Finite Element Analysis of Salt Caverns Employed in the Strategic Petroleum Reserve*

Dale S. Preece
Jerry T. Foley
Sandia National Laboratories
Albuquerque, New Mexico, USA

ABSTRACT

A finite element computer program, developed previously to predict the creep response of bedded rock salt, has also been used to successfully predict the creep closure rates of several caverns using an approximation of the cavern geometry and material properties from the site.

The caverns at Bryan Mound, Texas have been analyzed with this program by approximating each with a two-dimensional axisymmetric finite element mesh. Initial leaching and thermal effects were treated in an approximate manner. An element deletion technique was used to simulate the leaching that occurs when oil is withdrawn and replaced with fresh water.

Each cavern was analyzed for thirty years and an indication of the long-term stability and volume change was obtained. This information will be used in the formulation of operating procedures for the cavern.

INTRODUCTION

The U.S. Strategic Petroleum Reserves (SPR) is a National Program devoted to reducing America's dependence on imported oil. The program calls for storage of approximately 750 million barrels of crude oil or more. Salt caverns leached in salt domes around the Gulf of Mexico have been identified as economical sites to store the majority of this petroleum. This plan allows easy access to the shipping lanes and pipeline networks which already carry much of the flow of foreign oil into the country. The naturally occurring salt domes also provide an excellent underground storage medium that is safer and more economical than steel tanks.

Another advantage to the use of salt domes is the availability of an existing mine and numerous caverns which are suitable for purchase and immediate petroleum storage. The final storage volume will thus be split between an existing mine, existing caverns and newly leached caverns in five salt domes around the Gulf.

The purpose of this paper is to present results of finite element analyses of caverns at Bryan Mound, Texas which were previously leached by industry and recently purchased for use in the SPR.

*This work was performed at Sandia National Laboratories and was supported by the U.S. Department of Energy under contract number DE-AC04-76DP00789 for the U.S. Department of Energy.

BRYAN MOUND SALT DOME

The Bryan Mound salt dome is located in southeastern Texas near the city of Freeport, approximately two miles inland from the Gulf. The edges of the dome have been explored for oil since 1901, but the amount produced has been small. The major use of the site has been production of sulphur from the carprock and brine from five leached caverns. These five caverns were acquired by the U.S. Department of Energy (DOE) in April 1977 for use in the SPR program. All of the caverns underwent certification studies between 1977 and 1979 and all were deemed suitable for oil storage except Cavern Three, which appeared to have some fresh water circulation. New wells were drilled into the caverns to meet design injection and withdrawal, and oil injection started in October, 1977 (Hogan, 1970, pg. 1-1). The five caverns at Bryan Mound were analyzed in the present study to confirm the structural safety of the caverns and to predict the volume losses from the caverns due to creep closure. Figure 1 shows a plan view of the Bryan Mound salt dome and the five existing caverns in relation to each other and to the edge of the dome.

ANALYSIS APPROACH

Finite Element Program. The finite element method offers the flexibility to treat almost any geometrical shape

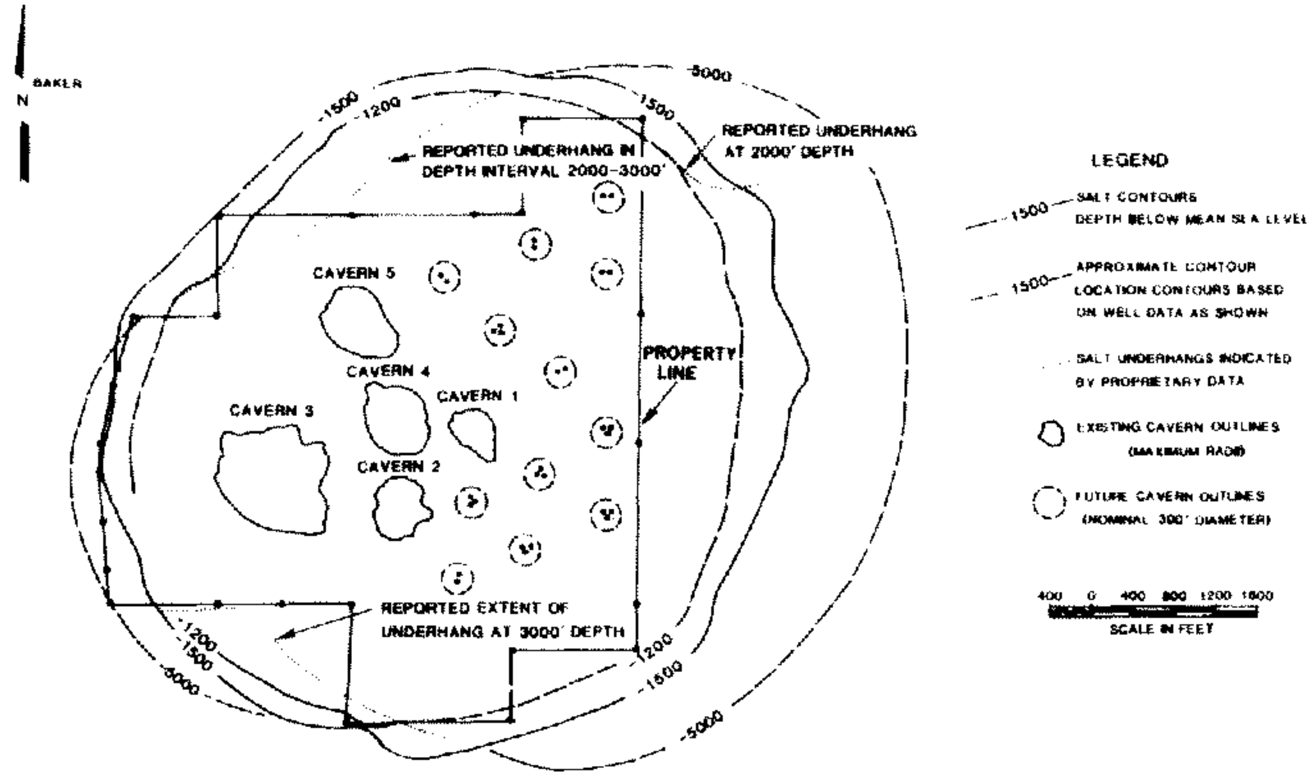

Figure 1. Plan View of Bryan Mound Salt Dome.

under a variety of loads. This makes it ideal for analyzing salt caverns that vary greatly in shape and average depth.

A considerable amount of development work has been done on a finite element program to predict the creep response of bedded rock salt (Key, 1980). This program was one of nine codes used in the Benchmark II exercise wherein a generic drift for nuclear waste isolation in bedded salt was analyzed (Morgan, 1981). The program's results compared very well with results from the eight other structural codes that were exercised in the benchmark study. This program was also used to analyze existing caverns that had been instrumented to provide pressure increase in capped caverns or volume change data due to creep closure. The results of the analysis were in agreement with the field data giving improved confidence in future work (Preece, 1982B).

Volumetric Calculations. The wellhead usually provides the only access to a cavern, and consequently it is the only point to monitor cavern response. Typical information coming from an instrumented wellhead includes pressure increase from fluid thermal expansion (due to heating the oil from injection temperature to in-situ temperature) and creep closure, and flow from the cavern when the wellhead is opened to reduce pressure. These two parameters provide operators with a daily cavern volume change which we will call cavern flow rate.

The finite element program computes the nodal displacements at the end of each time step specified by the user. The volume of the cavern at each time step is computed by using the coordinates and displacements at each node on the cavern surface. The volume and time data can then be manipulated into flow rates and pressure increases. It needs to be remembered that the predicted flow rates given later in this paper were obtained in this manner and do not include the flow rate due to thermal expansion of cavern fluid. Limited data have shown the pressure increase due to fluid thermal expansion to be about ten percent of that due to creep closure (Preece, 1982A, pg. 21).

Material Properties. The program uses an elastic constitutive model and a secondary creep strain model of the form

$$\dot{\bar{e}}_s = A\exp(-Q/RT)(\sigma)^n \quad (1)$$

where

$\dot{\bar{e}}_s$ = secondary effective creep strain rate
A = laboratory determined constant
Q = activation energy
R = universal gas constant
T = temperature in degrees Kelvin
σ = effective stress
n = stress exponent.

The coefficients in the above equation have been determined by thorough triaxial creep testing of Bryan Mound salt to be: (Wawersik, 1980)

$A = 9.51 \times 10^{17}$ (units in days and psf)
$Q = 12.1$ Kcal/mole° K
$n = 3.62.$

The elastic properties of the salt were determined from standard triaxial creep tests to be: (Wawersik, 1980)

$$\text{Youngs Modulus} = 6.80 \times 10^{8}\ \text{psf}$$
$$\text{Poissons ratio} = .33.$$

Determining Mesh Width. The program can currently analyze only two-dimensional plane strain or axisymmetric shapes and since the true caverns are three-dimensional, some approximation is required. If a cylindrical cavern were surrounded by six other equal sized cylindrical caverns, as shown in Figure 2, the width of the mesh shown in Figure 3 can be taken as one-half the center-to-center distance between caverns. An axisymmetric treatment of this mesh will provide an approximation to the three-dimensional geometry.

