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PREDICTION OF SUBSIDENCE RESULTING FROM CREEP CLOSURE OF SOLUTIONED-MINED CAVERNS IN SALT DOMES

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ABSTRACT

The prediction of subsidence rates over a range of areal configurations of solution-mined caverns in salt domes is possible, based on some fifty years of history in solution mining. Several approaches contribute to predictions: site-specific observations obtained from subsidence monitoring; numerical modeling, now becoming more practicable and credible; salt-creep data from testing; and rule-of-thumb methods, based on experience. All of these approaches contribute to understanding subsidence but none are totally reliable alone. The example of subsidence occurring at the Strategic Petroleum Reserve sites demonstrates several principles of cavern creep closure, the main cause of the subsidence, and shows that reliable projections of future subsidence are possible.

INTRODUCTION

Solution mining in salt is now a mature technology, having been practiced for more than 50 years, first in Europe and now extensively on the U. S. Gulf Coast. More than 500 permits for solution mining have been issued by the State of Texas alone, with the Barbers Hill dome at Mont Belvieu, Texas, having more than 100 caverns. Caverns are created as a result of dissolution during brine extraction, and intentionally for the storage of liquid or gaseous hydrocarbons, or other material such as industrial waste. Frasch mining of sulphur from the caprock overlying salt domes is a type of solution mining, strictly speaking, and the subsidence and collapse effects are reasonably well known (Deere, 1961). However, subsidence associated with it is not discussed here, but nonetheless is often concurrent with subsidence resulting from solution mining in salt. The phenomenology associated with subsidence induced from sulphur extraction differs from that associated with the creep closure of caverns or mine openings in salt.

Subsidence is an acknowledged fact of life wherever large underground voids have been created, and openings in salt follow specific rules related to its rheologic behavior. Although common in occurrence, subsidence has not been widely reported on, possibly because of the perception of adverse publicity which most companies and institutions wish to avoid, and because of difficulty in obtaining accurate measurements. Some ten years of history of Strategic Petroleum Reserve (SPR) operations demonstrate this phenomenology and point to means of prediction.

Observations of subsidence from leveling surveys, numerical modeling, lab creep testing, and rules-of-thumb have all been used to predict subsidence.

The 65 SPR caverns now contain some 500 million barrels (MMB) of crude oil in five salt domes [Fig. 1] and when full will contain about 675 MMB. An additional 73 MMB is contained in a former room and pillar mine at Weeks Island dome, Louisiana, but the subsidence phenomenology there is different because of its shallow depth and much different geometry.

ORIGIN OF CAVERN SUBSIDENCE IN SALT CREEP

The process of creep closure in underground caverns is understood qualitatively to occur radially into the cavern, with the largest amounts at the cavern bottom [Fig. 2]. The closure requires the concomitant flowage of salt from all directions and therefore a gradual lowering of the surface, i. e., subsidence. Factors that influence the observed variations in creep closure in caverns are the constitutive properties of the salt, the depth, which controls temperature and lithostatic pressure, the differential pressure between that in the cavern and lithostatic pressure, cavern shape, and cavern array configuration.

Laboratory tests conducted at 32° C revealed large variations in salt creep response between sites and within a single site and may be due to experimental and/or constitutive differences (Nelson & Kelsall, 1984. Many authors believe that the data scatter between samples results from characteristics at the molecular level, as attempts to correlate impurities, fabric, or crystal size have been unsuccessful. Some samples show greater sensitivity than others to temperature change. Cavern shape influences creep by virtue of surface area and depth; an equal-volume sphere possesses about 61% of the area of a 10:1 cylinder and consequently has less creep closure and more uniform pressure and temperature. Multiple cavern arrays display synergistic effects that result in additional subsidence over what would be expected for single caverns (Chow, 1974; Sutherland & Preece, 1986).

Observations in mines, boreholes, caverns, laboratory creep tests, and in calculations all show that salt under constant loading displays a rapid but transient initial strain response (primary creep), followed by a longer-term steady-state deformation (secondary creep), and sometimes an increasing rate of deformation leading to rupture (tertiary creep) [Fig. 3].

OBSERVED SUBSIDENCE AT SPR SITES

Subsidence observed at SPR includes multiple caverns and sites and illustrates various principles of salt creep and associated subsidence, demonstrating varying salt properties, differing cavern shapes, depths and configurations, and variable site geology. Regional subsidence from other sources is also occurring in addition to that induced by the SPR caverns but this contributes only a small amount to the overall subsidence. Repetitive surveys at approximately annual intervals have been conducted at each of the SPR sites (Table 1), showing values of average annual subsidence that ranged from 9 to 63 mm. A total of some 350 survey points include cavern wellheads, concrete foundations, and constructed monuments, all located over a total area of about 7 km . A wide range in values is observed both within and between sites; thus understanding the phenomenology is essential to establishing a predictive capability.

The data of Table 1 show a sevenfold variation between the smallest (Bryan Mound) and largest (West Hackberry) subsidence rates. Upon initial inspection basic parameters appear similar, but detailed examination reveals possible reasons for the variation. Laboratory creep rates of Bryan Mound salt are among the lowest of any salt studied (Wawersik & Zeuch, 1984), and the West Hackberry caverns are some 180 m deeper on average. While this may not seem significant, the exponential increase in creep with depth can account for the majority of creep occurring in the bottom 20% of the cavern [Figs. 2 & 4] (Todd, 1989; Heffelfinger, 1990).

