns. The third storage type, man-made caverns, include salt caverns the subject of the present paper.

The use of man-made underground caverns for the storage of natural gas has increased rapidly in recent years. Such facilities include conventionally

mined caverns and tunnels, solution mined caverns, and modified mine work-ings. In these types of storage facilities the role of water in limiting the storage pressure of the structure may, at least in some cases, be of less importance than in aquifer and reservoir facilities. Furthermore, such storage facilities offer the advantage that their dimensions, and often their location, may be conveniently tailored to the storage requirements; and in some cases, where suitable reservoirs or aquifers are not available, they provide the only available storage capability.

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" then, 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.

At present solution mined salt caverns are the most widely utilized of the man-made storage facilities. In spite of their numerous advantages, they do suffer from one serious limitation, namely, the fact that their structural stability is highly sensitive to the minimum storage pressure level.

2. Salt Cavern Storage Concept

Salt caverns for the storage of pressurized natural gas are simply large tanks created underground using solution mining (leaching) techniques. As shown in Figure 1A, when a cavern is being developed in a salt dome or in a pure, thick-bedded salt deposit, a single well is drilled, casing is cemented from the top edge of the salt layer to the surface and then a string of

smaller tubing is hung inside the casing. Using the so-called direct injec-

tion technique, fresh water is pumped down the inner tubing into the salt

formation, where it dissolves the salt. The resulting brine is then forced

up the annular space between the tubing and casing. This brine may be dis-

posed of by selling it to a salt company or by injecting it into a porous

rock formation located well below any fresh water reservoirs. By controlling

the fresh water flow rate and the bottom-end position of the inner tubing,

it is possible to generate caverns of specific size and geometry. Once the

required cavern has been developed, as determined by sonar techniques, the

cavern is dewatered by injecting gas through the casing and displacing the

brine out of the cavern through the tubing. Following suitable integrity

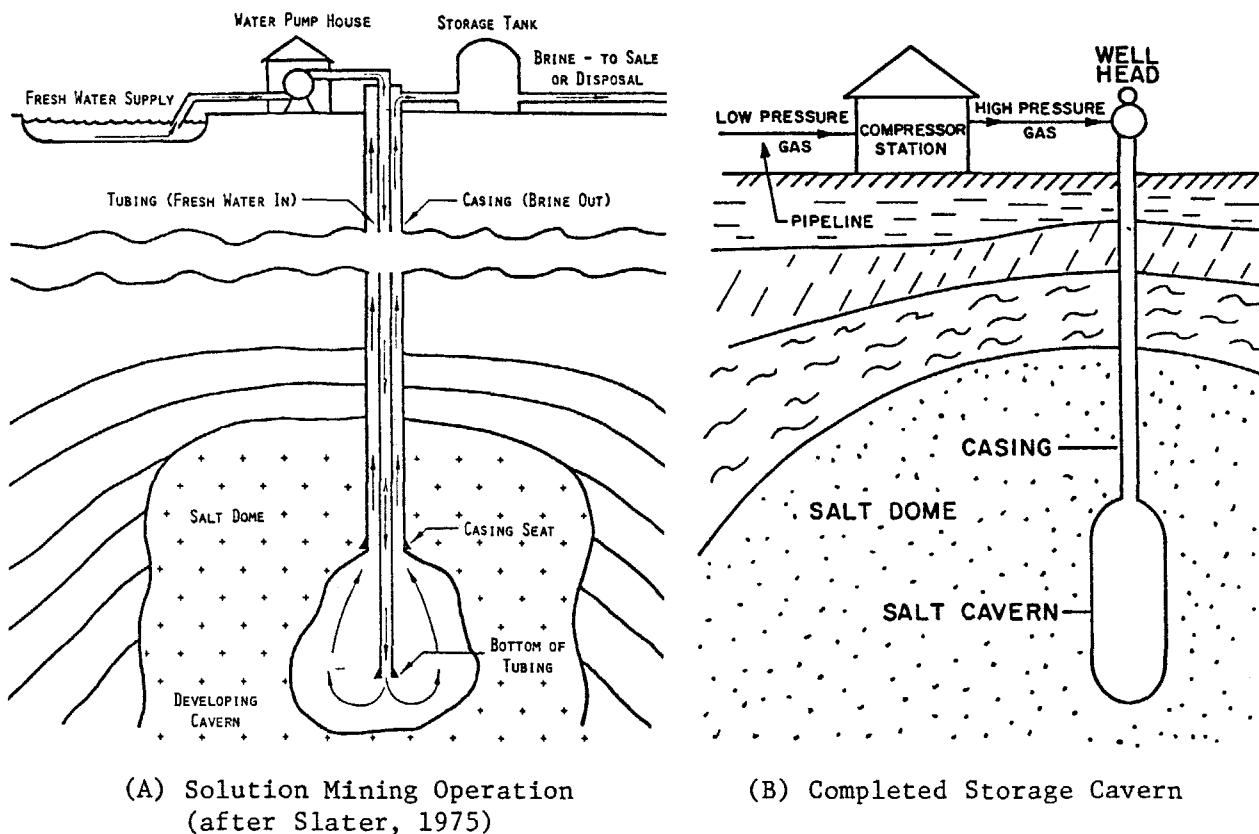evaluation, the cavern is ready for use as a storage facility (see Figure 1B).

(A) Solution Mining Operation   (B) Completed Storage Cavern
    (after Slater, 1975)

Figure 1 – Simplified Diagrams Illustrating Salt Cavern Development
and Utilization.

3. Development of Salt Cavern Storage

   Salt domes and bedded salt deposits are found throughout the world.
Within the United States, large salt deposits are found in the Gulf Coast,
Great Lakes, and the Mid-West regions. The availability of a suitable body
of salt, an adequate water supply, and a method of brine disposal determine
the suitability of a specific salt cavern storage site. According to a
recent A.G.A. survey (Anon., 1980A), as of 1980 there were eight salt cavern
facilities in operation in North America utilized specifically for the stor-
age 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, Kaveren Bau- und
Betriebs - GmbH (KBB), has in recent years constructed 16 storage caverns
for this purpose. It is obvious, therefore, that in the brief period since
the first successful use of a salt cavern for the storage of natural gas in
1971 (Anon., 1971), the use of such facilities has accelerated rapidly.

FUNDAMENTAL MECHANICS PRINCIPLES

1. General

   In order to put the current research in proper perspective, it is impor-
tant to define the problem of salt cavern design in terms of the fundamental
mechanics principles involved. In simple terms, salt cavern storage involves
the storage of pressurized fluid in a thick-walled underground container,

the walls of which are composed of salt. In use this container is loaded internally by the pressure of the stored fluid, 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 fluid 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.

2. Cavern Instabilities

A major concern in 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 2, 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 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.
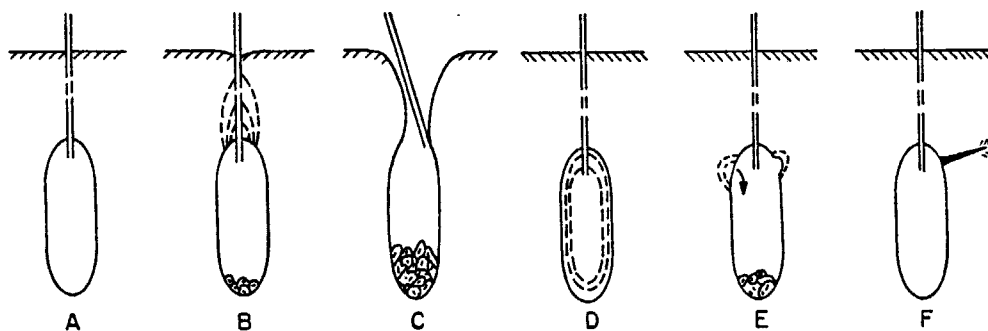
Figure 2 - Various Types of Mechanical Instability Which May Occur
in Solution Mined Caverns. (A - initially stable
cavern, B - development of subsurface subsidence,
C - piping subsidence and resulting surface subsidence,
D - cavern closure, E - local fracture and block flow,
F - deep fracture.)