If, however, an example cavern we desire to analyze is surrounded by caverns on the same level, as shown in Figure 4, the mesh width for analyzing cavern A is determined by averaging half the pillar widths to surrounding caverns. In cases where there is a 180-degree arc around a cavern, where no other caverns exist on the same level, we also include (in the averaging process) the pillar distance required to simulate an infinite boundary. This distance has been determined to be approximately eight times the cavern diameter (Preece, 1980A, pg. 14). Using this information, we can calculate the mesh width required for cavern A in Figure 4 as

$$W = \frac{AB/2 + AC/2 + AD/2 + 8d}{4} + \frac{d}{2}. \qquad (2)$$

The outer boundary of the mesh describing cavern A is also shown in Figure 4. Comparison with limited field data has

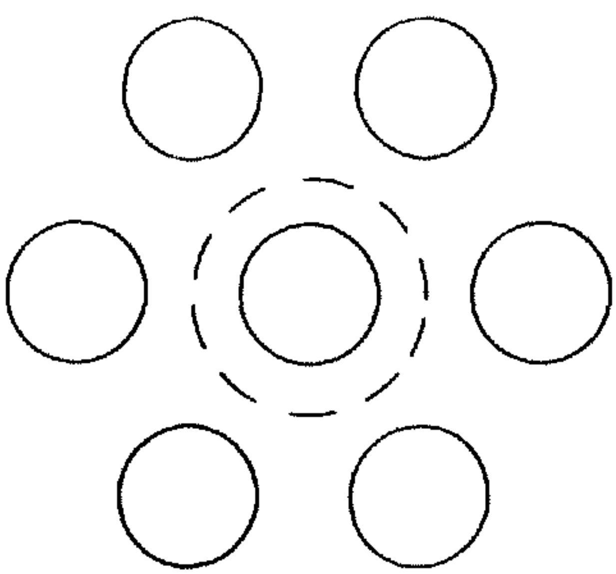

Figure 2. Top View of Cylindrical Cavern Array.

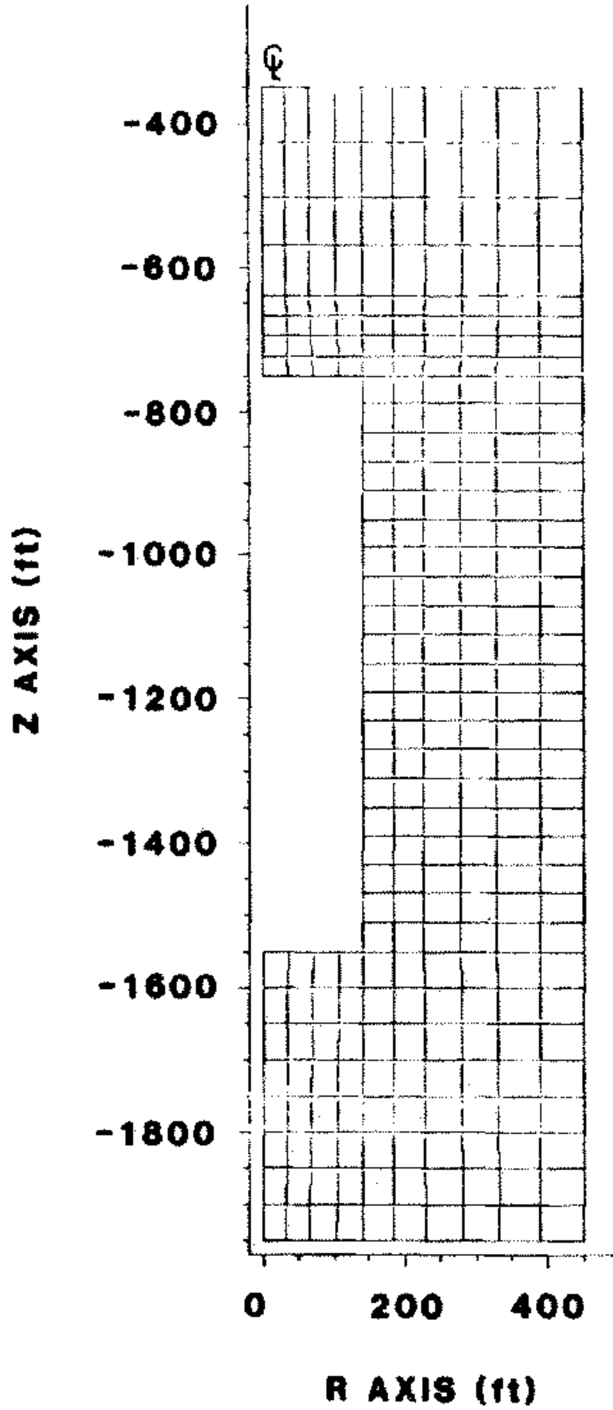

Figure 3. Vertical Axisymmetric Finite Element Mesh of Cylindrical Cavern.

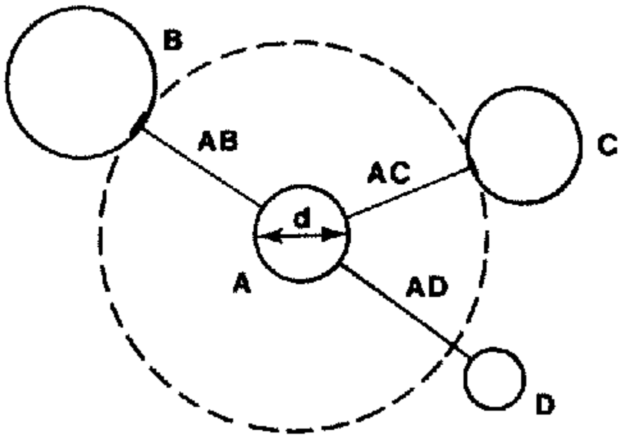

Figure 4. Top View of a Typical Cavern Group.

shown the method to be valid. However, more data and subsequent analysis of the data source would be helpful and is being actively pursued.

Sometimes, two caverns are close enough together to violate the recommended P/D (pillar to diameter ratio) of 1.8 (Hart, 1981, pg. 1-3). In this case, an analysis is performed to determine the stability of the pillar with the mesh width being chosen as half the pillar width plus the cavern radius. This is a conservative method which implies that there are six caverns surrounding the cavern of interest, each with the same pillar width. If this cavern configuration can be shown to be stable, then the actual cavern with only one other cavern at the specified pillar width should also be stable.

Determining Mesh Height. Prior to the present set of analyses, the vertical distance between top and bottom boundaries was made three times the height of the cavern with the cavern situated in the middle. This works very well with a long slender cavern, but some of the caverns at Bryan Mound are shorter and wider than normal. It was determined that there should be at least twice the widest radius of the cavern in the mesh above the cavern and preferably three times. This was determined from the state of effective stress at the top boundary after 60 years of creep stress relief. It is desirable to have the effective stress at the top of the mesh less than ten percent of the effective stress immediately surrounding the cavern. This assures minimal interference of the top of the mesh with the cavern response.

Boundary Conditions. The finite element mesh of Bryan Mound Cavern One is shown in Figure 5. The boundary conditions applied to this mesh are typical of those applied to the other caverns in this report. Across the top of the mesh is placed a lithostatic pressure corresponding to its depth (1 psi per foot of depth). Inside the cavern is a brinehead pressure from the surface of the ground (0.521 psi per foot of depth). Since brinehead pressure is less than lithostatic pressure, the cavern will creep inward.

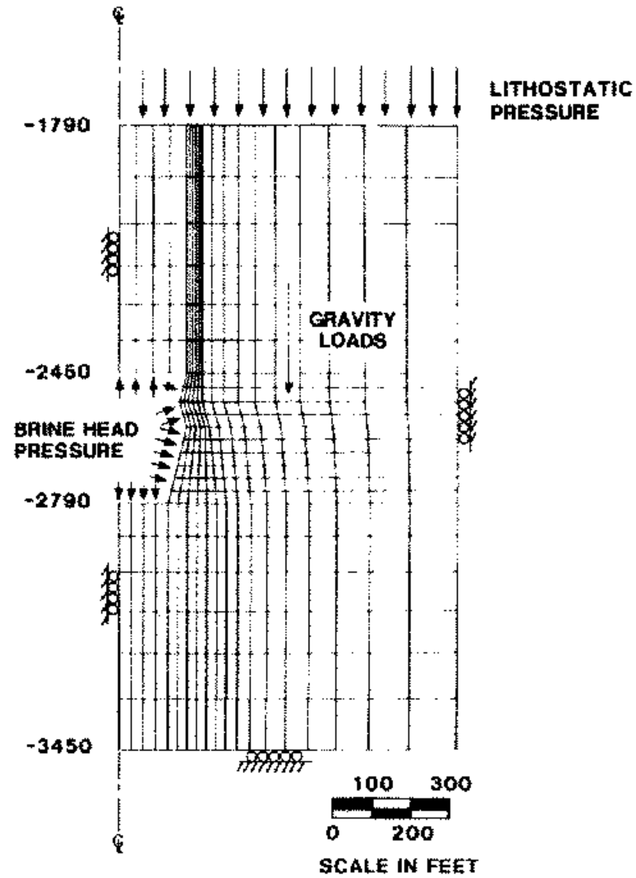

Figure 5. Axisymmetric Finite Element Model of Bryan Mound Cavern One.

