Borehole Tests to Predict Cavern Performance

R. L. Thoms and R. M. Gehle
Applied Geomechanics, Inc.
Baton Rouge, Louisiana, USA

ABSTRACT

Exploratory boreholes generally are drilled in rock salt deposits prior to construction of storage caverns. Cores are taken over selected intervals of depth for firsthand inspection of salt geological characteristics, and also for possible laboratory tests to determine the mechanical properties ("strength") of the rock salt relative to the intended storage application. Applications can include storage of liquids, e.g., oil and other hydrocarbon products, and gases, e.g., natural gas or compressed air (for energy storage). Storage of gases generally includes cavern stability considerations, which may be vital for deep caverns (depths greater than around 800 m) subject to cyclic internal pressure. Additional complications can occur if the rock salt formation contains "impurities," e.g., shale and/or clay, or if the in situ stress state is other than lithostatic, i.e., due to overburden alone.

Borehole testing can be used to predict cavern performance on the basis of dimensional analysis and physical model theory. Such tests have the advantages of incorporating site specific features. Effects of relatively undisturbed salt and in situ stresses are taken into account over the depths of planned cavern development. Test programs can be designed in stages of complexity (and cost) to fit the level of concern for the intended storage project.

A first stage of tests includes performing initial and subsequent borehole caliper surveys, along with monitoring outflow of drilling fluid from open boreholes. On the basis of dimensional analysis, predicted volume changes of a cylindrical cavern over a selected depth interval at the borehole site can be derived as $\Delta V_C = (D_C^2/D_B^2)\,\Delta V_B$, *where* ΔV, D *are volume change and diameter respectively, and the subscripts C, B refer to cavern and borehole respectively. More precise data can be obtained by sealing off portions of boreholes with packers or plugs.*

Other borehole tests are outlined and discussed, with potential benefits, for the geostorage industry working in rock salt.

INTRODUCTION

Usable volume of a storage cavern in rock salt generally decreases with time, and the volume loss rate can be used as a measure of cavern "stability." If the volume loss rate is integrated over the engineering life of the cavern, and thereby an uneconomical storage volume loss is projected, the cavern generally is defined as unstable. Corrective measures may include enlarging the cavern periodically with solution mining. However, most gas storage cavern operators probably would prefer to avoid such measures, so that a fairly uniform reservoir capacity is generally available.

A need obviously exists for estimating stability of storage caverns in rock salt formations. This need is more acute for gas storage caverns (including compressed air) than for liquid-storage, because the latter are inherently more stable at similar depths because of a larger, and more reliable hydrostatic head. Gas filled caverns thus are prime suspects for cases of instability among storage caverns in salt formations. Their stability has been analyzed both with physical models and with numerical modeling coupled with laboratory tests. (Dreyer, 1974; Lux and Rokahr, 1982; Hardy, 1982.) The laboratory tests generally are performed on salt specimens prepared from cores taken by drilling exploratory boreholes at the site and depth of the prospective storage cavern(s).

An alternate, or complementary method for estimating cavern stability can be implemented wherein the exploratory borehole itself serves as the test specimen. Dimensional analysis, as used in classic physical modeling, can be used to set forth modeling "laws" to predict cavern performance based on borehole test data.

This paper reviews the borehole tests approach for estimating cavern closure with time, and also includes examples of estimates based on closure data collected from two boreholes drilled to depths of 5000 feet (1500 m) in different North Louisiana salt domes.

BOREHOLE AND CAVERN CLOSURE IN SALT FORMATIONS

Factors affecting closure of openings (especially caverns) in salt formations were summarized in a recent presentation. (Thoms and Gehle, 1982). These factors included:

(1) the pressure difference, or "effective overburden" comprised of the difference between geostatic stress and cavern pressure; (2) salt formation mechanical (constitutive) properties; (3) salt formation temperature at planned cavern depths; and (4) cavern configuration or geometry.

The first three of the above factors can be made to act directly upon borehole closure at the location and depth of a planned cavern. A cement plug (or plugs) with access pipe can be set to isolate and test an interval of borehole depth planned for a prospective cavern. The test interval of borehole can be blown clear of brine by high pressure gas, and subsequently subjected to the same pressures as planned for a storage cavern under operating conditions. The casing seat is never endangered from this test procedure. Periodically, the test interval can be refilled with brine to measure loss in hole volume. By this approach hole closure data can be obtained for realistic operating pressures over depths of interest and with well established technology.