In general the mechanical stability of a salt cavern is dependent on

both its gross and fine scale geometry. In bedded salt the solubility of the

various salt layers and the presence of insoluble strata will influence the

gross geometry, whereas in both bedded and domal salt the presence of local-

ized insolubles are responsible for the irregularities in the fine scale

geometry. In general, based on rock mechanics principles, the optimal cavern

shape would be spherical or ellipsoidal, depending on the in-situ stress

field (k-value). Furthermore, if a suitably uniform salt is available, such

shapes are perfectly feasible in terms of present day solution mining tech-

niques. In practice, however, actual cavern shapes are normally dictated by

the characteristics of the salt at the desired storage site, and the fact

that an array of caverns (cavern field) rather than a single one, is normally

required. The latter factor often necessitates the use of long cylindrical-

shaped caverns.

3. Cavern Design Concepts

3.1 Introduction

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. Only after sufficient data and experience are obtained in regard to these components, and various proposed design criteria are evaluated in terms of actual prototype behavior (i.e., data acquired from actual field sites), will it be possible to develop meaningful design criteria.

It is clear, from the information obtained during recent studies, 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, a comprehensive design procedure based on mechanics principles is not presently available.

3.2 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
    Shut-in Time

(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. Furthermore, it is important
to note that many of the listed design factors are interdependent, for
example, optimum cavern dimensions depend not only on the volume of gas to
be stored but also on the in-situ stress field, cavern spacing, storage pres-
sure limits, temperature, and mechanical properties of the associated media.

Unfortunately, limited numerical data are available for many of the
design factors. 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 experience, 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 Europe the situation is somewhat better due to the fact

that considerably more salt caverns have been constructed for the storage

of natural gas, and that extensive research has been underway for some years

to develop realistic, rock mechanics based, design procedures. Nevertheless,

in terms of the complexity of the problem, relatively little numerical data

have been generated.

3.3 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 analytical 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.

In the specific area of salt cavern design the majority of the studies

undertaken to date have involved the theoretical technique. A notable excep-

tion is the work of Dreyer (1973), who has developed a design approach

based on the laboratory model technique.

3.4 Correlation of Analytical and Field Data

The most suitable method for evaluating tentative salt cavern design criteria is to compare predicted and actual field data. In such studies tentative criteria and associated design techniques would be utilized to predict the behavior of an existing operating storage cavern. Comparison of the predicted values of various parameters, for example cavern closure, with values of these parameters measured at the cavern site, would then provide an estimate of the suitability and accuracy of the tentative design criteria. This approach is currently being utilized by researchers at Gaz de France (Boucly, 1982) and the University of Hannover (Lux and Rokhar, 1982), and to a limited degree by consultants in the USA.

It is immediately apparent than, in order to carry out such studies, realistic basic data is necessary in regard to the geometry and environment of the cavern (e.g., in-situ stress field, dimensions, spacing, temperature, mechanical properties, etc.), cavern operating characteristics (e.g., pressure, volume stored, etc.) over one or a series of injection-withdrawal cycles, and cavern behavior characteristics (e.g., volume closure, temperature changes, etc.). Unfortunately, the majority of the required data are not generally available.

PENN STATE SALT CAVERN STUDIES

1. Outline of Current Studies

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. An initial review of the available literature early in the project indicated that three

important areas should be investigated, namely:

(1) Development of a better understanding of how salt behaves under conditions of stress and temperature equivalent to those found around a typical pressurized underground cavern.

(2) Application of established mechanics principles to the development of salt cavern design criteria.

(3) Evaluation of techniques for monitoring the mechanical stability of salt cavern storage areas.

Due to time and economic limitations it was decided early in the A.G.A. project to concentrate efforts on areas (1) and (2). A brief review of the PR-12-71 project has been presented in a number of recent papers (Hardy, 1982B, 1982C), and a more detailed description of the project is presented in an associated project monograph (Hardy, 1982D) to be published later this year. Comments on selected aspects of the project will be included later in this section.

Based on a growing interest in a number of secondary aspects of the recent A.G.A. studies, and the extensive fundamental and applied research presently underway relative to the use of salt as a storage medium for radioactive wastes and a variety of fluids, a number of additional salt-related studies have been initiated or are in the planning stage. These include both laboratory studies (e.g., cyclic loading tests, transient creep studies and investigation of basic deformation mechanisms), and field studies relative to the evaluation of salt cavern behavior. One major aspect of the latter studies, namely, the use of microseismic techniques for stability monitoring of operating caverns, will be discussed later in this paper.

2. American Gas Association Project

    2.1 General

    In general the basic problem under investigation in the current PR-12-71 study is that of formulating the criteria required for the design of economic

and stable storage caverns in salt. To accomplish this it was necessary to gain a firm understanding of the basic mechanical behavior of salt, the possible modes of instability associated with caverns located in such a material, and the manner in which in-situ stress, cavern geometry, cavern pressure and other factors influence such instabilities.

As illustrated in Figure 3, 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 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.

2.2 Laboratory Studies

As indicated earlier in this paper 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 parameters are required if a realistic design of a structure in salt is to be undertaken. As a result, laboratory tests on salt present a considerable number of problems not encountered with other geologic materials.

Figure 3 (components 1B, 3, and 4) illustrates the various phases of the laboratory study associated with the A.G.A. project; the ultimate aim of which was to develop a meaningful physical properties data base for salt.

During the early stages of the project the majority of the laboratory

effort was expended in reviewing the associated literature, isolating the

most-critical properties, evaluating methods for salt specimen preparation

and specimen strain measurement, and carrying out a variety of preliminary

tests. Details of these preliminary studies have been presented in an
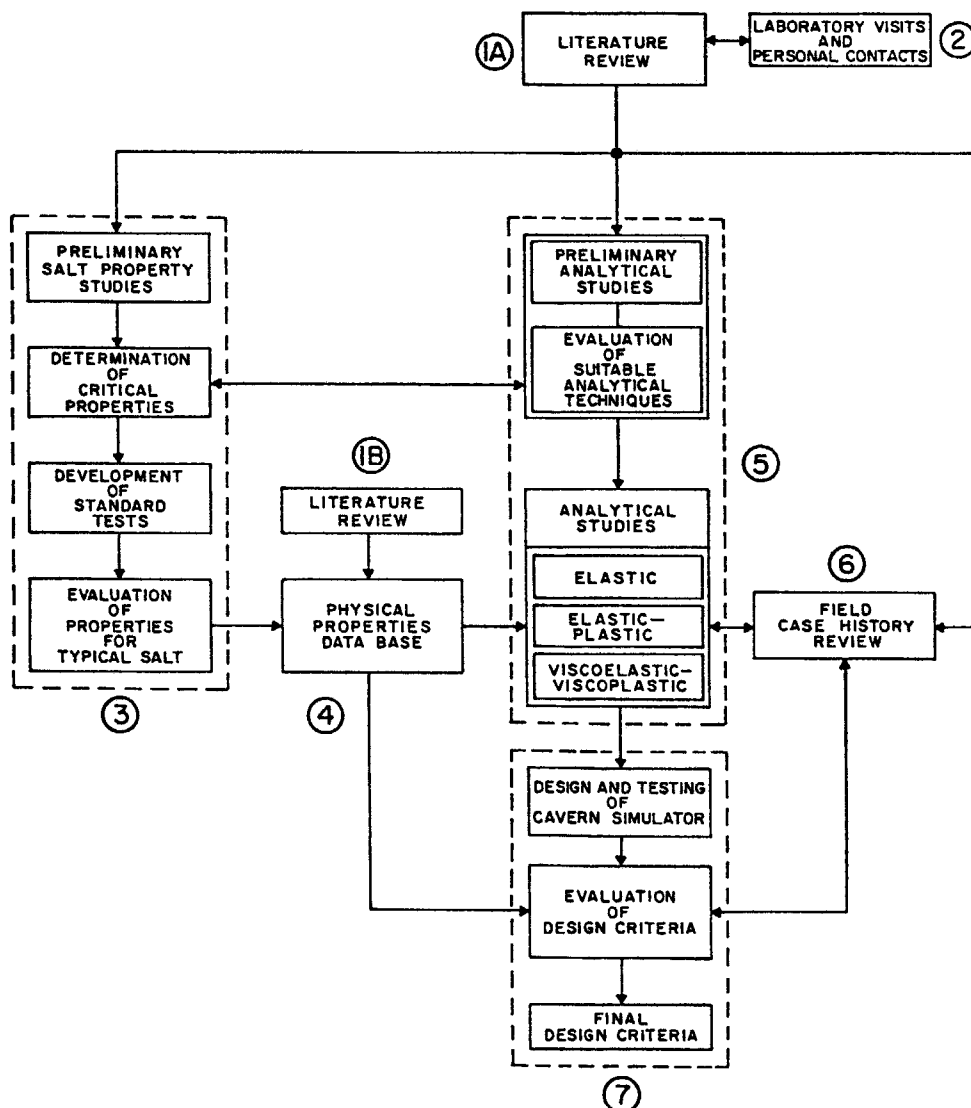
earlier paper (Hardy and Roberts, 1977).

