Development of Design Criteria for Salt Cavity Storage of Natural Gas

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ABSTRACT

There is little doubt that in the next twenty years, the utilization of cavities, from which salt has been extracted by conventional or solution mining techniques, will play a vital role in supporting the world's growing energy and environmental demands. Unfortunately, although salt has been studied for many years a review of the world literature indicates that the necessary expertise for designing, constructing and stability monitoring of engineering "structures" constructed in salt is relatively limited. This paper describes a detailed research project underway by the writer, on behalf of the American Gas Association to develop design criteria for salt cavity storage of pressurized natural gas. The project consists of two major study areas; the development of suitable analytical (finite element) techniques and the laboratory investigation of the required physical properties of salt. This paper outlines the overall project and reviews the progress to date.

INTRODUCTION

There is little doubt that in the next twenty years, the utilization of cavities, from which salt has been extracted by conventional or solution mining techniques, will play a vital role in supporting the world's growing energy and environmental demands. Although the storage of liquids in salt cavities was initiated early in the 1920's, it was not until the mid 1960's that such facilities were utilized for storage of compressed natural gas. The first salt cavity in the United States developed specifically for natural gas storage was constructed in 1970 by The Transcontinental Gas Pipe Line Corporation in the Eminence Salt Dome in Covington County, Mississippi (Anon., 1971). Recent statistics indicate that as of 1975 only four salt cavity storage facilities for natural gas are in operation in the USA and Canada, however, it is expected that the use of such storage will increase considerably in the future.

Salt cavity storage of natural gas in many cases offers considerable advantage over conventional reservoir storage due to the characteristic high deliverability of such facilities. Furthermore, salt deposits, suitable for solution mining of gas storage cavities, exist in many areas where conventional reservoir or aquifer storage facilities are nonexistent or economically unfeasible. It is interesting to note, however, that although salt has been studied for many years by geologists and geophysicists, a review of the world literature indicates that the necessary expertise for designing, constructing and stability monitoring of engineering "structures" constructed in salt is relatively limited. Based on the preceding, in 1975 the Pipeline Research Committee of the American Gas Association (AGA) initiated a new research project (PR-12-71), in the Geomechanics Section at The Pennsylvania State University, involving the design and performance of salt cavities 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 cavity.

2. Application of established mechanics principles to the development of salt cavity design criteria.

3. Evaluation of techniques for monitoring the mechanical stability of salt cavity storage areas.

Due to time and economic limitations it was decided to concentrate the current AGA project efforts on areas (1) and (2), with research on area (3) being deferred to a later date. The current AGA salt cavity project involves theoretical studies to develop suitable methods for analysis of cavity behavior, and laboratory studies in which the basic mechanical behavior of salt is being investigated in order to evaluate the necessary parameters for use in the theoretical studies. A block diagram illustrating the overall project is given in Figure 1.

This paper will outline the overall project and briefly review progress to date. The writer will first discuss the general problem of dimensional stability in salt cavities. This will be followed by an outline of the laboratory and analytical aspects of the project. The paper will conclude with comments on the present status of the project. It should be pointed out that much of the material contained in the current paper has been presented in earlier papers prepared by the writer specifically for those in the natural gas industry (Hardy, 1976; Hardy and Roberts, 1977). The writer's main purpose here is to bring this study to the attention of those engineers and scientists involved specifically with salt in the hope of generating mutually beneficial feedback.

DIMENSIONAL STABILITY

General. In order to put the research underway in proper perspective, it is important to define the problem in terms of the fundamental mechanics principles involved. In simple terms salt-cavity storage involves the storage of a 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 insitu ground stresses. The mechanical stability of such a container depends on the internal pressure, the insitu 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