Hole closure data can be interpreted directly in terms of potential cavern volume loss if "slender" caverns are planned. Here caverns will be called slender if their length to diameter ratio is greater than around 4 ($L/D > 4$). The number 4 is noted to be an engineering judgment at this time; it is an estimate of the configuration of caverns for which lateral closure clearly dominates over end effects for increasing L/D values. Numerical experimentation with accompanying laboratory tests would be useful to obtain a more rational basis for the lower limit of L/D defining slender caverns.

For slender caverns, the test interval of borehole can be regarded as a distorted physical model. (Thoms, Mogharrebi and Gehle, 1982). Then the theory of dimensional analysis (Langhaar, 1951) can be used to derive modeling "laws" which predict cavern volume loss directly from borehole closure data. The derivation of these laws was presented previously by Thoms and Gehle (1982); the resulting, relatively simple relationship between potential volume loss of planned caverns and test interval of exploratory borehole is:

$$\Delta V_C = \frac{D_C^2}{D_B^2}\,\Delta V_B, \text{ where}$$

$$\Delta V_C, \Delta V_B = \text{change in volume of cavern, borehole} \quad (1)$$

$$D_C, D_B = \text{initial diameter of cavern, borehole.}$$

In Equation 1, a common depth interval and similar pressure loading history have been assumed for the test borehole and planned cavern(s). Note cavern end effects and wall slabbing are not taken into account by Equation 1, nor are possible interaction effects between neighboring caverns.

As derived in previous work, Equation 1 can be used to relate volume changes at similar times. Field tests generally are limited in time, and estimates of long-term cavern behavior then must be obtained by extrapolation once an apparent "steady state" closure is indicated from test data.

A second major use can be made of borehole tests as described here; that is, the data can be used to verify site-specific numerical models for underground openings in salt formations. This concept is consistent with basic geotechnical engineering philosophy, i.e., any field data, as it becomes available, should be used to update predictive analysis for construction. (Terzaghi, 1960). Once verified with field data, numerical models can be used with improved confidence to analyze a wider class of geometrically dissimilar openings in the same salt formation. However, a major degree of uncertainty remains for the implementation of the test in conjunction with numerical modeling; that is, the initial geostatic stress state. For slender caverns where Equation 1 can be applied directly, using specific borehole closure data, the initial geostatic stress field need not be known.

If the salt formation is strongly anisotropic (e.g., some bedded salts), then this effect must be noted in use of borehole test data. Also, megascopic features such as anomalous zones must be identified and accounted for. Scale effects certainly will enter to some extent in borehole tests; however, they should be less severe for an 8 to 9 inch (200 to 230 mm) diameter borehole than for a 4 inch (100 mm) diameter conventional laboratory salt test specimen.

BOREHOLE CLOSURE DATA AND EXAMPLES OF PREDICTED CAVERN BEHAVIOR

In early 1978, exploratory boreholes were drilled to depths of 5000 feet (1524 m) in the North Louisiana salt domes of Vacherie and Rayburn's. An earlier report summarized the drilling of the exploratory holes or coreholes (Hawkins, 1978). The exploratory boreholes were logged several times with 4-arm caliper "tools" over a time period of approximately four years and accumulated borehole closure data were collected (Thoms and Mogharrebi, 1979; Mogharrebi and Thoms, 1980; and Mogharrebi, 1981). A final caliper logging of both holes was performed in April, 1982. The data presented here are taken from the summary report written after all data was collected and analyzed. (Thoms, Mogharrebi and Gehle, 1982). Data with a relatively high degree of confidence were selected for the discussion of this paper.

Data from drilling records and also from the initial caliper logging "runs" following "well completion" on April 11 and May 7, 1978, for Vacherie and Rayburn's respectively are presented in Figure 1. Downhole temperature data along with reference elevation and relative depth data are included in Figure 2. The notation DAIL designates "days after initial logging." Initial logging occurred in