Figure 3 - Block Diagram Illustrating the Various Components of the
Overall PR-12-71 Project. (Component 7 remains to be
completed.)

Once a decision was made as to the required critical properties, the development of the necessary equipment and procedures for carrying out the associated laboratory tests was initiated. In some cases existing standard techniques could be applied directly; however, in most cases, extensive development work was required. 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; Mrugala, 1982). 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 poly-crystalline 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, 1982; Hardy and Mangolds, 1980). Studies were conducted on artificial salt and on a number of types of natural salt.

Further details in regard to these studies have been presented elsewhere (Hardy, 1982B, 1982C; Hardy et al., 1982), and a detailed description of the overall laboratory study and the resulting physical properties data base are available in the associated project monograph (Hardy, 1982D).

2.3 Analytical Studies

2.3.1 General

The original intention of the analytical phase of the current salt cavern design project 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 both 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 block diagram in Figure 4 illustrates the major studies undertaken in the analytical phase of the project. These 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 characteristics as the
rate of cavern closure could not be evaluated.

(3) <u>Viscoelastic-Viscoplastic Studies</u>--In the final series of ana-
lytical studies it was assumed that the salt behaved as a visco-
elastic-viscoplastic material (Chabannes, 1982). Such materials,
in general, exhibit elastic, viscoelastic, plastic, and visco-
plastic behavior. Two sets of studies were carried out in this
series, namely, those based on closed-form and finite element
techniques. In the former 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 tempera-
ture. In the latter 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,
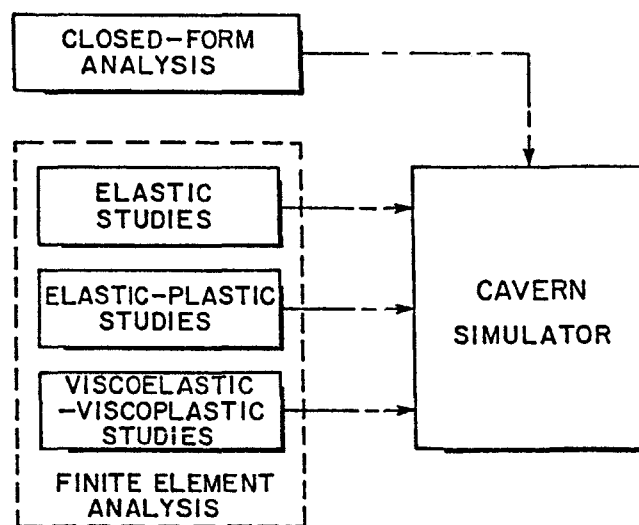the rate of cavern closure was investigated as a function of
cavern pressure.

Figure 4 - Block Diagram Illustrating the Major Studies
Undertaken in the Analytical Phase of the
Current Project.

Further general details in regard to the analytical studies are presented
in a recent paper (Hardy, 1982B), and a detailed presentation of the overall

analytical study is available in the associated project monograph (Hardy, 1982D). Material presented in this paper will be limited to certain aspects of the viscoelastic-viscoplastic studies.

2.3.2 Viscoelastic-Viscoplastic Studies

During the recent A.G.A. study both elastic and elastic-plastic analyses were found to provide useful insights into the overall problem of salt cavern design; however, they did not provide a suitable explanation for the large, time-dependent decreases in cavern volume noted in a number of actual field situations. In the final phase of the analytical studies, consideration was first given to assuming that salt behaved in a general viscoelastic-viscoplastic manner. However, due to the analytical complications resulting from this assumption, and the lack of the necessary mechanical property data, it was decided to reduce the complexity of the analyses by assuming that the salt behaved either as a rigid-viscoplastic material (closed-form solutions) or an elastic-viscoplastic material (finite element analysis).

During both the rigid-viscoplastic and elastic-viscoplastic analyses a temperature-dependent secondary creep law (Norton's law) was used to account for the creep strains, namely:

$$\dot{\varepsilon}_e^c = A \, \exp(-Q/RT)(\sigma_e/\sigma_c)^n \qquad \text{(Eq. 1)}$$

where $\dot{\varepsilon}_e^c$ is the effective creep strain rate, A, n, and Q (activation energy) are experimentally determined constants, R is the universal gas constant, T is the absolute temperature, σ_e is the von Mises effective stress, and σ_c is a constant used to normalize stress. Values used for the various parameters are presented in Table 1, where A, n, and Q were computed from available creep data for salt from the Tatum Salt dome, Mississippi.

Table 1

Values for Temperature-Dependent Secondary Creep Model
Parameters for Salt from the Tatum Salt Dome

Parameter (1)	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

(1) See Equation 1.

2.3.3 Rigid-Viscoplastic Analyses

During the rigid-viscoplastic analysis closed-form solutions for calculation of creep closure of cylindrical and spherical caverns, located in an infinite medium, and subjected to in-situ stress and internal pressure, were developed. These equations 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 (i.e., k = 1). In developing these equations it was assumed that the total strains and the strain rates were small, that the creep strain rate could be represented by Norton's law (Equation 1), and that the elastic analogy for stationary creep was valid.

The final product of the closed-form analyses were two equations from which the percent volume closure as a function of time for cylindrical and spherical caverns can be calculated, namely:

$$(\Delta V/V)_c = -200\ A\ \exp\left(-\frac{Q}{RT}\right)\left(\frac{\sqrt{3}}{2}\right)^{n+1}\left[\frac{2(P_o - P_i)}{n\ \sigma_c}\right]^n t \qquad \text{(Eq. 2)}$$

and

$$(\Delta V/V)_s = -150 \ A \ \exp\left[-\frac{Q}{RT}\right]\left[\frac{3(P_o - P_i)}{2n \ \sigma_c}\right]^n t \qquad \text{(Eq. 3)}$$

where A, Q, and n are the material parameters associated with the creep law (Equation 1) used in the current study, T is the absolute temperature of the cavern structure (salt) in degrees Kelvin, P_o is the in-situ hydrostatic stress field in psi (equivalent to approximately 1.0 psi/foot of depth), P_i is the internal cavern pressure in psi, t is the total duration of time for which the closure estimate is required in seconds, and R and σ_c are constants. For convenience in application, a suitable computer program incorporating Equations 2 and 3 was written for the HP 34C pocket calculator. Further details on this program are presented elsewhere (Hardy, 1982D).