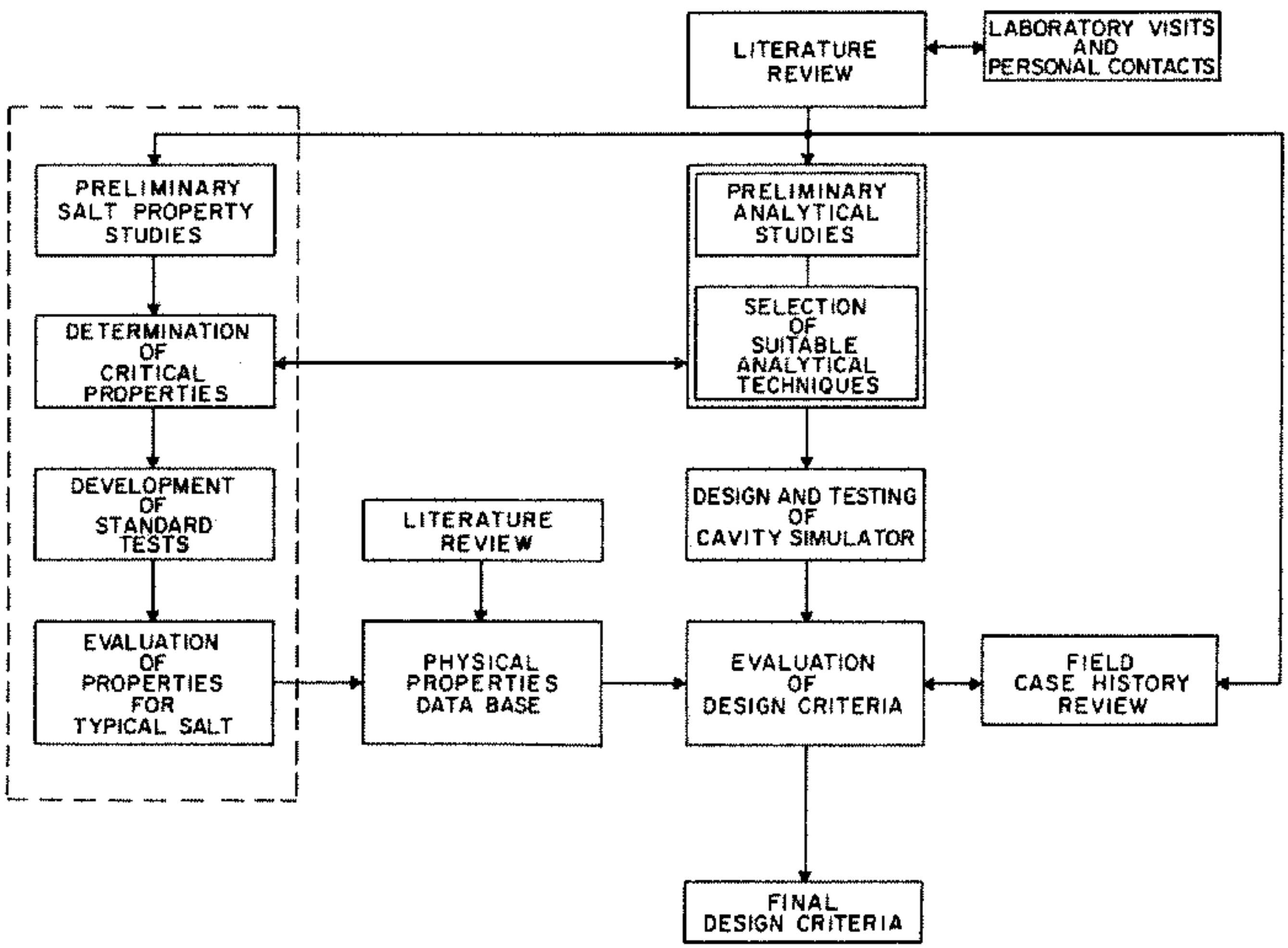

Figure 1. Block Diagram of Current AGA Research Project on Salt Cavity Design.

pressure as well as a maximum one. This 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 insitu stress field may be sufficient to overcome the "strength" of the surrounding salt causing cavity closure and/or failure.

State of stress near a cavity. Prior to solution mining of a cavity the vertical and horizontal virgin insitu stresses at the future cavity site are respectively σ_v and σ_h as noted in Figure 2A. It is assumed for simplicity in this discussion that the horizontal virgin stress field is isotropic in the horizontal plane, i.e., horizontal stresses are independent of direction. These stresses are a function of depth and of any orogenic conditions, and in general are homogeneous (constant) along a horizontal line such as A–B. When a single cavity is mined, as shown in Figure 2B, the homogeneous virgin stress field is distorted and stresses along a line such as C–D are found to vary with distance from the cavity (e.g., $\sigma_h' \neq \sigma_h$ and $\sigma_v' = \sigma_v$). A similar distortion of the stress field in fact occurs at all locations around the cavity, with stresses at various points increasing and decreasing from the original virgin values depending on location. It should be noted, however, that at distances of four to five times the maximum cavity dimension the stresses again approach the virgin values.