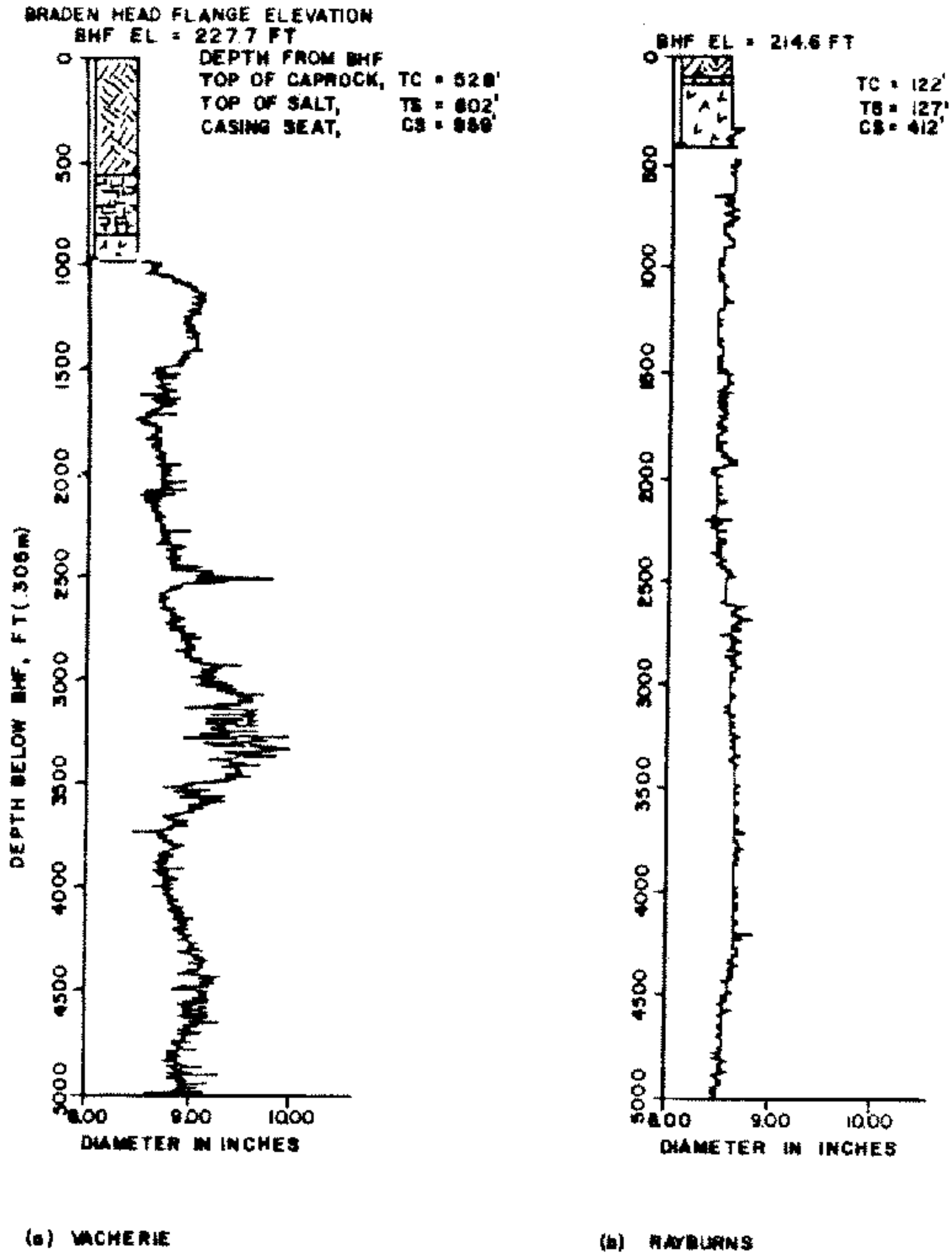

Figure 1. Configuration of boreholes.

Rayburn's twenty-six days after the Vacherie borehole, and this is reflected in subsequent DAIL references for later caliper logs performed on the same calendar day for both holes.

Closure data for the boreholes in the Rayburn's and Vacherie salt domes are reported in Figures 4 and 5. In Figure 3, referring to Rayburn's dome, the borehole is apparently relatively stable over its entire depth. An earlier logging at 137 DAIL is not depicted because the data were essentially the same as for 387 DAIL. Slight tendencies for accelerated hole closure occur for Rayburn's at two depths; first, around 2500 feet (750 m), and again around 3500 feet (1065 m). The effect of the depth of 3500 feet (1065 m) appears more significant for hole closure.