The closed-form solutions developed were extremely useful to illustrate the influence of various factors such as cavern shape, salt properties, temperature, internal gas pressure, and depth on cavern closure. For example, Figure 5 shows the critical influence of temperature on the volume closure of a cylindrical cavern. Based on this data a cylindrical cavern located at a depth of 4000 feet with an internal pressure of 1000 psi (i.e., $P_o - P_i$ = 3000 psi) would experience a closure after 200 days of ≈6 percent at a temperature of 120°F and ≈30 percent at a temperature of 180°F.

The primary limitation of the rigid-viscoplastic (closed-form) solutions is the fact that they do not account for the instantaneous and transient structural response of the salt. The degree of cavern closure due to these responses can be significant as illustrated by the results of later finite element analyses (see Figure 8).

In review the following general conclusions may be drawn from the preceding rigid-viscoplastic (closed-form) analyses:

(1) Using the closed-form equations developed in this study, along with appropriate values for the creep parameters, it should be possible to obtain an approximate estimate of the minimum internal gas pressure necessary to maintain an acceptable volume closure rate for caverns of approximately spherical and cylindrical shape. If more accurate estimates are required, or if more complex cavern shapes are involved, then finite element methods must be utilized.

(2) The closed-form solutions will always provide a lower bound on the solutions produced by a finite element model when comparable boundary conditions are used (see Figure 8 presented later). The results from the present study indicate that better agreement between the closed-form and finite element solutions is obtained at higher effective stress levels (i.e., for higher values of $P_o - P_i$).

(3) The availability of the closed-form solutions made it possible to evaluate the sensitivity of cavern closure to a number of parameters associated with the temperature-dependent secondary creep law (Norton's law). The results of such sensitivity studies indicated that cavern closure is highly sensitive to both temperature and the values of the experimentally determined creep parameters. The latter indicates that reliable, site specific creep data are necessary for meaningful cavern design.
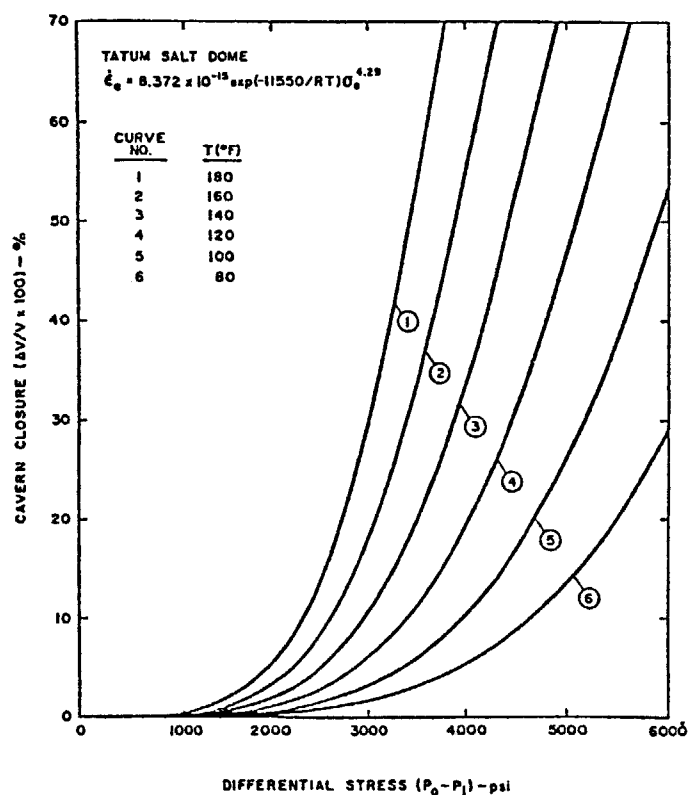

Figure 5 - Influence of Temperature (T) on Volume Closure Versus Differential Stress for a Cylindrical Cavern After 200 Days. (Based on closed-form solutions; the associated strain rate equation is shown in the top lefthand corner of the figure.)

2.3.4 Elastic-Viscoplastic Analyses

During the elastic-viscoelastic analyses the closure characteristics of three cavern shapes, spherical, teardrop, and tapered cylinder, as illustrated in Figure 6, were investigated. The dimensions selected for each cavern shape were such that in all cases the overall cavern volume was approximately 2.53×10^6 barrels. In all cases the caverns were assumed to be located in a hydrostatic stress field (k = 1) at a depth of 3000 feet, as shown in Figure 7. The overburden and salt were assumed to have densities of 154.20 and 138.54 lbs/ft^3, respectively.

In order to account for the influence of geothermal gradient in the analyses, the cavern structures were assumed to be at a uniform temperature of 110°F. This temperature was based on a geothermal gradient of 20°F/1000 feet and a mean surface temperature of 50°F. The total strains computed in the finite element analyses were assumed to be the sum of the elastic and viscoplastic (creep) strain components. The elastic strains for all cases were computed based on the assumption that the salt was a homogeneous, isotropic, linear elastic material with a Young's modulus of 1.0×10^6 psi and a Poisson's ratio of 0.4; and the viscoplastic strains were computed on the basis of Norton's law, as presented in Equation 1, and the parameters listed in Table 1.

The volume closure characteristics as a function of time for the three cavern shapes were analyzed using the BUMINES finite element program. During the study the effects of three different internal cavern pressures, 1000, 2000, and 2700 psi were investigated. The results of the finite element analyses for cavern pressures of 1000 and 2000 psi are shown graphically in Figure 8. Also included in Figure 8 are the results of closed-form (rigid-viscoplastic) studies on spherical and cylindrical caverns which were briefly discussed in the preceding section. The data presented in all cases are

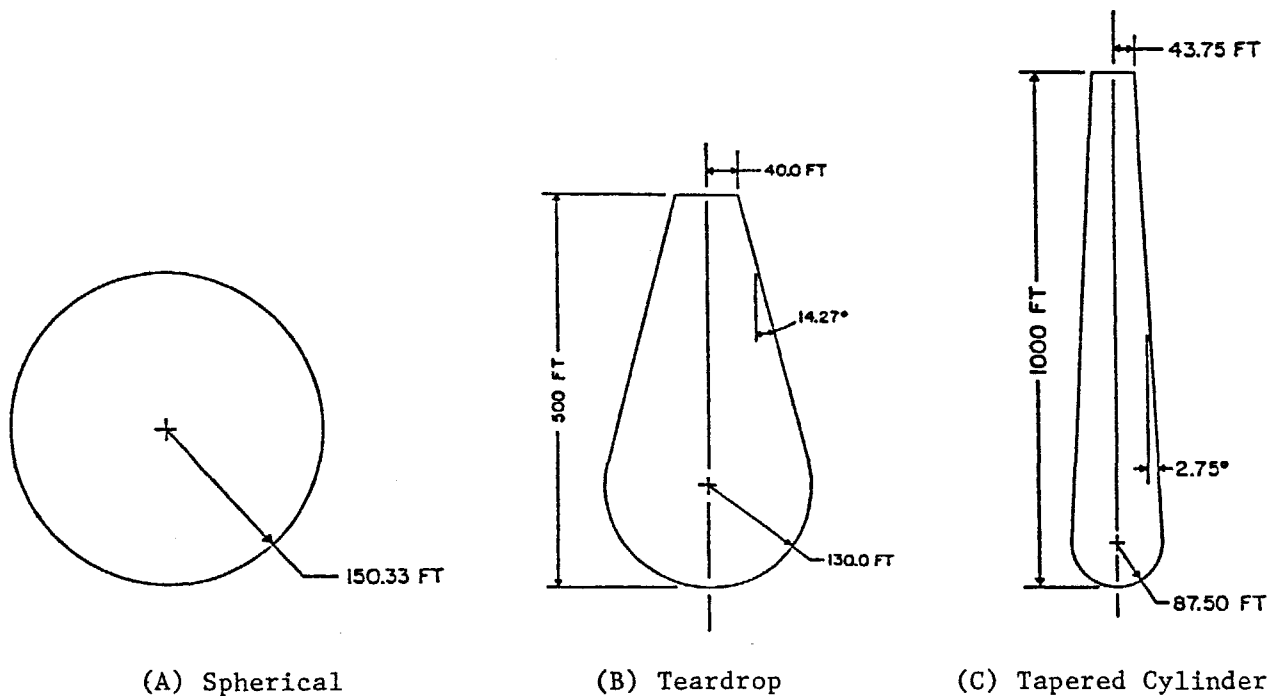(A) Spherical   (B) Teardrop   (C) Tapered Cylinder