The ratio of the stress at any point in the structure with the cavity present, to the stress at that point without the cavity, is called the stress concentration factor (SCF). Although the virgin stress field is usually compressive, stress concentration factors may be either positive or negative depending on the specific location and the geometry of the cavity. Positive and negative stress concentration factors indicate the presence of compressive and tensile stresses respectively.

The application of internal pressure (P_I) to the cavity also modifies the surrounding stress field and, as in the insitu stress case, the stress field in the vicinity of the cavity will also be inhomogeneous. The total stress field in the vicinity of an underground pressurized cavity will therefore be due to the superposition of the effects of σ_V, σ_H, and P_I. In the case of a single cavity the critical stresses will occur at points on, or close to, the cavity boundary.

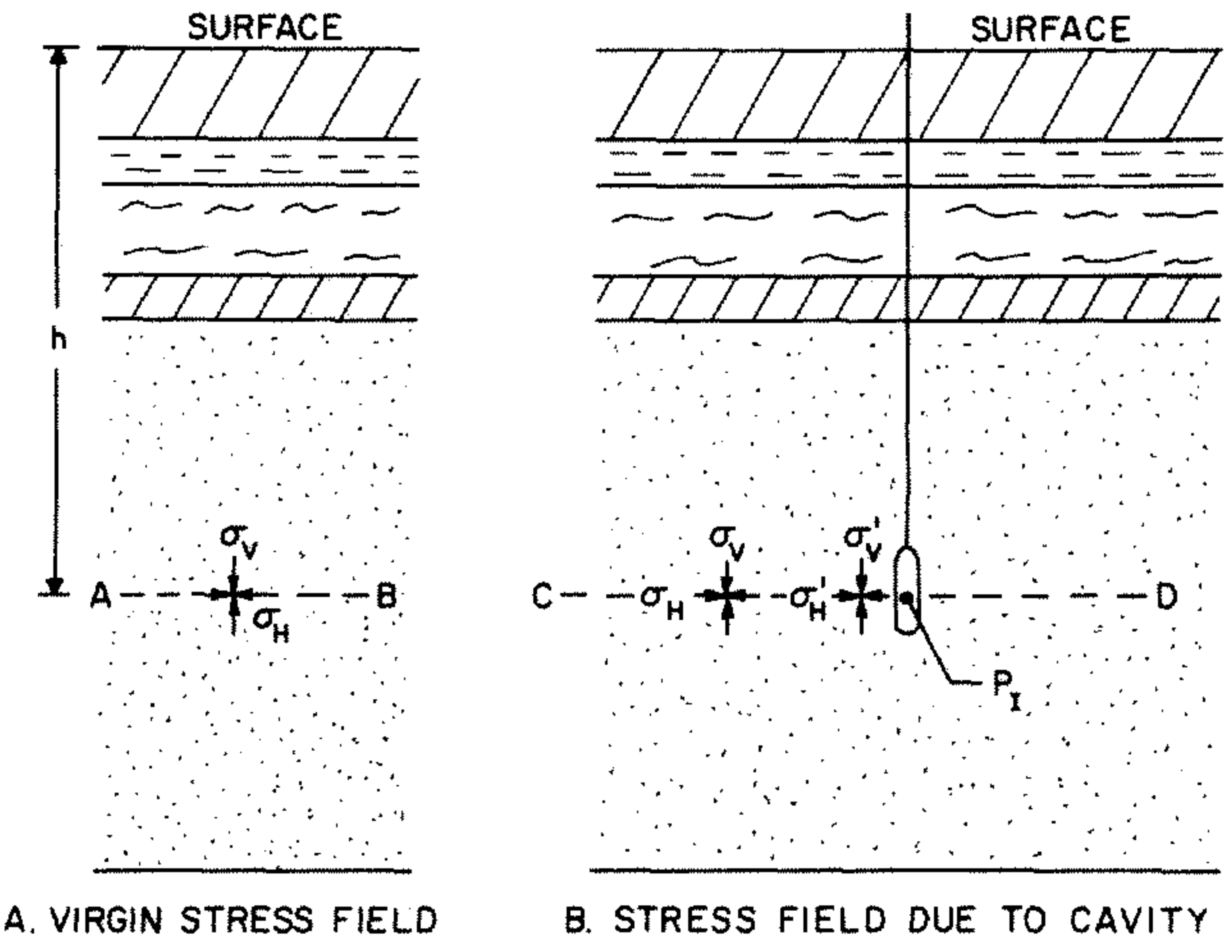

Figure 2. Underground Stresses Prior to and Following Cavity Formation.