Vacherie borehole closure data are given in Figure 4, and now a considerable variation of hole closure with depth

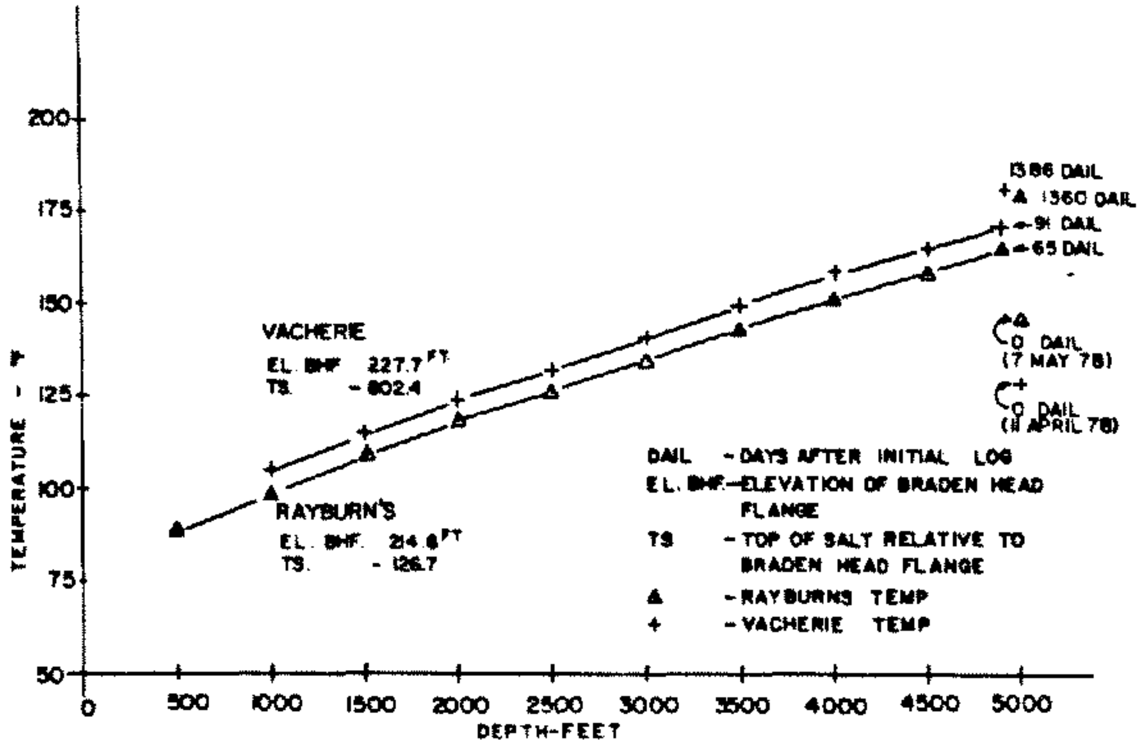

Figure 2. Temperature in Vacherie and Rayburn's boreholes (after Thoms, et al., 1982).