Figure 6 - Details of the Three Cavern Shapes Investigated Using an Elastic-Viscoplastic Finite Element Analysis.
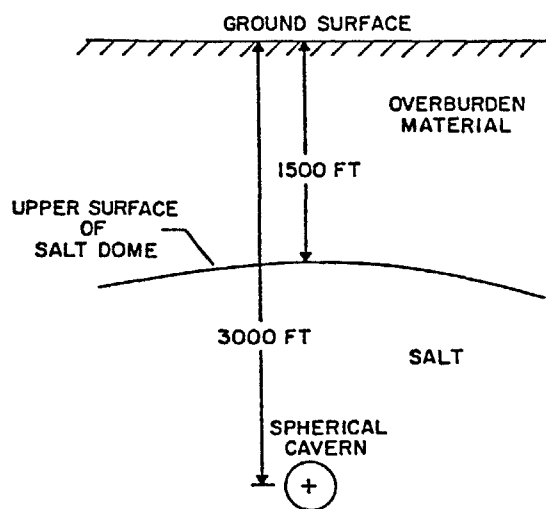

Figure 7 - Schematic Drawing of a Spherical Cavern Located at a Depth of 3000 Feet. (Figure is not drawn to scale.)
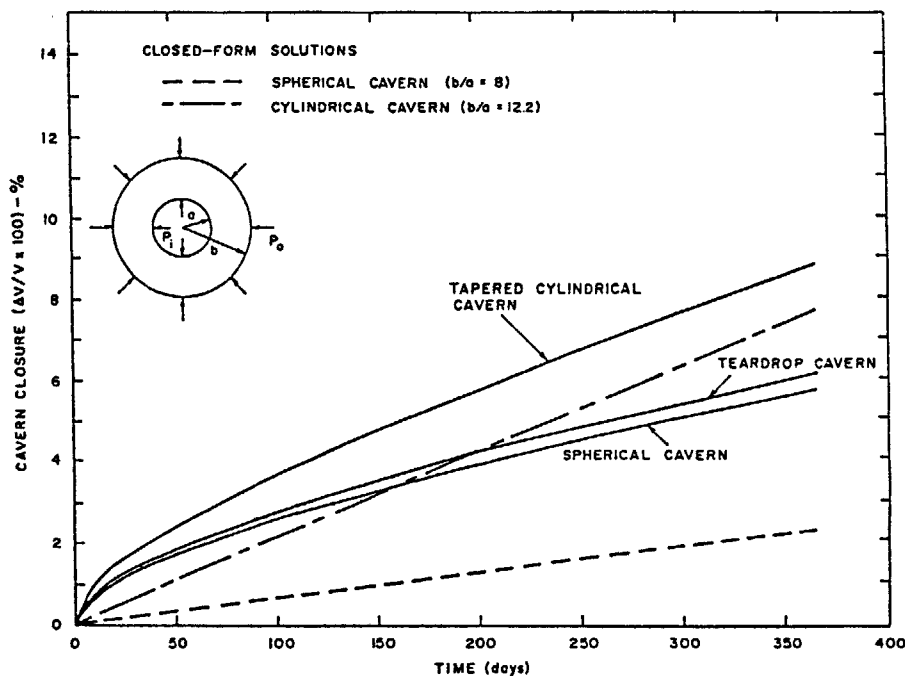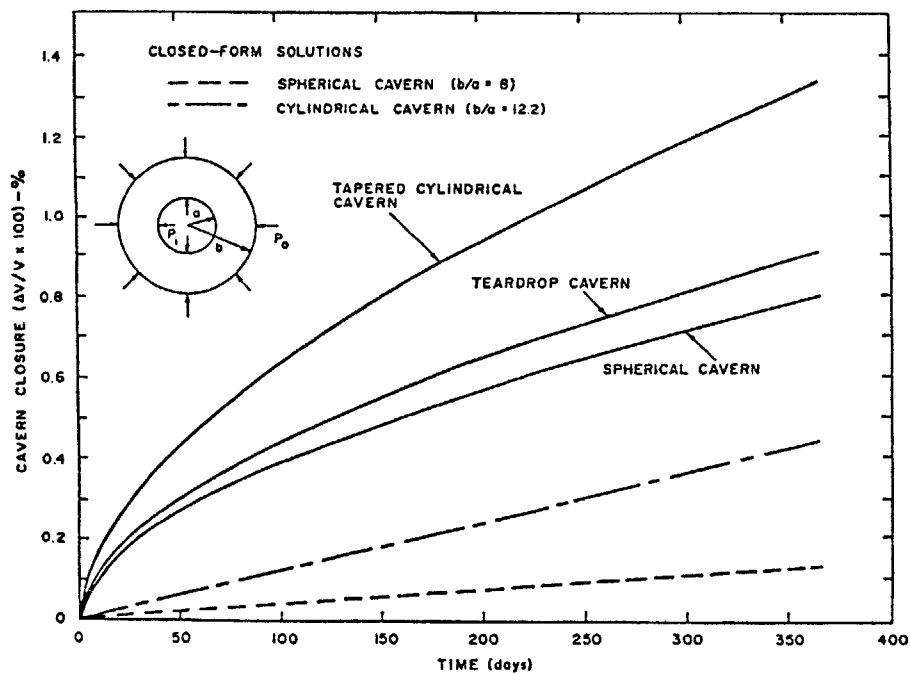
24

(A) P_i = 1000 psi

(B) P_i = 2000 psi

Figure 8 – Influence of Cavern Shape on Volume Closure as a Function of Time
for Two Different Values of Internal Gas Pressure. [Solid curves
represent data from elastic-viscoplastic (finite element) analyses
and dashed curves represent data from rigid-viscoplastic (closed-
form) analyses. Cavern depth – 3000 feet and in-situ tempera-
ture – 110°F.]

based on the assumption that the center of the caverns were located at a depth of 3000 feet, and that the material surrounding the caverns was at a uniform in-situ temperature of 110°F.

Based on the finite element data shown in Figure 8, it is evident that the spherical cavern exhibits the minimum closure followed by the teardrop cavern, with the tapered cylindrical exhibiting the greatest closure. For a non-hydrostatic initial stress field (k $\neq$ 1), the teardrop cavern would probably be the most suitable.

In review, a number of the more important results of the elastic-visco-plastic analyses were as follows:

(1) As indicated in Figure 8 the rate of cavern closure is highly sensitive to the level of the internal gas pressure. Further-more, even at storage pressures only slightly less than the in-situ stress level (e.g., $P_o - P_i$ = 300 psi), significant time-dependent closure was found to occur over extended periods of time.

(2) As would be expected for the case of a hydrostatic in-situ stress field, the closure characteristics of a spherical or a teardrop cavern are clearly superior to those of a tapered cylindrical cavern.

(3) The results from the current studies indicate that a secondary creep law (i.e., Norton's law) will provide a transient volume closure response (i.e., closure versus time curves are highly non-linear during the first 50-150 days).