In the final analysis it is the magnitude of the critical stresses, compared with the deformation moduli and "strengths" of the surrounding salt, that determine whether or not a specific cavity will be stable or not. It is important to note here that salt generally behaves as an inelastic material, whose mechanical behavior (deformation moduli and strength) depend on time and stress history. Furthermore, recent studies suggest that residual stresses associated with salt dome formation and/or other tectonic action may well play an important part in salt cavity stability.

Types of instabilities. There are a number of possible types of mechanical instabilities that may occur in solution mined storage cavities during and after their development (Hardy, 1977). These are illustrated in somewhat simplified form in Figures 3 and 4, and include subsurface and often eventual surface subsidence, closure, local fracture and block flow, deep fracturing, and various combinations of the above. It should be emphasized that at present the occurrence of gross instabilities of the type noted are rare; although small scale instabilities of most types probably occur frequently. It is apparent, however, that as salt cavity storage becomes more popular, and larger and more sophisticated cavity facilities are contemplated, careful site selection, more rigorous design techniques, and methods of early instability detection will be necessary to insure long-term cavity stability.

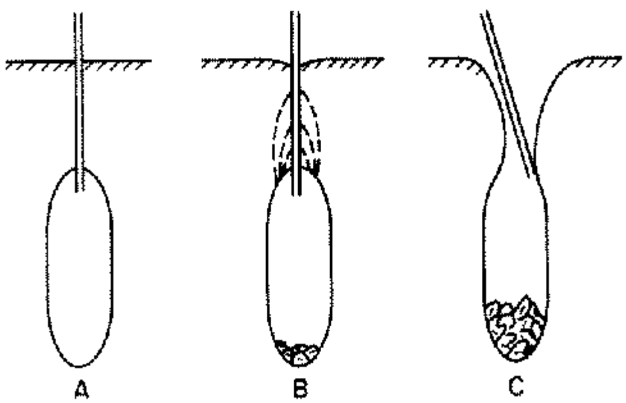

Figure 3. Subsurface and Surface Subsidence Associated with Storage Cavity Instability (A—initially stable cavity, B—development of subsurface subsidence, C—piping subsidence and resulting surface subsidence).

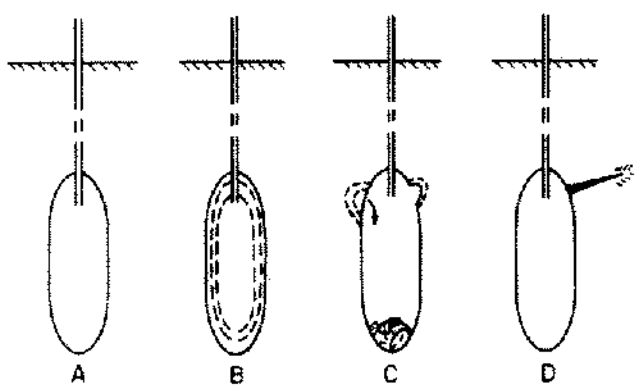

Figure 4. Closure, Local Fracture and Block Flow, and Deep Fracture Associated with Storage Cavity Instability (A—initially stable cavity, B—cavity closure, C—local fracture and block flow, D—deep fracture).

Subsidence. This type of instability, as illustrated in Figure 3, usually occurs during the development stage of storage cavities or in cavities originally developed for brine production. The potential for eventual surface subsidence and possible total cavity failure is greatest for shallow cavity depths. It may in some cases be initiated by poor cementing of production casing, lack of adequate blanket control, or high stress concentrations in the upper region of the cavity. Initially sections of the roof of the cavity are destroyed by solution and/or fracturing due to high localized stress concentrations; the damaged roof begins to sag and fracture; the fractured zone propagates upwards; and under certain conditions the motion of the fracture zone continues upwards causing either gentle surface subsidence, or in some cases massive, violent piping subsidence with extensive sink hole development. This type of instability is of particular concern in those cases where consideration is being given to converting cavities, originally developed for brine production, to storage use.