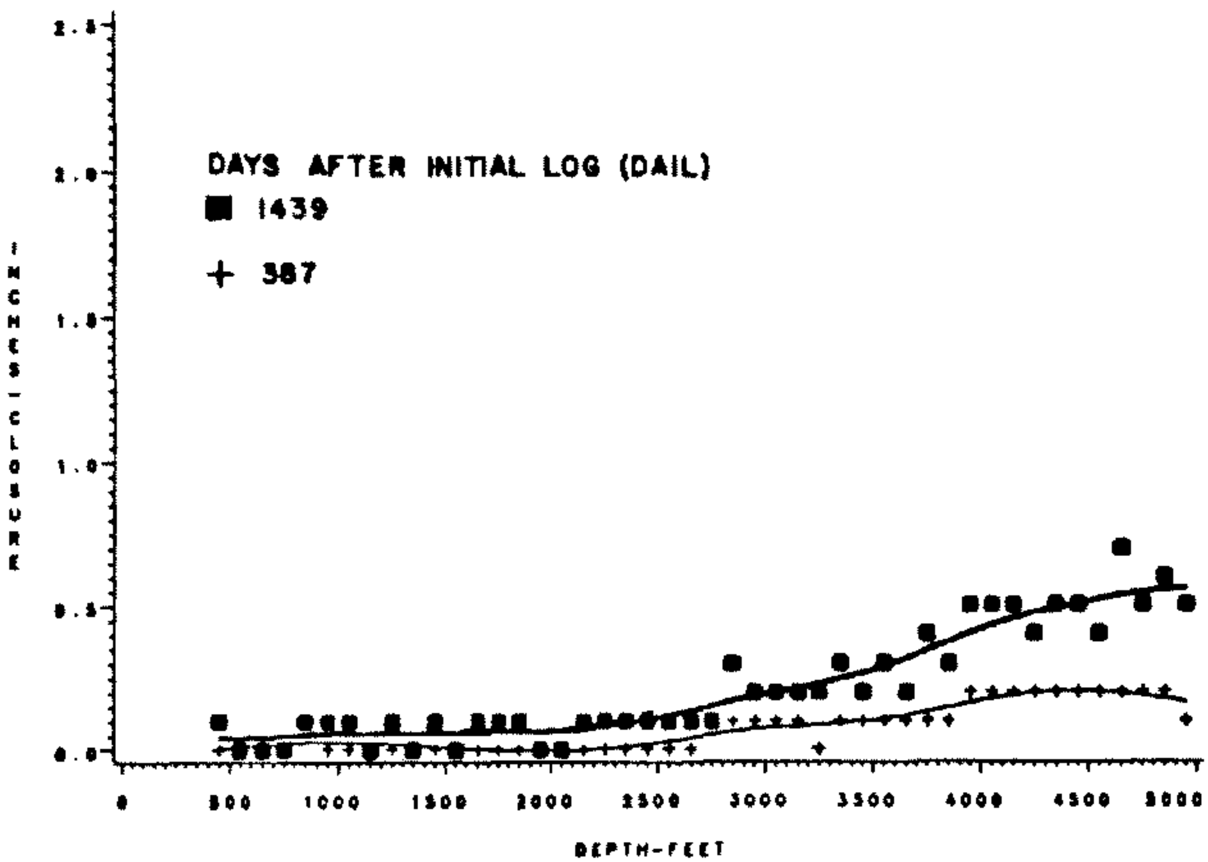

Figure 3. Rayburn's hole closure.

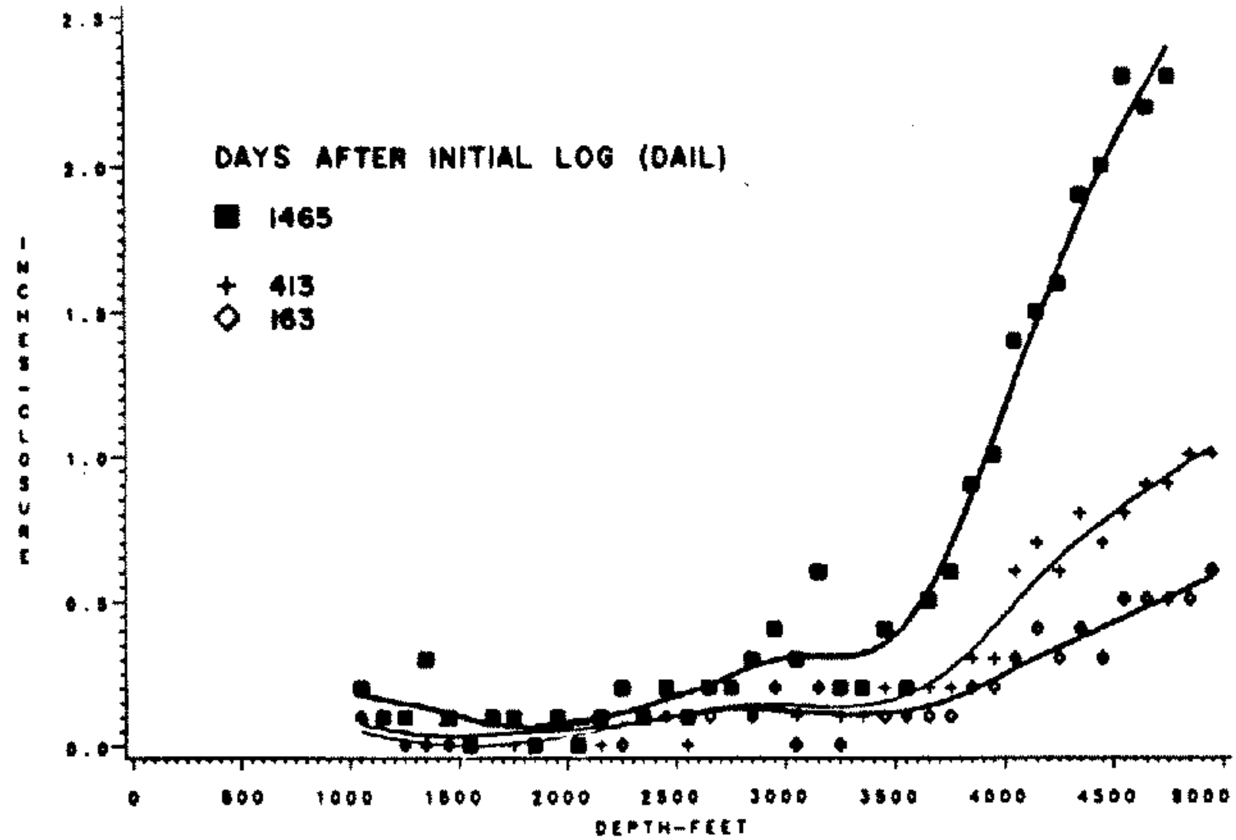

Figure 4. Vacherie hole closure.