(4) A comparison of the results of the rigid-viscoplastic (closed-form) and the elastic-viscoplastic (finite element) analyses, shown in Figure 8, indicates that the rigid-viscoplastic analyses predict considerably lower values of cavern closure than the elastic-viscoplastic analyses. However, after a period of approximately 200 days the rate of cavern closure computed by both types of analyses are generally of the same order of magni-tude.

2.4 Discussion

Based on the studies carried out to date, it is apparent that the present expertise and basic data necessary for the development of specific criteria and procedures for the design of salt caverns for the storage of natural gas

are limited. A considerable number of recommendations in regard to desirable improvements in laboratory and analytical techniques, specific areas which urgently require additional study, and various concepts and techniques which should be investigated further have been discussed in the associated PR-12-75 project monograph (Hardy, 1982D). In particular, a number of specific high-priority studies are recommended by the writer for future study, namely:

(1) A detailed research project is urgently required 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 which vary over a wide range during a typical 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. In the writer's opinion such a study is a first-order priority for future development of meaningful salt cavern design criteria.

(2) Additional long-term creep studies under triaxial stress and over a range of elevated temperatures are required. Such studies should be carried out on a range of salt types (perhaps three or four) typical of those expected at future gas storage cavern sites. At present the availability of reliable long-term creep data is extremely limited, and such data are critical if the long-term closure characteristics of salt caverns are to be calculated.

(3) Based on the fact that a viscoelastic-viscoplastic analysis is required to realistically predict cavern closure, future analytical studies are required to complete the final development of the PSU-BUMINES finite element program and to put it in a suitable form for routine cavern design. In particular, techniques should be developed for incorporating, at least in an approximate manner, variation of storage pressure over an injection-withdrawal cycle.

(4) Further development of closed-form solutions for approximate analysis of cavern closure should be undertaken. In particular, consideration should be given to incorporating a more realistic creep law, which includes transient as well as steady-state creep behavior. Attempts should also be made to develop closed-form solutions which would allow for variations in storage pressure characteristic of those associated with a typical injection-withdrawal cycle.

(5) It is recommended that in the future studies be carried out to correlate predicted and actual field data from a number of operating storage caverns. As a first step studies should be carried out to determine the required field parameters, investigate techniques available for their measurement, and establish a program to collect and compile these for future criteria evaluation.

3. Field Evaluation of Salt Cavern Behavior

3.1 General

As indicated earlier, the development of a meaningful procedure for the design of salt caverns will require that tentative design criteria, based on laboratory and analytical studies, be tested using actual field data. A study is therefore necessary to evaluate the present state-of-the-art of techniques available for field monitoring of salt cavern behavior. Such techniques include methods for measuring cavern volume and geometry during solution mining, and after various periods of storage; cavern closure during special studies; general mechanical stability of the cavern structure and surrounding area; and cavern temperature. Initial investigation of various cavern monitoring procedures were undertaken during the recent A.G.A. project (Hardy and Scovazzo, 1977; Hardy, 1980); however, further more detailed study is required.

3.2 Cavern Stability Monitoring

An area which should be of considerable concern to those involved in the design, construction, and operation of salt cavern storage facilities is that of overall cavern stability. At present no on-line method of monitoring the structural stability of operating caverns is available. In this regard the writer recently attended the "International Symposium on Rock Mechanics Related to Caverns and Pressure Shafts," sponsored by the International Society for Rock Mechanics, held in Aachen, West Germany (Wittke, 1982). Some 500 engineers and scientists, from over 40 countries, attended this symposium, and a number of interesting papers were presented in the area of salt mechanics. It was interesting to note, however, that papers dealing specifically with the stability evaluation of operating underground storage caverns, either in salt or hard rock, were extremely limited. Although there

was considerable discussion as to the need for stability evaluation of such caverns, besides the writer's paper, which dealt with the potential of microseismic techniques for monitoring structural stability of underground storage facilities (Hardy, 1982E), only two or three other papers even briefly touched on this subject. Based on discussions at the Aachen symposium and elsewhere, it is clear that although there are growing concerns in regard to long-term stability of underground storage caverns, relatively little research is presently underway to develop the necessary monitoring techniques.

In the writer's opinion, one of the major problems associated with the accelerating use of underground storage and the extraction of minerals by solution mining is the fact that the development of techniques for monitoring the long-term mechanical stability of the resulting structures are lagging seriously behind developments in other associated areas such as excavation. There can be little doubt that suitable techniques are required to evaluate the long-term mechanical stability of such underground structures. Such techniques are necessary to insure first that the associated cavern itself is suitably stable, and second, that the surrounding environment is not influenced significantly by the solution mining and/or storage operation. Looking into the future (possibly the near future), it is not unrealistic to anticipate the time when those involved in solution mining and the use of the underground for storage purposes will be held legally responsible for verifying that their activities do not seriously disturb the equilibrium of nature outside their specific area of operation.

Due to the size and often inaccessible nature of salt caverns, the microseismic technique appears to offer one of the more suitable methods for stability monitoring of such structures.

3.3 Microseismic Techniques

3.3.1 Microseismic Concept

The phenomenon of microseismic activity is associated with the fact that when a structure composed of materials such as rock is loaded the resulting deformation and/or localized failure cause the generation of seismic signals within the structure. These signals are indicative of the overall stability of the structure, and with suitable instrumentation they may be detected at considerable distances from their source. Basic and applied microseismic research has been underway for some 40 years, although the major developments in the subject have taken place since about 1965.

In recent years, extensive use has been made of microseismic techniques for evaluating the stability of such geologic structures as mines, rock and soil slopes, tunnels, earth filled dams, and more recently underground storage facilities. A detailed discussion of the microseismic concept and information on a variety of applications is available in a number of recent publications [for example, Hardy (1981) and Hardy and Leighton (1977, 1980, 1982)].

In geologic materials the origin of microseismic activity is not well understood, but it appears to be related to processes of deformation and failure which are accompanied by a sudden release of strain energy. In such materials, microseismic activity may originate at the micro-level as a result of dislocations; at the macro-level by twinning, grain boundary movement, or initiation and propagation of fractures through and between mineral grains; and at the mega-level by fracturing and failure of large areas of material and/or relative motion between structural units. It is assumed that the sudden release of stored elastic strain energy accompanying these processes generates an elastic stress wave (seismic wave) which travels from the point of origin within the material to a boundary where it is observed
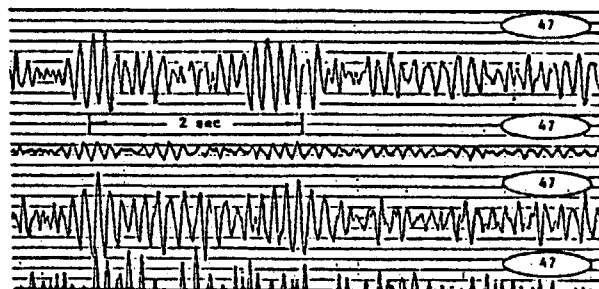
as a microseismic signal or a discrete microseismic event. Figure 9 illustrates a number of typical microseismic signals monitored at a number of Penn State field sites.
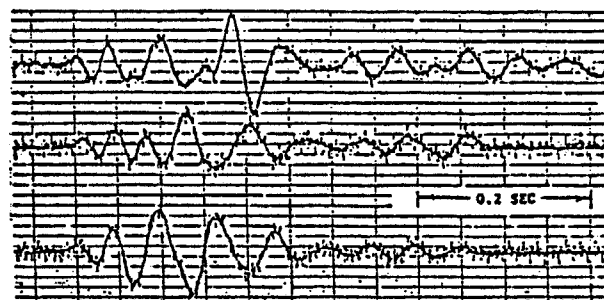
A. Event Recorded on Three Transducers Above a Longwall Coal Mine Site.
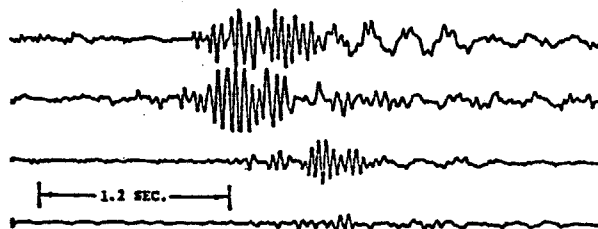
B. Event Recorded on Four-Transducers at a Shallow Underground Gas Storage Site.