The right and left sides of the mesh are allowed to move vertically, but they are fixed horizontally, as indicated by the vertical rollers. The bottom of the mesh is allowed to move horizontally, but it is fixed vertically. The creep algorithm requires a stress state to predict the next set of creep displacements in time. To start the algorithm correctly, an initial lithostatic stress state is computed for the entire mesh and is used during the first time step.

Simulating Initial Cavern Leaching. Each cavern starts as a borehole and gradually grows as fresh water is pumped in and brine is pumped out. The borehole disturbs the global state of stress away from the hole very little, leaving a state of lithostatic stress throughout the region where the cavern will be leached. The stress at the current cavern surface gradually changes with time from lithostatic to brinehead as the cavern develops from a borehole to its present state. It has been determined that this leaching process must be simulated in order to accurately predict the cavern response immediately after leaching is completed. One method is to linearly reduce the pressure inside the current cavern geometry from lithostatic to brinehead over a finite period of time. Figure 6 shows the predicted flow rate from a cavern for three different treatments of

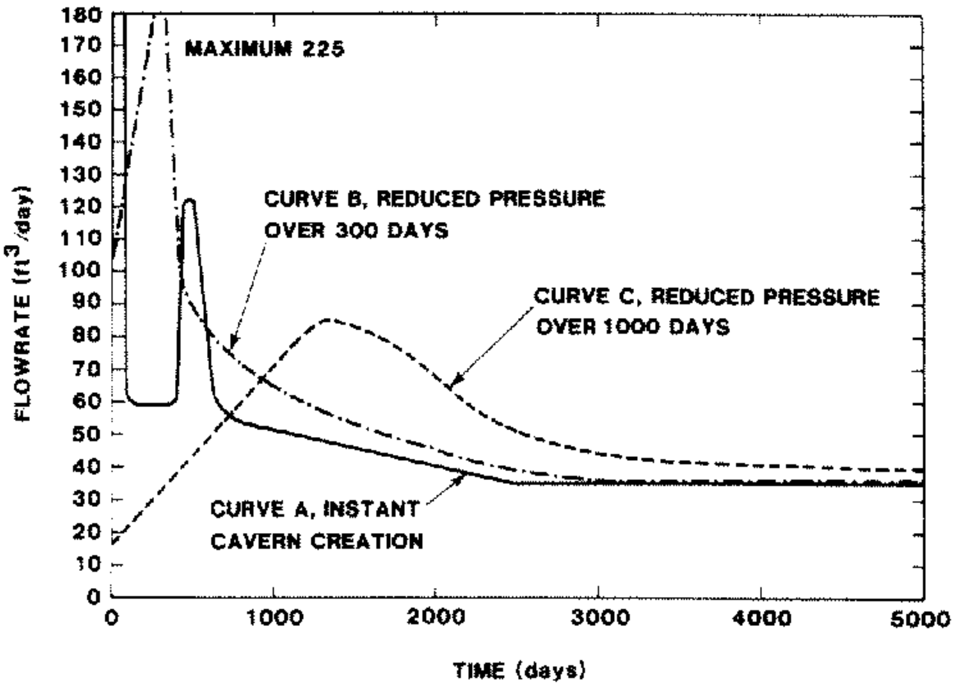

Figure 6. Flowrate Versus Time for Three Different Treatments of the Initial Leaching Process.

the initial leaching. Curve A shows the cavern response when it is loaded initially with brinehead pressure inside. In this case, the effective stress around the cavern is very large initially and gradually decays through creep stress relief. The jump in Curve A at 500 days is probably not real but is the result of numerical oscillation as the system adjusts to the instantaneous loading. Curves B and C show the cavern response when the pressure inside is reduced from lithostatic to brinehead over 300 days and 1000 days, respectively. In these cases, the initial effective stress around the cavern is zero as it would be before the cavern was leached. The effective stress increases as the inside pressure is reduced. At the time the interior reaches brinehead pressure, the effective stress around the cavern is at a maximum, then it gradually dissipates with time to steady state effective stress. In all three cases, the steady state effective stress distribution on the mesh is essentially the same and it corresponds to the steady state flowrate from about 3000 days on in Figure 6. In all three cases, the flow rate at time zero results from the initial elastic response of the cavern.

Simulating Cavern Leaching During Oil Withdrawal. The SPR program is designed to allow five oil withdrawals of each cavern during its thirty-year life. When the oil is withdrawn, it is replaced by fresh water, which leaches the cavern to a larger size. A computer program (Saberian, 1977) for predicting leaching was obtained by the Fluid and Thermal Sciences Department at Sandia and changed to better meet SPR needs. This program (Russo, 1981) was used to predict the new cavern size after each leaching cycle. The cavern leaching was taken into account during the finite element analysis by predefining the mesh to match the layers that were predicted to be leached, as shown in Figure 7. The timing of the five withdrawals is not known a priori, since it depends on the national energy situation. For analytical purposes, the withdrawals were divided evenly over the life of the SPR program (30 years), which results in one withdrawal every six years. At the time the withdrawal occurs, the pressure is transferred from the current cavern surface to the newly created surfaces as the layer of leached elements is removed. The creep closure, and hence the flow rate, from the cavern in-

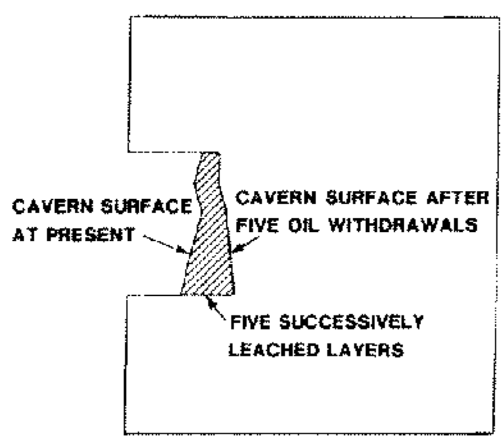

Figure 7. Bryan Mound Cavern One with Leached Layers Crosshatched.

creases because the volume has increased. Figure 8 shows the total volume of Cavern One plotted against time. Each step in the curve represents a volume increase due to leaching. After each volume increase, the cavern continues to creep inward as shown in the close-up of one leaching cycle in Figure 9.

Temperature Effects. As can be seen in Equation (1), the creep rate is an exponential function of temperature. The fluid going into the cavern is approximately 70°F and gradually heats to the in-situ temperature of the cavern (between 100°F and 130°F depending on depth). This has two effects. First, the fluid expands as it heats and flows from the cavern if the wellhead is open, or the internal pressure increases if the wellhead is shut. Second, the fluid cools the walls of the cavern, resulting in thermal contraction and temporary reduction in creep rate. The computer program has the capability to treat the thermal stress problem and also the thermal influence on creep. A thermal analysis of one cavern included the initial placement of cool fluid in a cavern and subsequent injections of cool fluid for the drawdown/leaching cycles. This time-dependent thermal field was included in the structural creep analysis of the cavern. The same analysis was also made without the time-dependent thermal field but using a constant temperature corresponding to the average temperature of the mesh. Immediately after the first cool fluid injection, the analysis that included the thermal field had a flow rate that was 50% less than the flow rate in the constant temperature analysis. Within three or four years, however, the two flow rates were about the same. Including a thermal analysis in each cavern structural analysis proved to be more expensive than the current computing budget allowed, so each analysis was performed with a constant temperature. It is felt that this gives a good representation of the cavern performance three or four years from the time of injection.

Predicting Salt Fracture. A function which conservatively predicts when rock salt will fracture or crush has been proposed by Wolfgang Wawersik (Miller, 1982, pg. 36–37). This function relates confining pressure and effective creep strain and becomes positive when the potential for fracture or crushing exists:

$$\phi = 150.0\,(\epsilon - 0.023 - f(P))$$

$$f(P) = \begin{cases} 0.132 \text{ for } P \geq 1.256 \times 10^5 \text{ psf} \\ (2.117 \times 10^{-6})P - (8.450 \times 10^{12})P^2 \\ \quad\text{otherwise} \end{cases}$$

where

ϕ = fracture/crush function

$P = (\sigma_1 + \sigma_2 + \sigma_3)/3.0$ (confining pressure)

$f(P)$ = function of confining pressure.

Possible problem regions around a cavern are determined by post-processing the finite element data to determine whether the function ϕ is positive anywhere on the mesh. There is no provision for computing ϕ during the analysis and redistributing stresses when fracture occurs.

BRYAN MOUND CAVERN ONE

The well for Bryan Mound Cavern One was initially drilled in 1942. The volume of the cavern is currently 5.3 million barrels (mmb) (2.98×10^7 ft^3). The cavern is located well away from the edge of the dome and the caprock but has a pillar of only 245 feet between it and Cavern Four. Caverns Four and Five are the only existing caverns that are on the same level as Cavern One. Two new caverns will be leached about 800 feet away and two more new caverns will be leached about 1000 feet from Cavern One on the same level. The shape and dimensions of the cavern as determined from sonar data are shown in Figure 10 (Hogan, 1980, pg. 4). The finite element model of Cavern One is shown in Figure 5 and has a volume of 5.0 mmb (2.80×10^7 ft^3). The volumetric response of the cavern versus time is given in Figure 8 and a summary of the flow rates immediately before each oil withdrawal is given in Table 1.