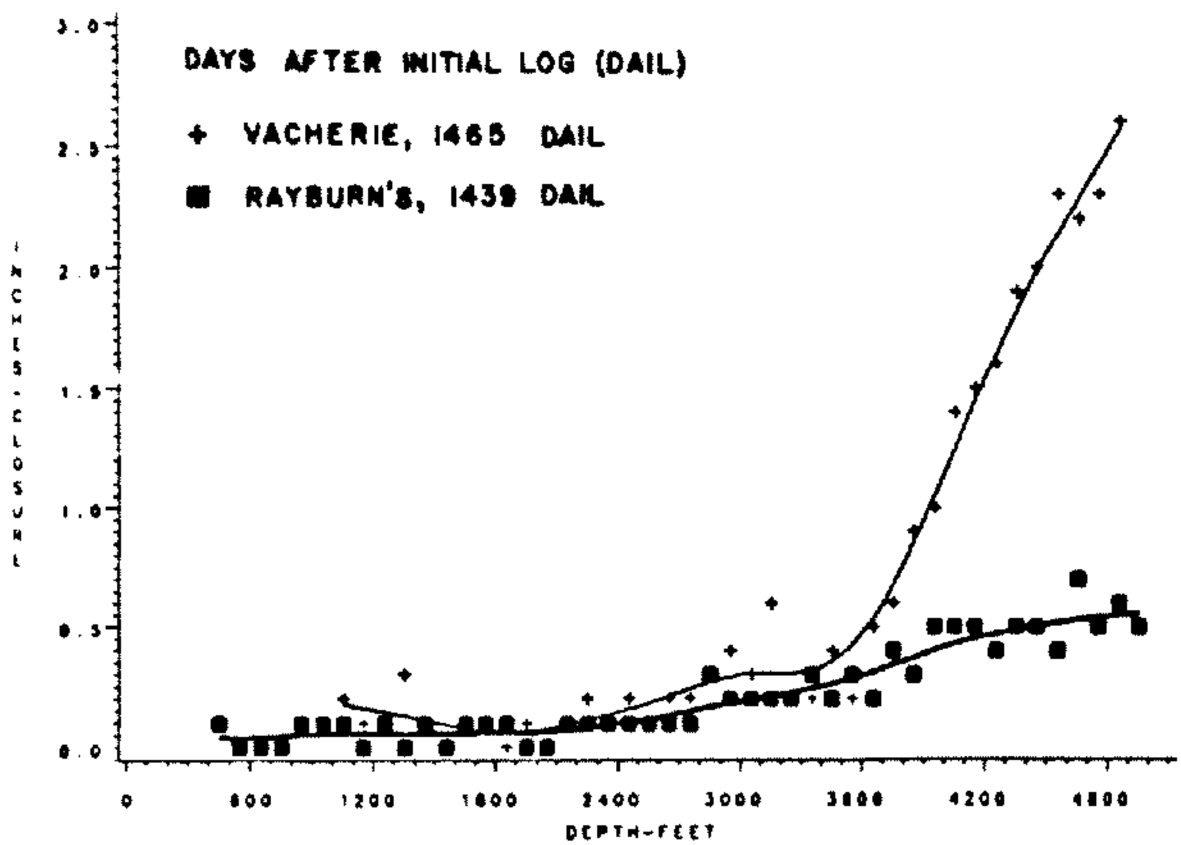

Figure 5. Vacherie and Rayburn's hole closure.

anticipated to be site specific, and will depend upon previously noted factors, i.e., temperature, salt bulk mechanical properties, and effective overburden. For example, a cavern for liquid hydrocarbon storage with a brine "leg" may be located slightly above a yield depth; but if it is converted to natural gas or compressed air energy storage, it may then be located below a more shallow yield depth associated with an increased effective overburden (or pressure difference). Thus care should be taken in converting liquid however, the magnitude of closure varies considerably between the two holes at greater depths. The relative closure of the two holes from the final logging (Figure 5).