C. Events Recorded on Three Transducers at a Scenic Cavern Site.

Figure 9 - Typical Microseismic Signals and Discrete Events Monitored at a Number of Different Penn State Field Sites.

One of the major advantages of the microseismic technique over more conventional geotechnical monitoring techniques is its ability to delineate the area of instability. From a fundamental point-of-view, therefore, accurate microseismic source location is extremely important. First, unless

the actual source is accurately located, it is impossible to estimate the true magnitude of an observed microseismic event. For example, a series of small observed events may be due to a weak source located close to the transducer or due to a strong source located a considerable distance away. Secondly, in order to determine the mechanism responsible for the observed activity, it is necessary that the location of the source be accurately known. In general, source location techniques involve the use of a number of monitoring transducers located at various points thoughout the structure under study. Such a set of transducers is termed an array.

Figure 10 illustrates, for example, a typical field situation where microseismic techniques are being employed to monitor the mechanical stability of an underground storage cavern. Here suitable transducers have been installed at accurately known locations, and data from these are monitored during product input, output, and long-term storage. Microseismic activity occurring during such an evaluation is detected at each transducer at a different time depending on the distance between the particular transducer and the microseismic source. The difference in arrival-time between the closest transducer and each of the others yields a set of arrival-time-difference values which, along with the geometry of the transducer array and the velocity of propagation in the material, may be used to determine the spatial coordinates of the microseismic source. In such a study, source location makes it possible to determine the location of any instabilities which may influence the safety and operating performance of the facility and, furthermore, it provides a means (spatial filtering) of eliminating from subsequent analysis any activity occurring outside the immediate area of the facility.

In review then, from an application point-of-view, the important microseismic concepts are as follows:

(1) Microseismic activity originates at locations where the material is mechanically unstable.

(2) It propagates through the surrounding material undergoing attenuation as it moves away from the source.

(3) With suitable instrumentation such activity may be detected at locations a considerable distance from its source.

(4) The rate of occurrence and magnitude of the observed microseismic activity provides indirect evidence of the type and degree of instability.

(5) Microseismic data obtained from a number of transducers (array) make it possible to determine the actual location of the associated instability.
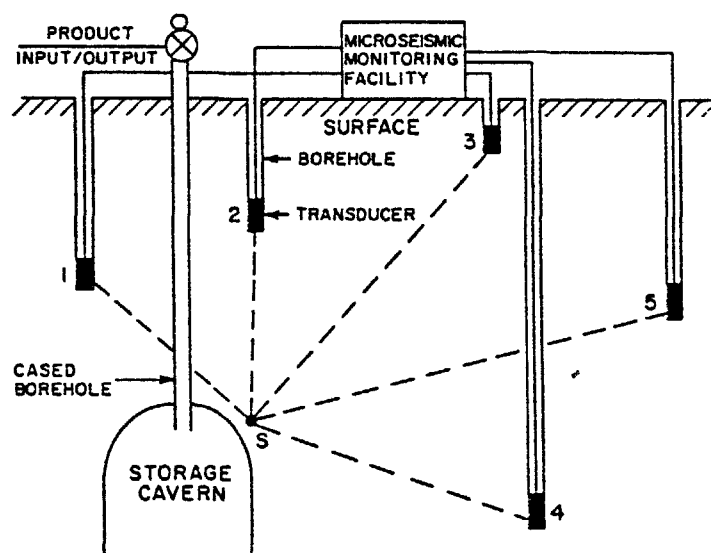

Figure 10 – Transducer Array Installed to Monitor the Stability of an Underground Storage Cavern.

3.3.3 Monitoring and Analysis Techniques

At a field site microseismic signals are obtained by installing a suitable transducer, or usually a number of transducers (an array), in locations where they can detect any activity which may be originating in the structure under study. A simple single-channel monitoring system involves a transducer, an amplifying and filtering system, and a recorder. Figure 11

illustrates a typical system which might be used, for example, to monitor

the microseismic activity occurring in a shallow underground storage cavern.

In such an application the transducer could be a geophone (velocity gage)

located in a suitable borehole perhaps 25-100 feet below surface. In this

case the transducer would monitor ground velocities due to microseismic

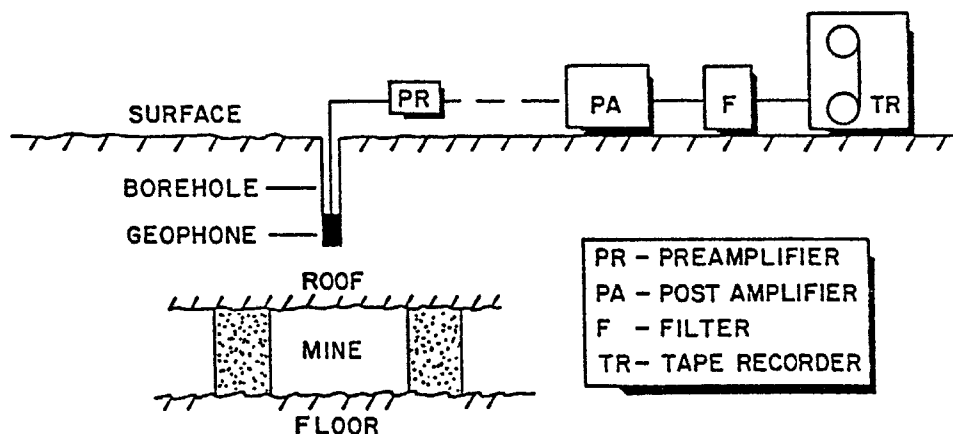activity occurring in, or around, the cavern structure.

Figure 11 - Block Diagram of a Typical System for
Microseismic Field Monitoring.

The output of the transducer, resulting from the presence of typical

microseismic activity, is normally only of the order of a few microvolts,

and it is necessary to amplify this small signal, without introducing noise

and distortion, for subsequent processing and/or recording. Furthermore, to

properly match the impedance of the transducer to the relatively low input

impedance of the post-amplifier, it is necessary to employ an intermediate

preamplifier. A band-pass filter is also normally included in such systems

in order to eliminate undesirable extraneous low and high frequency signals.

Past experience has shown that a magnetic tape recorder often provides the

most satisfactory means for direct recording of microseismic signals, since

it introduces a minimum of distortion and makes it possible to conveniently

analyze the recorded data at a later date.

In the past, analysis of microseismic field data has been for the most part based on manual and/or "hardwired" techniques. In recent years, with the increasing availability of compact and relatively inexpensive computers, the use of computer-based data analysis systems have become more common. Such systems make it possible to carry out on-line evaluation of such parameters as microseismic rate, amplitude, and source location.

Space does not permit a detailed discussion of microseismic monitoring and analysis techniques here; however, the reader is referred to recent papers by Hardy (1981, 1982E) and Hardy, Mowrey, and Kimble (1981) for further information on these techniques.

3.4 Microseismic Monitoring of Salt Caverns

A recent paper by the writer (Hardy, 1982E) deals specifically with the evaluation of the mechanical stability of underground storage facilities and natural caverns using microseismic techniques. A number of current field applications of microseismic techniques in the area of salt cavern storage are those related to strategic petroleum reserves, compressed air energy storage, storage of natural gas, and isolation of radioactive wastes. Brief comments on each of these applications will be included here.