Post-processing of the fracture/crush function given earlier shows the cavern to be structurally sound and will continue as such through the first several drawdown cycles. There is the possibility of coalescence with Cavern Four on the second or third drawdown, requiring that the growth of both caverns be monitored closely. Because of our two-dimensional approach, the present analysis will not predict the stresses or fracturing of the pillar as the two caverns approach each other. This can, however, be treated approximately by performing another analysis with a narrower mesh.

BRYAN MOUND CAVERN TWO

The initial well for Cavern Two was drilled in 1942 and the 5.5 mmb (3.09×10^7 ft^3) cavern shown in Figure 11 was subsequently developed. Cavern Three is the only cavern (including the new caverns) on the same level as Cavern Two and it is located 450 feet away. The cavern is well away from the edge of the dome, but it is only 365 feet below the caprock. This distance has been found suitable by past and present finite element analyses (Hogan, 1980, p. 4). The finite element model, as shown in Figure 12, has a volume of 4.9 mmb (2.75×10^7 ft^3). The volumetric response of the cavern versus time is given in Figure 13 and the flow rates immediately before each oil withdrawal are given in Table 2.

TABLE 1

Cavern One Flowrates

Withdrawal Number	Initial	1	2	3	4	5
Volume ($\times 10^7$ ft^3)	2.80	3.29	3.90	4.56	5.27	6.00
Flowrate (ft^3/day)	22.0	31.3	39.6	51.8	64.0	75.3

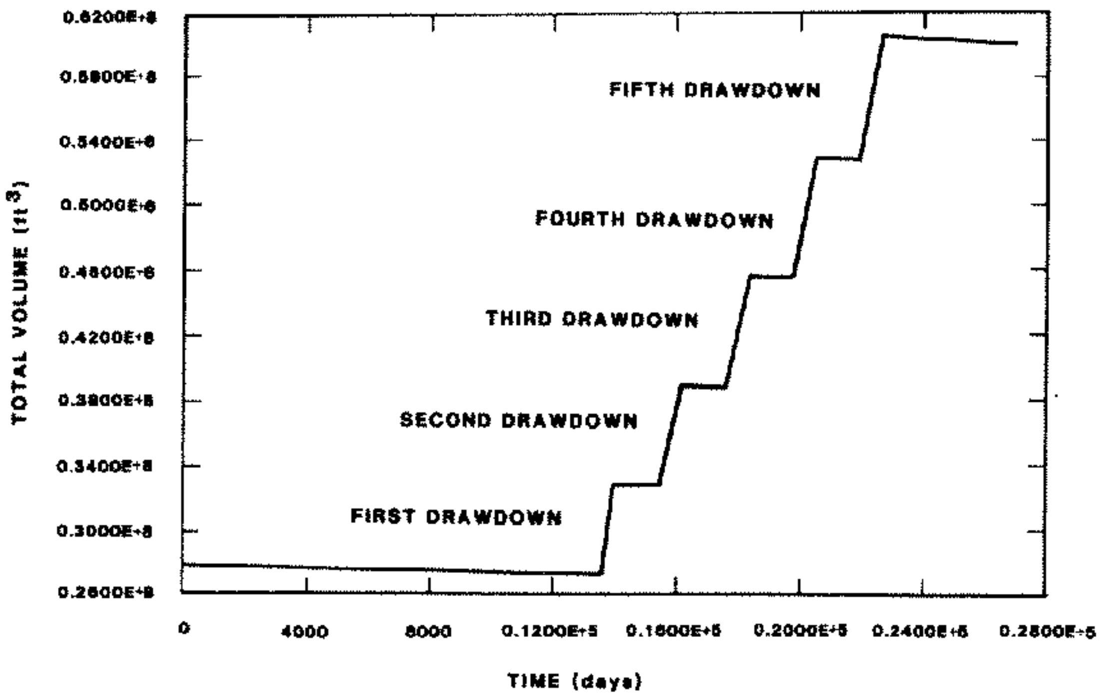

Figure 8. Volumetric Response of Cavern One.

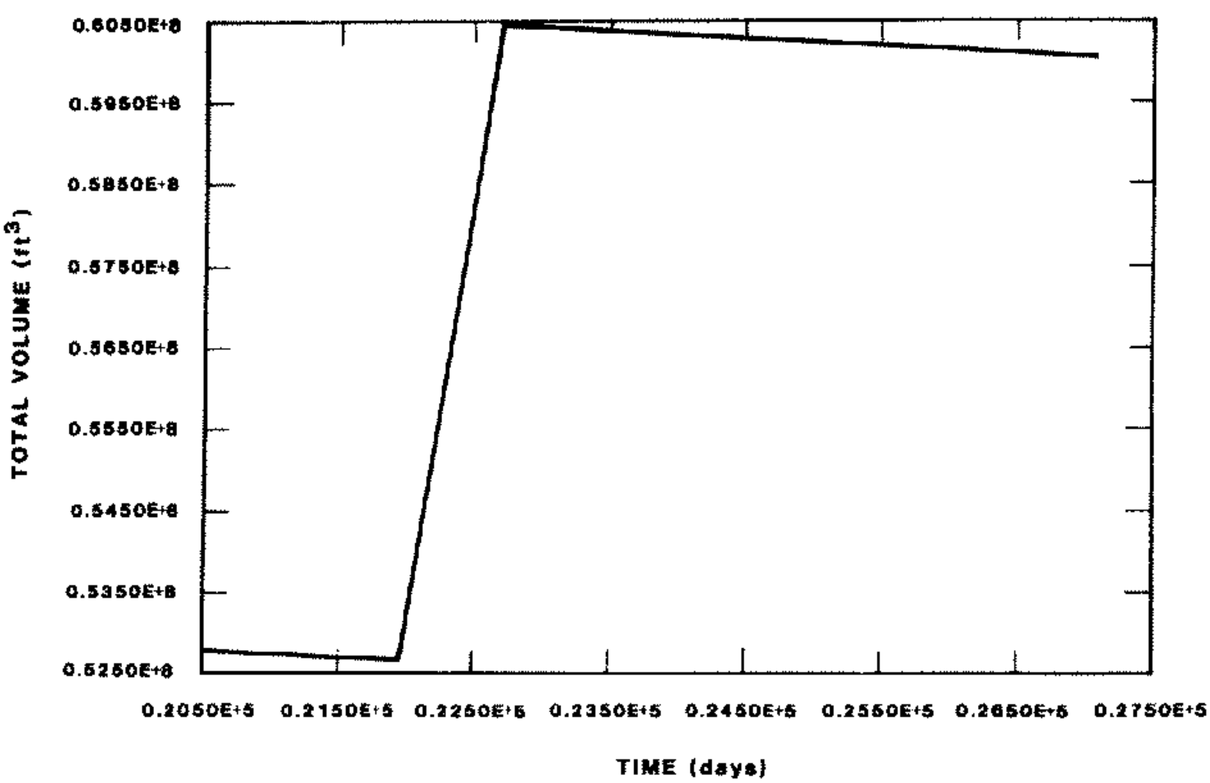

Figure 9. Final Leaching Cycle of Bryan Mound Cavern One.