The depth of openings at which accelerated creep closure occurs in salt will be called the "yield depth" in this paper. (Thoms and Gehle, 1982). For the brine filled holes of Vacherie and Rayburn's domes, the yield depth is approximately 3400 feet (1036 m). In general, yield depths can be can be observed. Clearly a considerable increase in hole closure occurs at a depth of around 3400 feet (1036 m). Thus, hole closure consistently increases at approximately the same depth in both the Vacherie and Rayburn's domes, storage caverns to gas storage. Conversely, marginally useful gas storage caverns possibly could function satisfactorily for liquid storage (if creep closure is the main difficulty).

Equation 1 can be used with the data in Figures 3 and 4 to predict closure of example caverns. From Equation 1, for the same depth and at similar times, the percent decrease in volume per unit of depth is identical for borehole and slender cavern(s), provided they have similar loading histories.

Percent volume closure versus time for different depths in the Vacherie and Rayburn's boreholes is depicted in Figure 6. Extrapolation to longer time periods can be visualized by the reader. With reference to Figure 6, it appears brine displacement storage caverns would be satisfactory to depths of around 3400 feet (1036 m) in both the Vacherie and Rayburn's domes. At greater depths the Rayburn's dome appears generally more stable; and depending upon economics beyond the scope of this paper, might be considered sufficiently stable for brine displacement storage to depths of around 5000 feet (1524 m). By contrast, the Vacherie dome appears less than satisfactory for storage at a depth of 4000 feet (1220 m), and essentially unacceptable

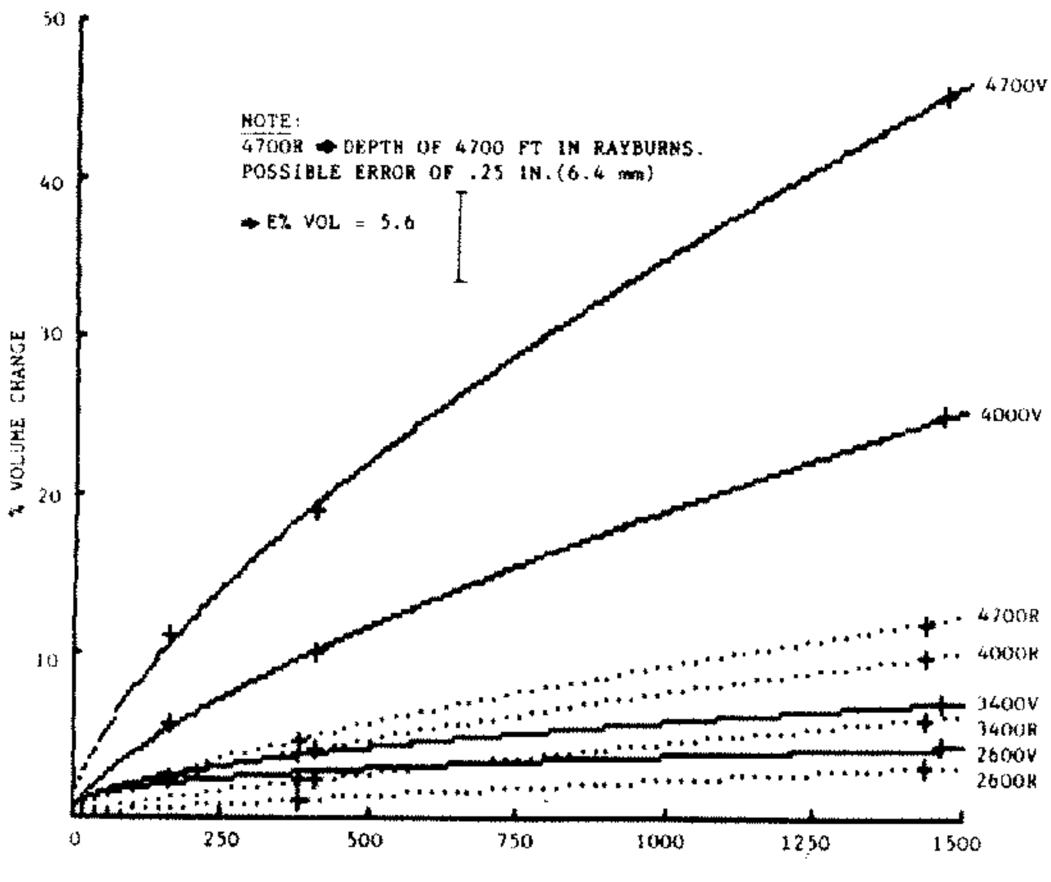

Figure 6. Percent volume change versus time for different depths (ft) in Rayburn's and Vacherie boreholes.

at a depth of 4700 feet (1430 m). Volume closure data at other depths can be generated from the curves of Figures 1, 3, and 4 if the reader desires.