Closure. Salt cavity closure, in which the cavity volume effectively shrinks, is normally due to the presence of high insitu stresses and/or elevated temperatures. Figure 4B illustrates the phenomenon. Here the original cavity decreases in size as a function of time. Experience has shown that solution mined salt storage cavities normally experience an initial 5–10% closure during the first year or so following completion; however, there are cases where closures of 40–70% have been observed. Such situations would certainly have to be defined as a "facility failure." Since cavity closure is a stress dependent instability it is directly related to cavity depth and possibly in some instances to the presence of orogenic stresses. Such orogenic stresses may play an insignificant role in the closure of cavities located in bedded salt deposits, however, they may well be extremely important in those cases where the cavities are located in salt domes. Unfortunately the mechanics of salt dome formation and the associated insitu stress fields are not well known.

Local Fracture and Block Flow. In this type of instability regions of high stress, due to cavity geometry and/or stress field inhomogeneities, develop resulting in localized failure as shown in Figure 4C. Sections of the cavity wall fracture, eventually break away, and fall to the bottom of the cavity. Such an instability may continue indefinitely leading to extensive subsurface subsidence and at shallow cavity depths perhaps even failure to surface. On the other hand the local fracture may modify the cavity to a more stable geometry, reducing the associated stress concentration factors, and stopping the fracturing process. In salt this type of instability may well be more common in cavities located at shallow depths where lower internal cavity pressures are involved. Under these conditions the salt would behave as a brittle, elastic material and hence prone to fracture. In contrast in cavities located at greater depths storage conditions would more likely result in the salt behaving inelastically where flow rather than fracture would result.

Deep Fracturing. Under certain conditions deep, rather than surface fracturing, may occur in salt storage cavities as shown in Figure 4D. Here a condition similar to that occurring in hydrofracturing occurs, with one or a number of massive fractures, initiated at the cavity wall, propagating out into the salt surrounding the cavity. The initiation, extent, and propagation direction of such fracturing depends on the cavity geometry and internal pressure, and the direction and magnitude of the insitu stress field.

Occurrences of this type of instability have been reported associated with pressurized cavities in rocks other than salt, in gas storage reservoirs, and in waste disposal wells. In some cases the final result of such an instability has been of rather large scale; for example, horizontal strata displacements cutting-off active oil wells, and triggering of earthquakes.

Discussion. In review then the basic problem under study in the current project is that of formulating the criteria necessary for the design of economic and stable storage cavities in salt. To accomplish this it is necessary to gain a firm understanding of the basic mechanical behavior of salt, the possible modes of instability associated with cavities located in such a material, and the range of insitu stress fields (including possible residual stresses) in and around areas of domal and bedded salt.

PHYSICAL PROPERTY STUDIES

A major phase of the current project is associated with the evaluation of the physical properties of salt (Hardy and Roberts, 1977). Figure 1 presented earlier shows the relationship of the physical property studies to the overall project. Under room temperature and confinement most rocks behave as brittle, elastic materials, and a knowledge of their failure strengths and elastic moduli are often sufficient to describe their behavior under mechanical loading. Salt on the other hand is a much more complex material exhibiting a yield strength (initiation of plastic behavior), and time-dependent strain characteristics at a stress level considerably below its failure strength. A review of the literature available on the behavior of salt indicates that it must therefore, in general, be considered as an inelastic material most probably best described as viscoelastic-plastic in character.

Early in the project consideration was given to which of the mechanical properties of salt were most urgently required for use with the analytical procedures under development. Although these procedures were not yet finalized, it was evident early in the project that the following properties would be required: Young's modulus, Poisson's ratio, yield and ultimate strengths, and creep parameters. Furthermore, a review of earlier research by other workers on salt indicated the need for evaluation of the above properties for a range of temperatures and confining pressures.

During the early stages of the project an additional factor, namely the potential ability of salt to retain residual stress, was considered. Since it is possible that such residual stresses (particularly at salt dome storage sites) could result in excessive unpredicted cavity closure, it was decided to investigate this factor during the current project.