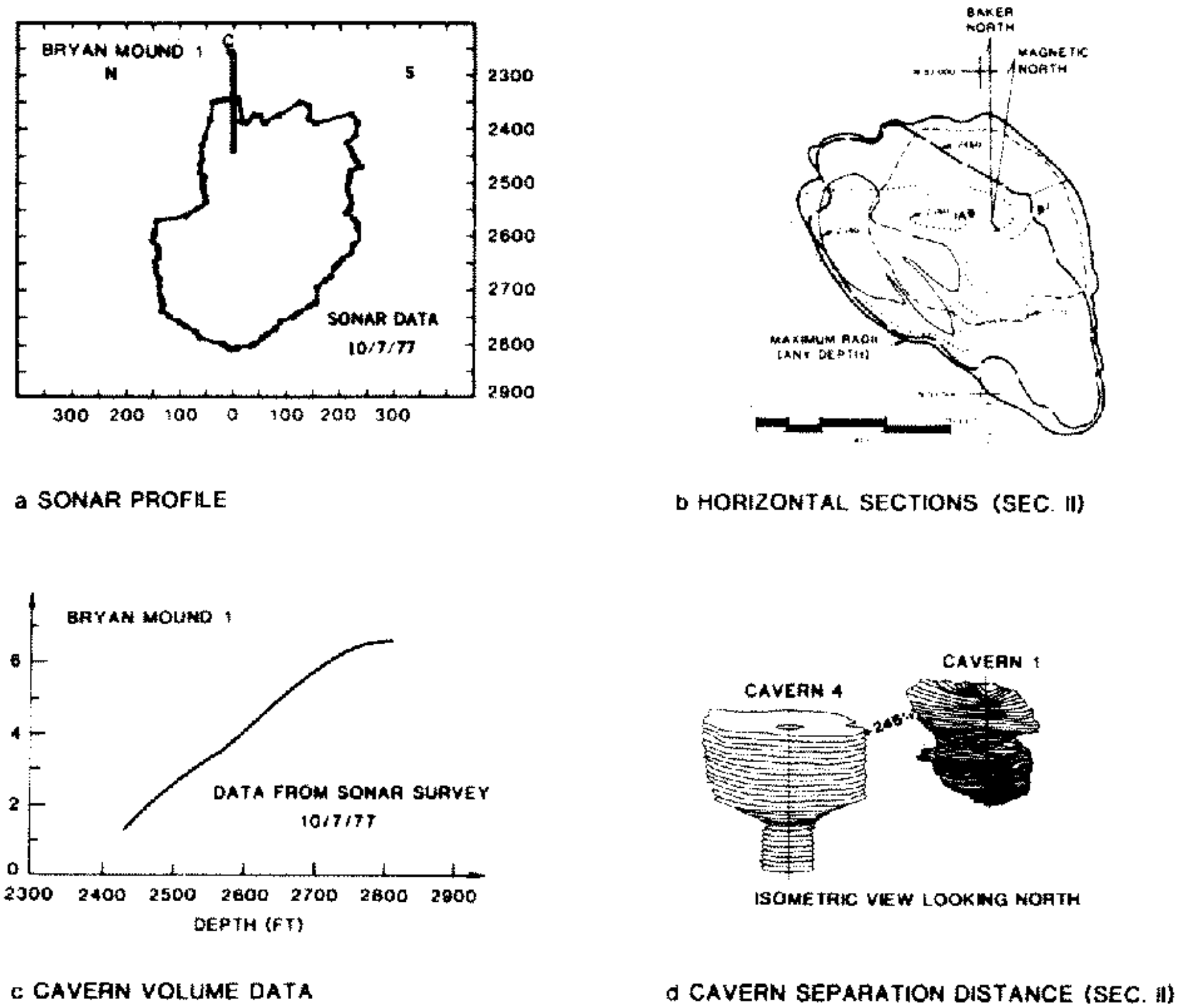

Figure 10. Bryan Mound Cavern One.

Results from the fracture/crush function show this cavern to be structurally sound throughout its entire SPR life including the five drawdown cycles.

BRYAN MOUND CAVERN THREE

Cavern Three was initiated in 1941 and currently has a volume of 6.4 mmb (3.59×10^7 ft^3). This cavern was purchased for oil storage along with the rest of the caverns but was subsequently deemed unsuitable for oil storage. Early in its testing, it appeared to have fresh water circulation and continual leaching taking place within the cavern. There are also problems with the well leaking, and until both of these problems are fixed or reconciled, oil will not be stored in this cavern (Hogan, 1980, pg. 5).

A finite element analysis of the cavern was carried out in the present study to confirm its structural stability over the life of the SPR program and to predict the creep closure rate of the cavern.

The Cavern, shown in Figure 14, is relatively shallow and Cavern Two is the only other cavern on the same level. The finite element mesh which has a cavern volume of 12.76 mmb (7.16×10^7 ft^3) is shown in Figure 15. The mesh was made using the largest cross-section found in the sonar surveys. It was used because showing that this larger cavern is structurally sound would also indicate the safety of the actual cavern. The fracture/crush function shows this cavern to be stable throughout the life of the SPR program. The analysis predicts a loss of approximately two percent of the original volume over sixty years. Unfortunately, there does not seem to be any field data for comparison.

BRYAN MOUND CAVERN FOUR

Cavern Four is the second largest cavern in the SPR program with a volume of 16.3 mmb (9.15×10^7 ft^3). The well for this cavern was drilled in 1942 and gradually developed into the shape shown in Figure 16. This cavern is approximately in the center of the dome and is 1500 feet

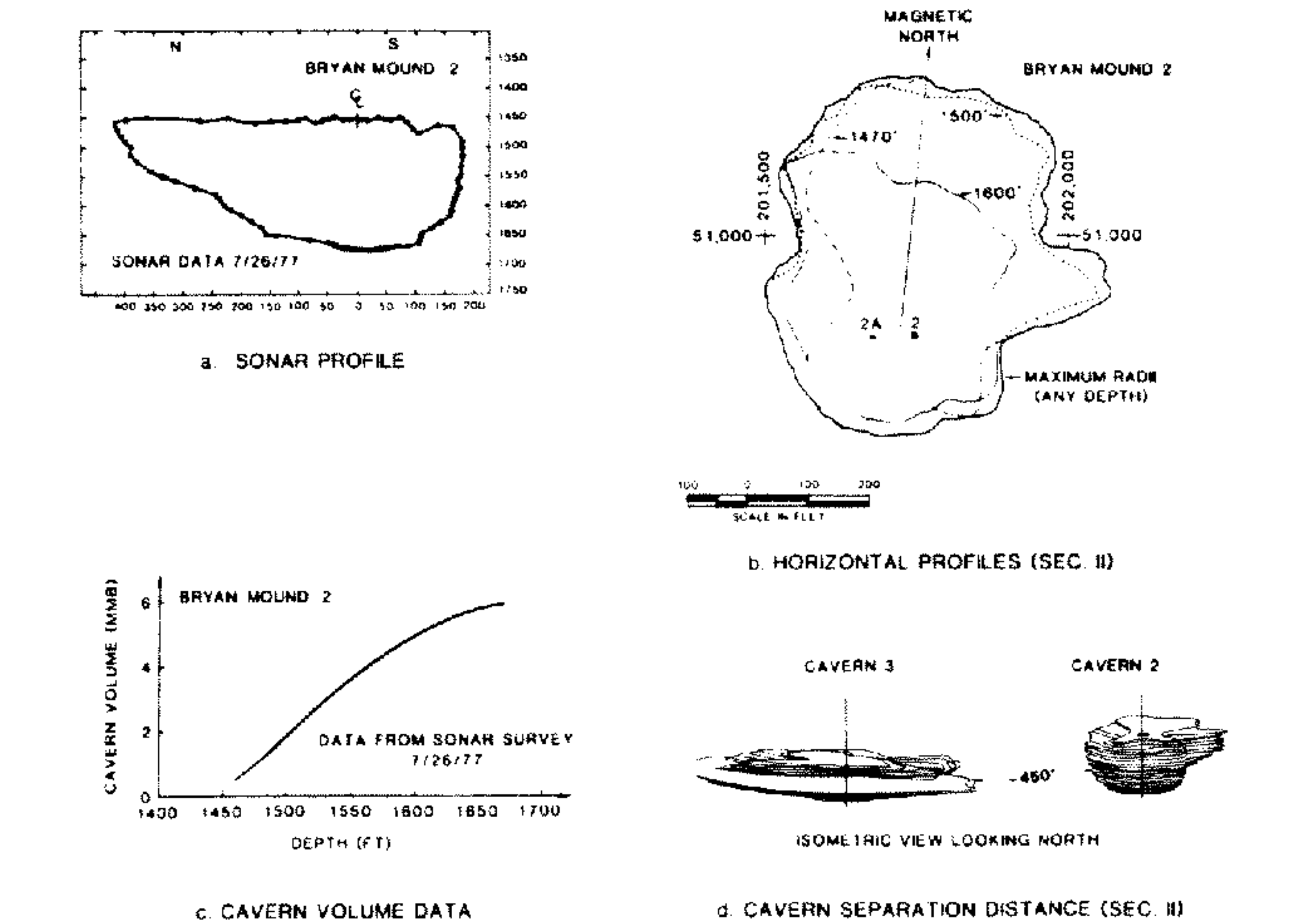

Figure 11. Bryan Mound Cavern Two.

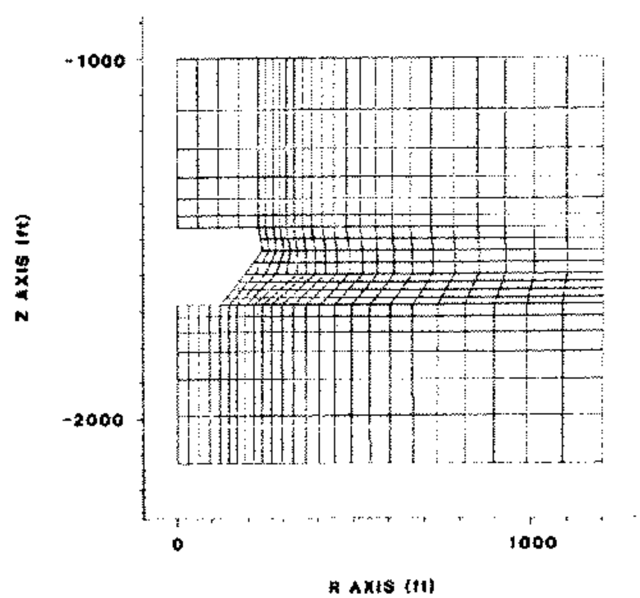

Figure 12. Axisymmetric Finite Element Mesh of Bryan Mound Cavern Two.