SUMMARY AND CONCLUSIONS

A field test method has been reviewed for predicting performance of storage caverns in salt formations. Percent volume loss per unit depth of appropriately tested boreholes should be identical with slender storage caverns over similar depth intervals.

Two exploratory boreholes in North Louisiana salt domes exhibited different amounts of closure below a yield depth of around 3400 feet (1036 m). Based on these data and a modeling "law" for predicting cavern closure, depth ranges in the example domes can be classified as satisfactory (or unsatisfactory) for storage caverns, depending upon planned usage and economics.

In conclusion, borehole tests can be performed in the field to explore the utility of salt formations over a range of depths for storage of both liquids and gasses. For planned facilities requiring large investments, a complementary series of laboratory and field tests with numerical modeling is recommended.

ACKNOWLEDGMENTS

Borehole closure data used for examples in this paper were collected while the authors were members of the Institute for Environmental Studies at Louisiana State University. This paper is based in part upon two research efforts for the United States Department of Energy: (1) Utility of Gulf Coast Salt Domes for the Storage or Disposal of Radioactive Wastes, with coordination by the Office of Nuclear Waste Isolation, Battelle Memorial Institute, E530-02200, and (2) Laboratory Tests of Rock Salt for Compressed Air Energy Storage, via Pacific Northwest Laboratory operated by Battelle Memorial Institute, subcontract No. B-67966-A-O.

REFERENCES

Dreyer, W. E. 1974. Results of Recent Studies on the Stability of Crude Oil and Gas Storage in Salt Caverns, Proc. 4th International Symposium on Salt, V.2, Coogan, A. H., ed., Northern Ohio Geol. Soc., pp. 65-92.

Hardy, H. R., Jr. 1982. Basic Studies Associated with the Design of Salt Caverns for the Storage of Pressurized Fluids. Rock Mechanics: Caverns and Pressure Shafts, V.2. Wittke, W., ed., ISRM Symposium, Aachen, A. A. Balkema, Rotterdam, p. 903-921.

Hawkins, M. F., Jr. 1978. An Engineering Report of the Coreholes at Vacherie and Rayburn's Salt Domes—North Louisiana Salt Dome Basin, Institute for Environmental Studies, Louisiana State University, Baton Rouge, p. 356.

Langhaar, H. L. 1951. Dimensional Analysis and Theory of Models, John Wiley and Sons, New York.

Lux, K. H. and R. B. Rokahr. 1982. *Einige Ergebnisse aus Laborversuchen zum mechanischen Verhalten von Steinsalz und ihre Bedeutung fur den theoretischen Entwurf von Speicherkavernen*, Rock Mechanics: Caverns and Pressure Shafts, V.1. Wittke, W., ed., ISRM Symposium, Aachen, A. A. Balkema, Rotterdam, pp. 71-83.

Mogharebbi, M. and R. L. Thoms. 1980. In Situ Behavior of Salt from Closure of Deep Boreholes, Underground Rock Engineering, CIM Special Vol. 22, Proc. 13th Canadian Rock Mechanics Symposium, Toronto, Canadian Institute of Mining and Metallurgy, Montreal, pp. 199-203.

Mogharrebi, M. 1981. Inelastic Deformation of Deep Boreholes in Salt, Thesis for Masters of Science Degree, Louisiana State University, Baton Rouge, 63 p.

Terzaghi, K. 1960. From Theory to Practice in Soil Mechanics. John Wiley and Sons, New York, p. 39.

Thoms, R. L. and M. Mogharebbi. 1979. Borehole Closure in Salt Domes, Proc. 20th U.S. Symposium on Rock Mechanics, The University of Texas, Austin, pp. 407–410.

Thoms, R. L., M. Mogharrebi and R. M. Gehle. 1982a. Geomechanics of Borehole Closure in Salt Domes; Proc. Gas Processors Association Spring Meeting, March, Dallas, pp. 228–230.

——— 1982b. Borehole Closure in the Vacherie and Rayburn's Salt Domes, in press as one of a collection of topical reports prepared by The Institute for Environmental Studies at Louisiana State University, Office of Waste Isolation, Battelle, Columbus, OH.

Thoms, R. L. and R. M. Gehle. 1982. Field Testing of Rock Salt for CAES Reservoirs, presented at International Conference on Underground Pumped Hydro/Compressed Air Energy (UPH/CAES), American Institute of Aeronautics and Astronautics and Electrical Power Research Institute (AIAA-EPRI), September 20–22, San Francisco, 5 p.