Figure 5 presents a block diagram of the overall physical property laboratory program. As indicated, the necessary physical property data (accessory, elastic, strength and inelastic properties) will be generated by the five studies shown to the right of the figure, 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) have been underway for some time. Besides these mechanical parameters a number of accessory parameters, such as specific gravity, are also under study.
2. *Creep Studies.* Creep studies under both uniaxial and triaxial conditions are underway to evaluate the visco-elastic-plastic parameters for salt. Two series of creep studies are involved. The first is a preliminary series where the total test duration is of the order of 14 days. These studies were completed in August 1977. The second series of tests involve test durations of a number of months and began in late 1977.
3. *Yield Strength Studies.* Here acoustic emission and petrofabric techniques are being employed in an attempt to develop objective means for evaluating the yield point in salt. These studies have been underway now for about 12 months and are expected to be completed by June 1978.
4. *Residual Stress Retention Studies.* Since residual stresses may be important in the analysis of salt cavity stability, particularly in salt domes, experiments were carried out to evaluate if and how residual stresses may be stored in salt. Preliminary studies were completed in late 1977.
5. *Failure Criteria Studies.* Initial analysis of the stress states associated with pressurized cavities loaded under typical insitu stresses have indicated that mixed states of compression (C) and tension (T) may occur. Studies are planned to evaluate the failure criteria of salt under the following states of stress: T–T–C, T–C–C, and C–C–C. At present however these studies are of low priority relative to the other four and only preliminary considerations have been given to initiation of the necessary test program.