TABLE 2

Cavern Two Flow Rates

Withdrawal Number	Initial	1	2	3	4	5
Volume ($\times 10^7$ ft^3)	2.75	3.39	4.14	4.99	5.89	6.87
Flowrate (ft^3/day)	6.4	7.8	12.7	20.0	35.8	29.0

TABLE 3

Cavern Four Flow Rates

Withdrawal Number	Initial	1	2	3	4	5
Volume ($\times 10^7$ ft^3)	9.49	10.63	12.17	13.86	15.68	17.44
Flowrate (ft^3/day)	160.1	206.7	271.5	340.0	423.1	503.77

TABLE 4

Cavern Five Flow Rates

Withdrawal Number	Initial	1	2	3	4	5
Volume ($\times 10^7$ ft^3)	18.8	—	—	—	—	26.3
Flowrate (ft^3/day)	448.8	—	—	—	—	849.6

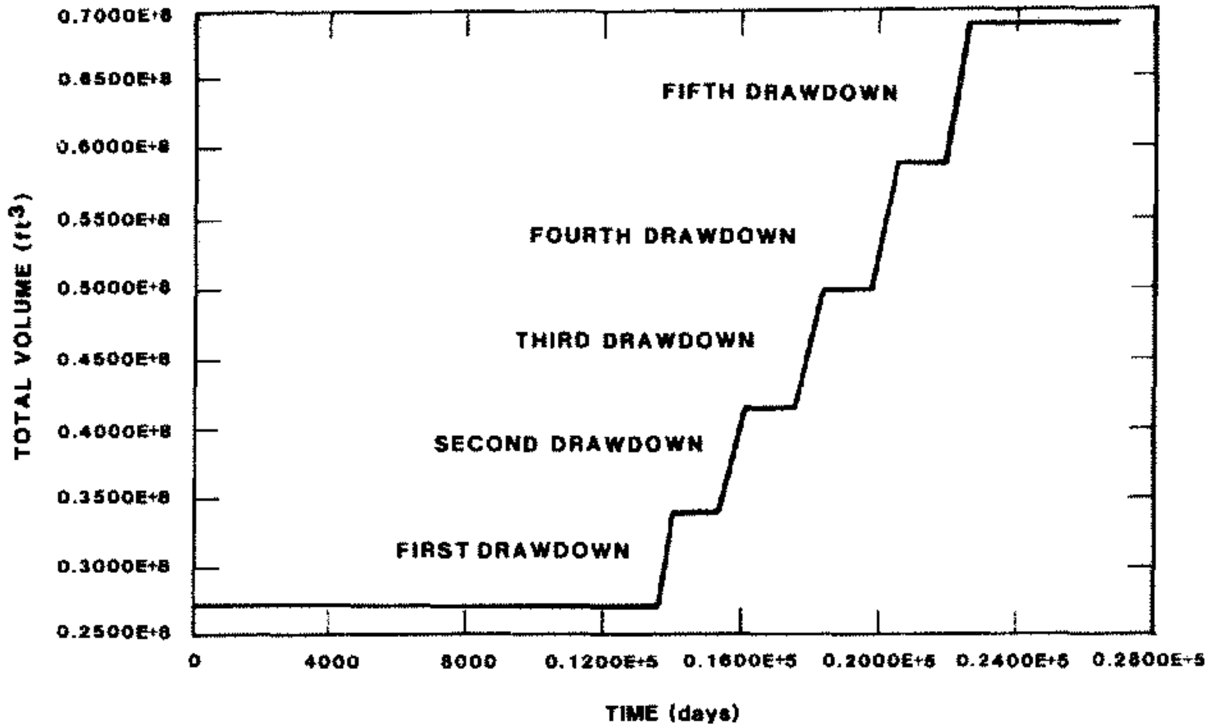

Figure 13. Volumetric Response of Cavern Two.

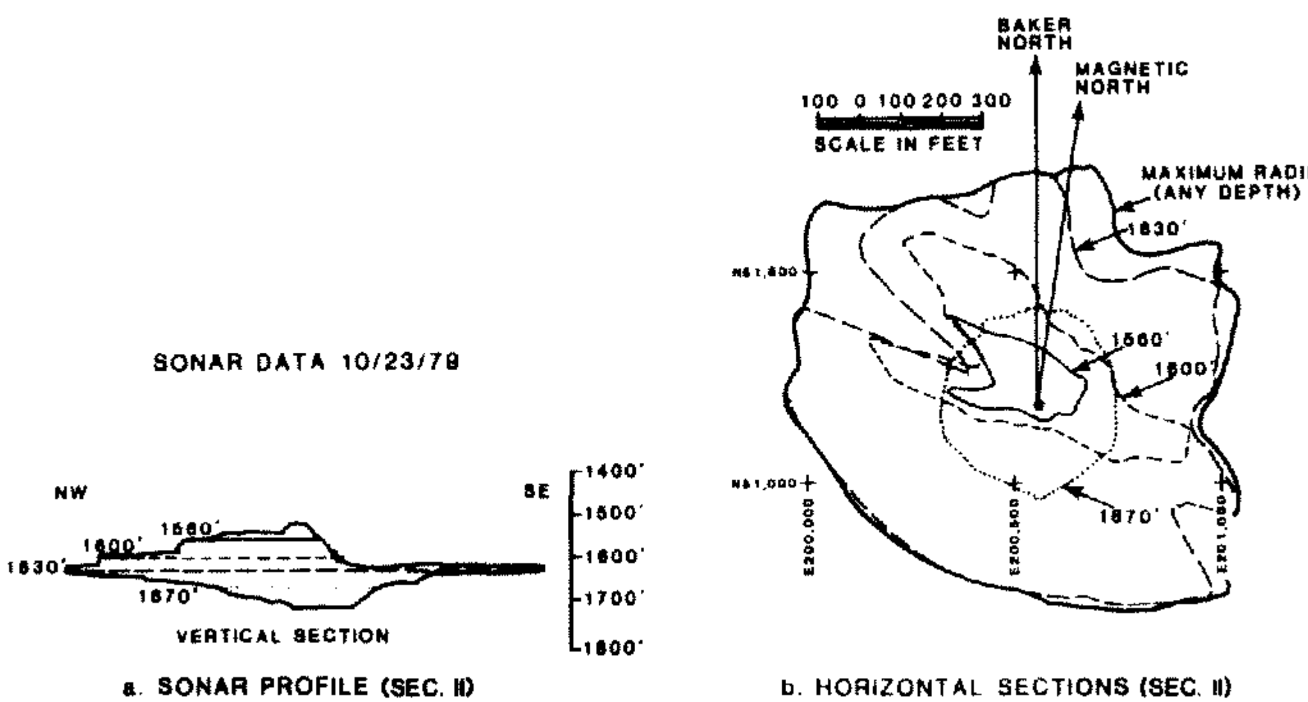

Figure 14. Bryan Mound Cavern Three.

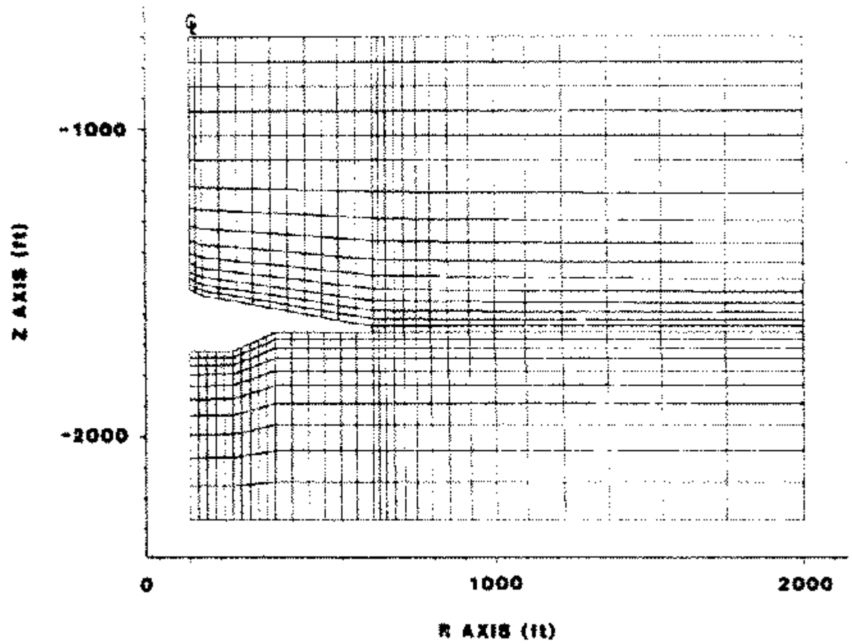

Figure 15. Axisymmetric Finite Element Mesh of Bryan Mound Three.