3.4.1 Strategic Petroleum Reserves

In the USA, over the past several decades, a large number of caverns have been solution mined in Texas and Louisiana salt domes for the production of brine for use in the chemical industry. A number of these caverns are now being used to store strategic reserves of petroleum. In 1978 depressurization experiments were carried out at one of these storage sites, which consisted of an interconnected upper and lower cavern. During these studies, microseismic activity was monitored by a team from the Los Alamos Scientific

Laboratory (Albright and Pearson, 1982) using a down-hole transducer package similar to that utilized in their geothermal fracture mapping program. Although these studies indicated essentially no microseismic activity prior to depressurization, an abrupt increase in such activity was noted immediately following partial depressurization. Maps of hypocenter distribution for the microseismic events indicated a concentration of sources at a thick ledge of salt located between the upper and lower caverns, where theory predicted possible structural instabilities could occur. These studies concluded that "the presence of detectable acoustic emissions [microseismic events] strongly indicates material fracture on at least a very localized scale. Further research is required to isolate the source mechanisms of these acoustic signals. It may be, especially if microcracking is the source, that repeated load cycles could cause localized failures to coalesce into macroscopic rock falls within the cavern." To the writer's knowledge, the preceding study was the first successful one in which it was possible to evaluate the stability of a solution mined salt cavern using microseismic techniques.

3.4.2 Compressed Air Energy Storage

In recent years Dr. R. L. Thoms, and others at the Louisiana State University, have been involved in a number of research programs related to the engineering behavior of salt. At present this group is actively involved in the problem of designing solution mined caverns for compressed air energy storage (CAES), and have made extensive use of microseismic techniques both in the laboratory and underground (Gehle and Thoms, 1982).

3.4.3 Storage of Natural Gas

The increasing worldwide use of solution mined salt caverns for the storage of natural gas presents another area where microseismic stability

monitoring may well play an important role. As noted earlier in this paper, since 1975 the American Gas Association has supported a research program in the Penn State Rock Mechanics Laboratory relative to the design and performance of salt caverns for the storage of natural gas (Hardy, 1982B). During this program microseismic techniques have proven extremely useful for laboratory evaluation of salt properties, and in the future it is planned to evaluate their applicability for field monitoring of operating natural gas storage caverns.

Similar studies relative to salt cavern storage of natural gas have been underway in Denmark (Hardy, 1980). Recent discussions with Professor Vagn Askegaard, director of the Structural Research Laboratory (SRL) at the Technical University of Denmark, indicate that his laboratory has been involved in a variety of microseismic related projects and recent studies have been associated with the design of facilities for the underground storage of natural gas in Danish salt domes. Although to date microseismic studies on salt at the SRL have been limited to laboratory tests, consideration is being given to the possibility of employing "down-hole" microseismic techniques in full-scale field measurements of salt cavern stability, possibly at depths of up to 5000 feet.

3.4.4 Isolation of Radioactive Wastes

Microseismic monitoring of experimental radioactive waste repositories have been underway in the U.S.A., Sweden, and West Germany (Hardy, 1981). West Germany has two such repositories under study: the Konrad site, located within an abandoned limestone mine, is used exclusively for low-level waste; and the Asse site, located in an abandoned salt mine, is used for both low- and medium-level waste. Both sites are situated in northeastern Germany near the city of Hannover, and are operated by the Gesselschaft für Strahlen-

and Unweltforschung (GSF), a Government organization, concerned with the safety of nuclear operations. In order to monitor the overall structural stability of these repositories, a suitable microseismic monitoring system has been installed at both sites (Hardy, 1980).

Detailed microseismic studies at the Asse (salt mine) site were scheduled to begin late in 1980. Here microseismic signals from a number of transducers, installed on concrete pads or directly on the floor of the underground entries, are first pre-processed using an event detector and then recorded on magnetic tape. The resulting tapes are later processed using a computer system developed specifically for this purpose.

Plans are presently underway to install "close-in" facilities to monitor in detail the microseismic activity in the actual storage areas. In particular, studies are planned at an experimental high-level waste disposal area at the Asse site where electrical heaters are presently being used to stimulate the thermal effect of high-level waste. The purpose of these studies will be to determine if the motion of the associated thermal front can be traced using microseismic transducers installed at various distances from the location of the simulated waste (heaters).

3.5 Discussion

As indicated earlier in this paper there is a pressing need to evaluate the state-of-the-art of techniques available for monitoring of salt cavern behavior both during development and later under actual operating conditions. In particular, an on-line method for monitoring the overall structural stability of salt caverns is urgently required. Due to their size and often inaccessible nature, the microseismic technique appears to offer one of the most suitable methods for stability monitoring of such structures.

Although the microseismic technique has been in existence for some 40 years, many of the major technical difficulties have only been resolved within the last 10 years. Due to recent advances in electronics, resulting in improved monitoring equipment and automated data analysis facilities, microseismic field studies which were impractical a few years ago are now routine. Furthermore, field studies, such as salt cavern stability monitoring, where low-level microseismic signals and high background (e.g., noise from pumps, brine flow, etc.) are involved, are now feasible with the aide of a range of monitoring system optimizing techniques (e.g., bandpass and notch filtering) and sophisticated data analysis methods.

With respect to the application of microseismic techniques to the stability monitoring of solution mined caverns, it is the writer's opinion that the main problems yet to be overcome are those associated with the selection and installation of suitable transducers at the field site. In this regard, limited field studies are required to investigate the following:

(1) selection of the most suitable type of transducer for this application,

(2) optimization of transducer array geometry, and

(3) development of suitable transducer installation techniques for use in such studies.

Since underground salt caverns are normally inaccessible except by the normal boreholes involved, and since they are usually of considerable depth below surface, the use of a variety of transducer installations have been considered for such applications. These include down-hole hydrophones, which would be inserted through the existing wells into the caverns, and the use of a limited number of three-dimensional transducers mounted in specially drilled boreholes.

There is no doubt in the writer's mind that the microseismic technique can be effectively utilized to monitor salt cavern stability associated with solution mining and long-term operation of salt cavern storage facilities. However, industrial assistance, including limited financial support and the provision of field sites for technique development and evaluation, are urgently required in order to optimize the technique relative to this specific application.

SUMMARY

In this paper the writer has briefly reviewed a number of concepts and in-house research studies relative to the design and stability monitoring of salt caverns. The first part of the paper dealt specifically with the laboratory and analytical phases of a recent study carried out to develop criteria for the design of salt caverns for the storage of natural gas. This study has been underway for some seven years and at present a detailed monograph describing the progress to data is in preparation (Hardy, 1982D). As noted, results to date have been encouraging; however, due to the complexity of the problem, additional research remains to be carried out before fully acceptable design criteria can be developed.

The second part of the paper dealt with the need for field data relative to the behavior of salt caverns and the development of techniques for stability monitoring of such structures. At present it appears that the most promising technique for this purpose is that based on microseismic phenomena.

In this paper the writer briefly reviewed the fundamentals of the microseismic technique and briefly discussed how this technique could be applied specifically to the monitoring of salt cavern stability. As indicated early in the paper, the microseismic technique is at present commonly

utilized in a wide range of geotechnical applications, and its use in many fields of mining, in particular strata stability evaluation, have become almost routine. It is the writer's opinion that the application of micro-seismic techniques to other areas, such as underground storage and salt caverns in particular, are long overdue.

Finally, although there is little doubt that microseismic measurements are somewhat more sophisticated and expensive than those involving conventional rock mechanics instrumentation, such measurements provide data unobtainable by any other method. Furthermore, due to the size and often inaccessible nature of solution mined salt caverns, the microseismic technique appears to provide the only practical means for overall stability monitoring of such structures.

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