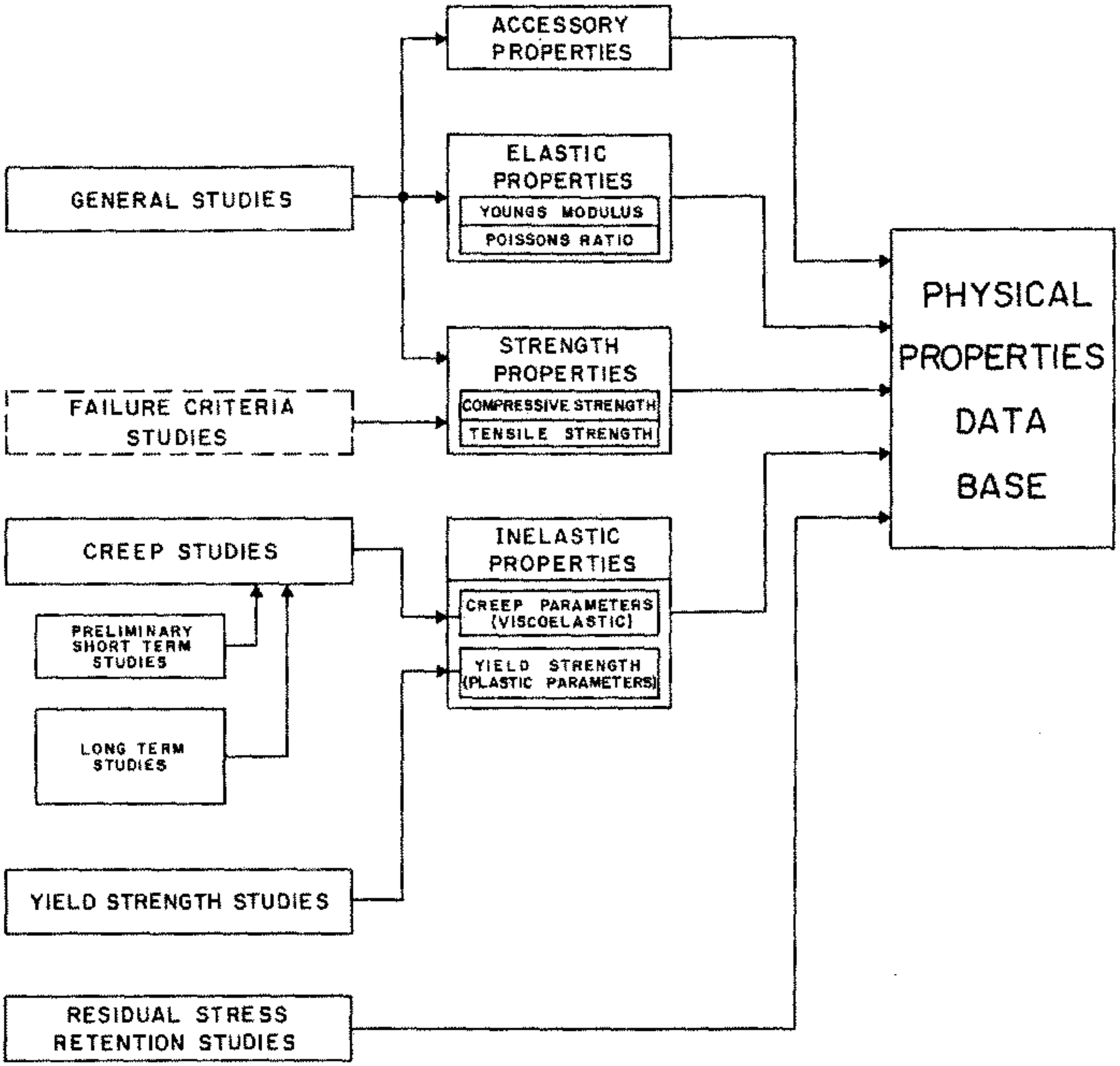

Figure 5. Block Diagram of Overall Physical Property Laboratory Program Associated with the Salt Cavity Design Project.

In order to gain a better appreciation of the overall mechanical behavior of salt a number of diagnostic parameters, such as ultrasonic velocity and acoustic emission, are being monitored during many of the mechanical tests.

As the associated analytical studies proceed, the need for laboratory values for additional critical properties may arise, however, until then the laboratory test program will be limited to evaluating the parameters noted earlier in this section. Where possible it is planned to obtain physical property data for as wide a range of salt as possible so that the effects of such factors as grain size, composition, fabric, etc. may be evaluated. All physical property data obtained during the current project, along with selected data abstracted from the literature, will form a physical property data base for use in the associated analytical studies.

ANALYTICAL STUDIES

In planning and designing of underground cavities, it is of considerable importance that the stresses and displacements in the rock mass subjected to arbitrary sequences of unloading and loading be within allowable limits. Analytic solutions are available only for a limited class of problems of simple geometry and idealized material properties. Non-linearity and time dependent behavior, material non-homogeneity and anisotropy coupled with complex geometrical configuration and initial stress fields, that are always pre-existent in rock masses at great depths, render the problem intractable by closed-form analytical methods. Approximate solution techniques, using numerical procedures, are therefore necessary in such cases.

One of these approximate techniques, the Finite Element Method (FEM), has developed during the last decade into a powerful tool for the analysis of various field problems in structural and continuum mechanics, having found extensive use in the area of soil and rock mechanics.

Essentially, the FEM consists in the replacing the actual continuum by a finite number of discrete elements or subregions. The geometry of the elements is defined by a set of points in space called the nodal points of the system. Figure 6, for example, shows a section of a FEM model for a spherical cavity (Khair, 1972). The fundamentals of finite element analysis have been presented in recent publications by a number of authors (e.g., Desai and Abel, 1973; Zienkiewicz, 1971; Martin, 1973).

The finite element technique is basically the only analytical tool available for evaluating the mechanical behavior of salt cavities. The technique has been employed at Penn State in an earlier AGA project associated with reservoir pressure optimization (Hardy, 1972) with considerable success. Basically this technique allows the researcher to mathematically carry out the following operations:

1. model the storage cavity and surrounding strata,
2. apply various insitu ground stresses and storage pressures, and,
3. observe the resulting stress distribution and deformation occurring in and around the reservoir.