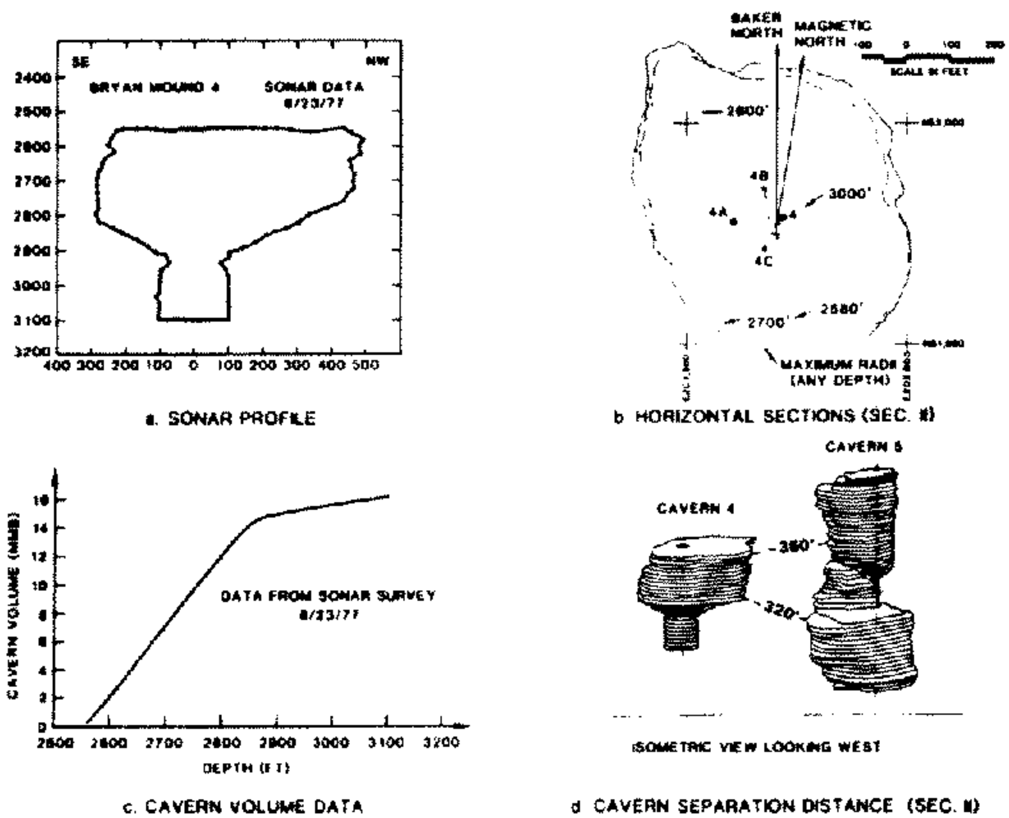

Figure 16. Bryan Mound Cavern Four.

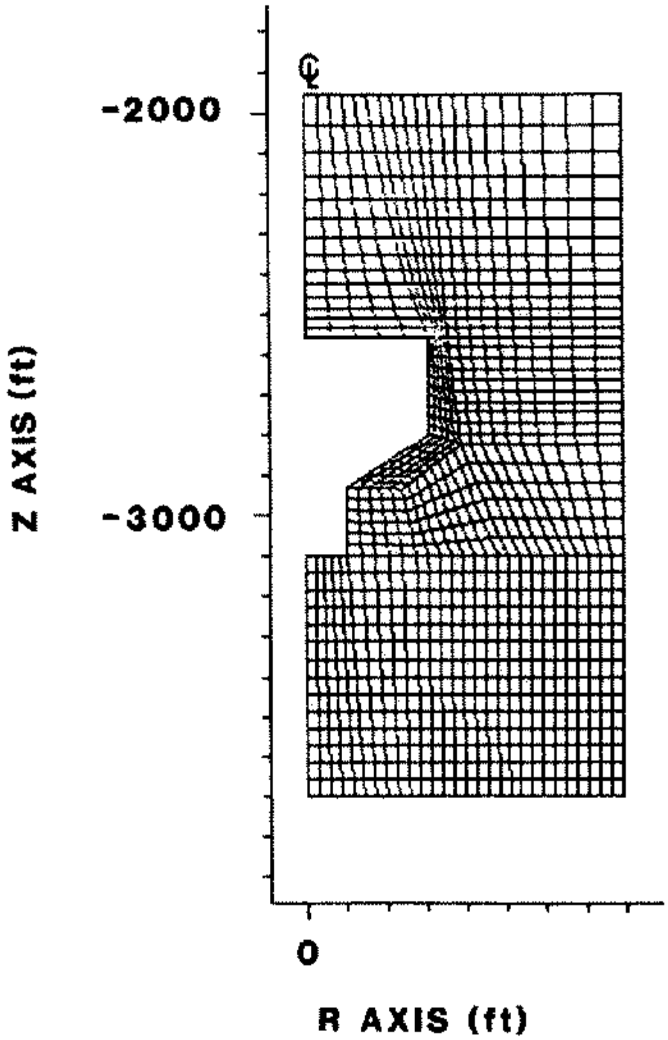

Figure 17. Axisymmetric Finite Element Mesh of Bryan Mound Cavern Four.

below the caprock, so no edge of dome or roof thickness problems are anticipated. Caverns One and Five are on the same level and relatively close (pillar thicknesses of 245 feet and 320 feet, respectively). Three of the new expansion caverns are also on the same level and within approximately 1100 feet (Hogan, 1980, p. 6). The finite element mesh shown in Figure 17 has a cavern volume of 16.9 mmb (9.49×10^7 ft^3). The volumetric response of the cavern is given in Figure 18 and a summary of the flow rates from the cavern immediately before each drawdown is given in Table 3.

Post-processing of the fracture/crush function indicates the present and future (after five drawdown cycles) stability of this cavern. There is the possibility of coalescence with Cavern One, as mentioned previously, and also with Cavern Five. The growth of these three caverns and the pillar distances between them needs to be closely monitored.

BRYAN MOUND CAVERN FIVE

Cavern Five was initiated in 1957 and subsequently developed into the 33.4 mmb (1.88×10^8 ft^3) cavern shown in Figure 19. The cavern has an upper and lower lobe separated by what appears to be an insoluble layer (the ledge may also be the result of the leaching process rather than insolubility). This cavern is the largest in the SPR program, but since it is over 650 feet from the dome edge and 1000 feet from the caprock, no edge of dome or roof thickness problems are anticipated. Cavern Four and two new expansion caverns are located on the same level as this cavern. Also included in the determination of the mesh width was the distance to the edge of the dome (Hogan, 1980, pg. 6). The finite element mesh of the cavern in Figure 20 has a volume of 33.4 mmb (1.88×10^8 ft^3). This mesh does not include a layer of elements for each drawdown. An attempt was made to include the layers, but the

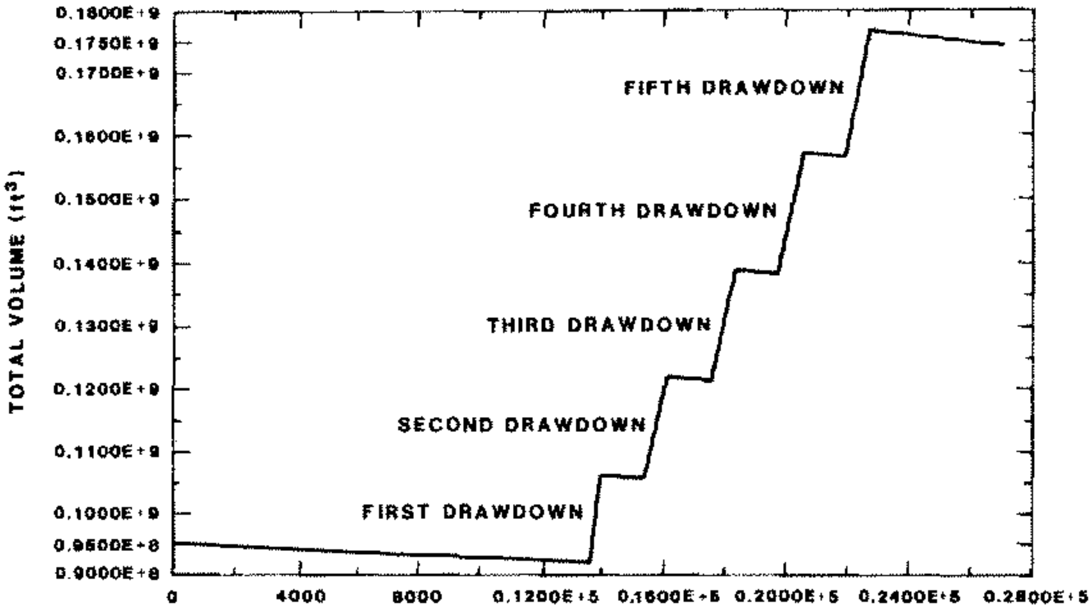

Figure 18. Volumetric Response of Cavern Four.