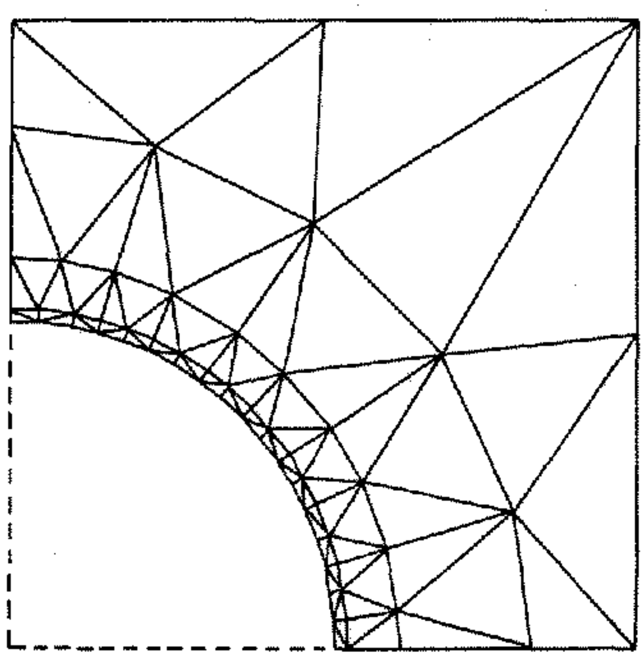

Figure 6. Section of a FEM Model for a Spherical Cavity. (After Khair, 1972).

For example, once the computer is programmed for a specific cavity shape and for the mechanical properties of the surrounding strata then the insitu stress and reservoir pressures can be varied over a wide range to ascertain their effect on cavity behavior. In contrast the computer can be programmed for cavity shape, and insitu stress and cavity pressure, then the mechanical properties of the surrounding strata can be varied to study their effect on cavity behavior. In effect the FEM provides a technique for simulating salt cavity behavior, i.e., a "cavity simulator." In this study it is planned to first investigate the behavior of various shaped single cavities, then later the behavior of multiple cavity arrays.

Unfortunately the quality of the information obtained using the finite element technique is only as good as the input data. For example, as indicated earlier in this paper in order to carry out meaningful analytical studies requires a knowledge of the mechanical properties of the surrounding salt. Furthermore, the format of the finite element program used will depend on whether the salt is considered to behave as an elastic, elastic-plastic, or viscoelastic-plastic material, and on the type of failure or yield criteria utilized.

Figure 1, presented earlier, shows the relationship of the analytical studies to the overall project. The main object in these studies is to develop a suitable cavity simulator which may then be utilized to study the theoretical behavior of various cavity shapes, under a wide range of field conditions, leading to the development of a variety of tentative cavity design criteria. Finally, these tentative criteria will be examined in detail using input information obtained from the physical properties data base, and from field case history reviews. If successful the final product of the project will be a set of practical salt cavity design criteria.

PRESENT PROJECT STATUS

The salt cavity design project has been underway now for approximately three years, although the first year of the project was in effect a brief feasibility study. During this time an extensive literature review has been completed, detailed physical property studies have been carried out on salt, and progress has been made in the development of suitable analytical techniques.

From the physical properties point-of-view, a variety of problems associated with the acquisition of suitable sample material, specimen preparation and strain instrumentation, and the adaptation of a wide range of laboratory test techniques to salt have been resolved. During 1977 major studies associated with the measurement of short-term creep, residual stress retention, and yield strength have effectively been completed. As well as a variety of general mechanical studies have been carried out. Further details on a number of these studies have been presented elsewhere (Hardy and Roberts, 1977; Mangolds, 1978; and Richardson, 1978). The major physical property study presently underway is associated with the evaluation of the long-term creep behavior of salt under uniaxial and triaxial stress conditions.

Progress in the analytical phase of the project has been somewhat slower than anticipated due to difficulties inherent in the development of suitable finite element computer programs applicable to viscoelastic-plastic materials such as salt. Initially a series of elastic analyses were undertaken utilizing the SOLID SAP program (*Solid Structural Analysis Program*) developed at the University of California, Berkeley (Wilson, 1971). In particular the behavior of a spherical cavity has been investigated under typical insitu stresses and internal pressure.

More recently research has been underway to modify the BOPACE-3D program (*Boeing Plastic Analysis Capability* for *3-Dimensional* Solids) developed by the Boeing Aerospace Company, Seattle (Vos and Staayer, 1974) for use in the current studies. In its original form this program was developed for analysis of elastic-plastic-creep behavior in three-dimensional structures under a wide range of temperature conditions. Unfortunately the program was originally written for UNIVAC computer systems and much of the effort to date has involved translating the program for use with the Penn State IBM/168 computer facilities. It is hoped that the BOPAC-3D program will be debugged and fully operational later this year. If so, it should prove to be an extremely powerful analytical tool for the analysis of salt cavity behavior.

In summary it is felt that the current salt cavity design project is progressing satisfactorily considering the inherent complexity of the problem.

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