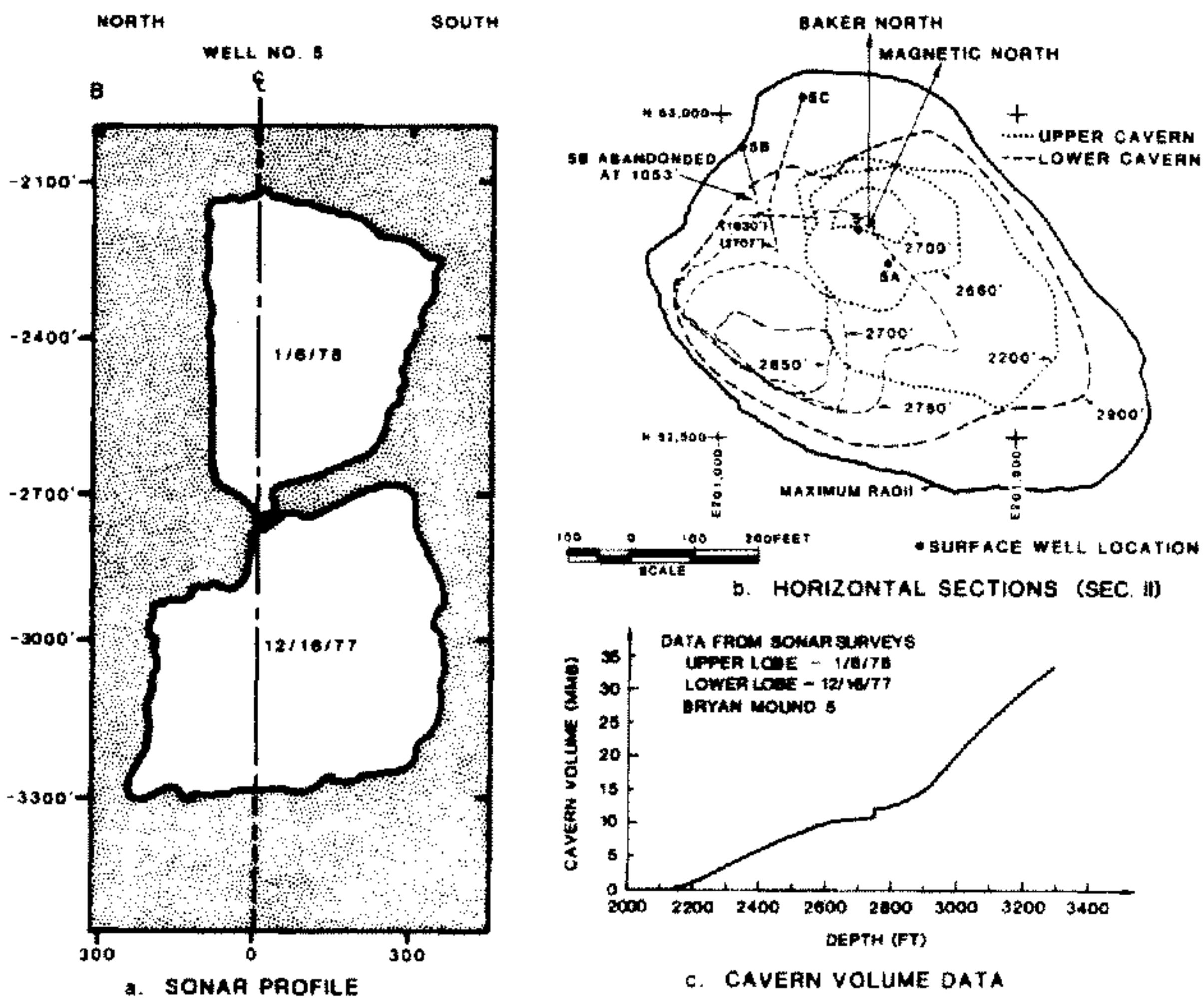

Figure 19. Bryan Mound Cavern Five.

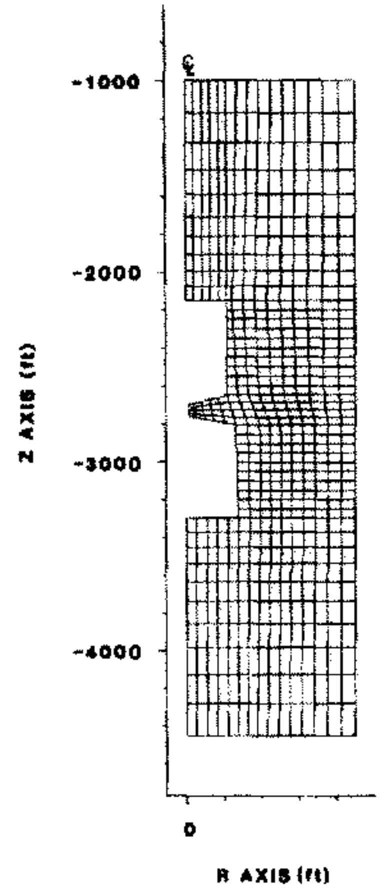

Figure 20. Axisymmetric Finite Element Mesh of Bryan Mound Cavern Five.

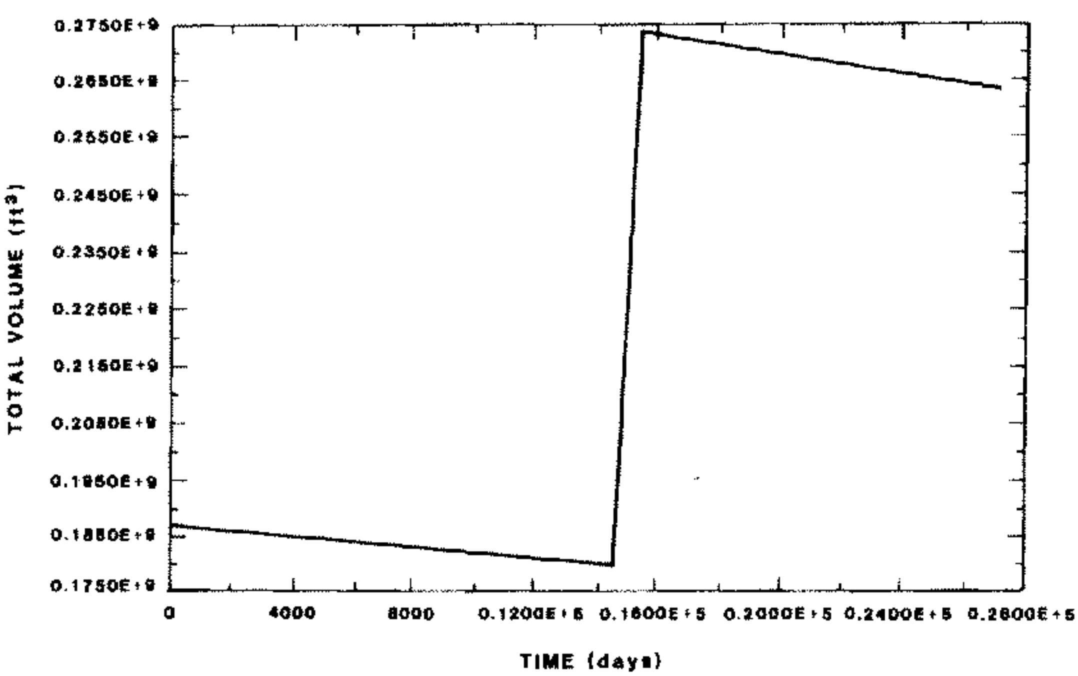

Figure 21. Volumetric Response of Cavern Five.

resulting mesh was so fine and had so many elements as to make the analysis overly expensive. The present mesh has one layer of elements between the original and final size. The volumetric response of the cavern is given in Figure 21 and a summary of the flow rate after each drawdown is given in Table 4.

The post-processed fracture/crush function does not indicate any stability problems of the cavern at present or in the future. As mentioned previously, there is the possibility of coalescence with Cavern Four. The present model is not suitable for predicting pillar stability problems associated with this coalescence process.

SUMMARY

The methods presented in this paper for determining creep response of leached salt caverns seem to work reasonably well, considering the limits of two-dimensional approximations of the actual shapes. The volume change versus time data, which have been predicted, will be useful to cavern operators in the planning of bleed-down schedules, brine buffer sizes and disposal of brine displaced from the cavern due to creep closure. This aid in predicting and planning should result in a more efficient cavern operation.

ACKNOWLEDGMENTS

The thermal analyses used to study temperature effects were done by A. J. Russo, Sandia National Laboratories, 1512. C. M. Stone, Sandia National Laboratories, 1521, implemented the element removal capability into the computer code.

REFERENCES

Hart, R. J., T. S. Ortiz and T. R. Magorian. 1981. Strategic Petroleum Reserve (SPR) Geological Site Characterization Report Big Hill Salt Dome, Sandia National Laboratories, SAND81-1045.

Hogan, R. G. 1980. Strategic Petroleum Reserve Geological Site Characterization Report Bryan Mound Salt Dome, Sandia National Laboratories, SAND80-7111.

Key, S. W., C. M. Stone and R. D. Krieg. 1980. A Solution Strategy for the Quasi-Static Large Deformation Inelastic Response of Axisymmetric Solids, presented at U.S. European Workshop *Nonlinear Finite Element Analysis in Structural Mechanics*, Ruhr-Universitat; Bochum, W. Germany.

Miller, J. D., C. M. Stone and L. J. Branstetter. 1982. Reference Calculations for Underground Rooms of the WIPP, Sandia National Laboratories, SAND82-1176.

Morgan, H. S., R. D. Krieg and R. V. Matalucci. 1981. Comparative Analysis of Nine Structural Codes Used in the Second WIPP Benchmark Problem, Sandia National Laboratories, SAND81-1389.

Preece, D. S. and C. M. Stone. 1982A. Use of Laboratory Triaxial Creep Data and Finite Element Analysis to Predict Observed Creep Behavior of Leached Salt Caverns. Sandia National Laboratories, SAND82-0678.

Preece, D. S. and C. M. Stone. 1982B. Verification of Finite Element Methods Used to Predict Creep Response of Leached Salt Caverns, 23rd Symposium on Rock Mechanics, Berkeley, CA.

Russo, Anthony J. 1981. A Solution Mining Code for Studying Axisymmetric Salt Cavern Formation, Sandia National Laboratories, SAND81-1231.

Saberian, A. and A. L. Podio. 1977. A Computer Model for Describing the Development of Solution-Mined Cavities, in situ, 1(1), p. 1-36.

Wawersik, W. R., D. J. Holcomb and D. W. Hannum. 1980. Quasi-Static and Creep Data for Dome Salt From Bryan Mound, Texas, Sandia National Laboratories, SAND809-1434.