TABLE 1 Summary of measured subsidence, SPR sites, 1982-88 (Goin and Neal, 1988)

SITE (Capacity, in MMB)	**WEST HACKBERRY** (219)	**WEEKS ISLAND*** (73)	**SULPHUR MINES** (26)	**BAYOU CHOCTAW** (72)	**BRYAN MOUND** (226)
Ave. Subsidence ($mm\ year^{-1}$)	62.5	34.8	29.1	18.7	9.0
Min./Max., ($mm\ year^{-1}$)	27/82	12/58	21/38	12/34	3/20
Standard Error ($mm\ year^{-1}$)	3.14	4.02	3.84	1.83	2.93
Cavern Depth,m top/bottom	823/ 1372	140/ 226	823/ 1106	762/ 1220	640/ 1250
Salt Roof Thickness,m	186	99	375	670	320
Caprock Thickness,m	152	0	305	61	99
Volume Area^{-1} ($MMBBL\ ha^{-1}$)	1.92	0.64	1.46	1.24	1.98
Other Activity	oil	salt; oil	sulphur; oil	oil	sulphur
Extraction Ratio, %	~7	~25	---	---	~7

*Data from Weeks Island is included here, but storage is in a former room-and-pillar salt mine; Big Hill dome is not included, being just now developed, and subsidence measurements are only beginning.

Some of the data is not entirely consistent, and this difficulty has been attributed to inaccurate or shifting reference monuments, to instabilities in individual monuments, and possibly to leveling inaccuracy. Changes in survey practices, monuments, and reference points are expected to improve future measurements. The West Hackberry data are the most consistent, and this site has high interest within SPR because of the low surface elevation and location within coastal marshlands.

TREND FORECAST OF WEST HACKBERRY SUBSIDENCE

Projections of subsidence trends of the lower elevation areas of the West Hackberry site are shown in Table 2 based on rates established over some eight years of measurements. No indications of rate change were noted in any of the data, thus it is assumed to represent steady-state (secondary) creep primarily, with most of the primary creep closure [Fig. 3] having occurred early during the three-year leaching process to create the caverns. Thus the projections are linear, based entirely on observed rates. The projections allow for no change in regional subsidence or uplift rates, but this is only an insignificant small portion of the total subsidence measured. The results show that the already low areas of the site within a few years will be at or below the level of Black Lake on the northern perimeter, which has a mean tidal elevation of 0.6 m. These projections allow time to consider engineering solutions, e.g., diking.

TABLE 2 Projected Surface Elevations for Selected West Hackberry Stations in Meters, Relative to Mean Sea Level, based on 68 months data, 1982-88.

STATION	DELTA	ELEV (9/88)	SUBSIDENCE RATE ($mm\ mo.^{-1}$)	Projected Elevations 1995	2000	2005	2010	2015
SMS 3	0.162	0.909	2.38	0.72	**0.57**	**0.43**	**0.29**	**0.15**
SMS 4	0.320	2.13	4.71	1.75	1.47	1.18	0.90	0.62
SMS 5	0.329	1.70	4.84	1.31	1.02	0.73	**0.44**	**0.15**
WH 6C*	0.332	1.58	4.89	1.18	0.89	**0.60**	**0.30**	**0.01**
WH 8A*	0.271	4.01	3.99	3.69	3.45	3.21	2.97	2.73
WH 108*	0.165	2.28	2.42	2.08	1.94	1.79	1.65	1.50
WH 110*	0.399	2.03	5.87	1.55	1.20	0.85	**0.50**	**0.14**
WH 111*	0.387	2.08	5.69	1.62	1.28	0.94	**0.59**	**0.25**
WH 113*	0.408	1.86	6.01	1.37	1.01	0.65	**0.29**	**-0.07**
WH 114*	0.412	1.84	6.05	1.35	0.99	0.62	**0.26**	**-0.10**
WH 115*	0.466	2.32	6.86	1.76	1.35	0.94	**0.53**	**0.12**
WH 116*	0.378	2.10	5.30	1.67	1.35	1.03	0.71	**0.40**

* Wellhead elevations are measured at unknown height above the ground surface. **Bold** values are below mean tide level of Black Lake, 0.60 m.

Another mitigating measure would be to operate the caverns at the highest possible differential pressure (~90% of lithostatic at casing seat) to slow creep to the extent practicable. The effects of operating pressure on closure vs depth are shown dramatically in the calculations by Heffelfinger, 1990 [Fig. 4]; to operate at the lower differential pressures could exacerbate existing subsidence.

NUMERICAL PREDICTION METHODS

Finite element modeling can be used to predict the creep of materials under loading and is commonly applied to engineering problems such as this. Segalman (1989) calculated creep closure and subsidence of a generic (average material properties and depth) West Hackberry cavern, using the JAC code (Biffle, 1984). Caverne volume loss rates are plotted along with subsidence volume and show close parallelism [Fig. 5]. The ratio of subsidence volume to cavern volume loss is also plotted and shows that after 10 years some 70% of the closure will have manifested in subsidence, increasing only to 80% after 30 years, and showing the same steady-state trend. These calculations reveal volumes close to measured subsidence rates, and they appear useful primarily in explaining phenomenology at this point.

A more direct method of predicting cavern performance has been proposed by Thoms and Gehle (1983) in which the borehole that is constructed for the eventual cavern is observed over a period of several years and its measured closure rate is ratioed with the projected cavern dimensions. A limiting factor is that all measurements of closure are time dependent; thus long-term behavior can be estimated best when steady-state closure is indicated. Field tests are normally limited in duration, making it difficult to obtain such information. However, long term projects that emplace multiple caverns offer excellent opportunities to use this method. Once the creep closure behavior is known, then subsidence estimates can follow, using other geologic information on caprock and overburden in conjunction. In this regard, similar experience and conditions are needed for extrapolation, unless modeling as described above is used.

SUBSIDENCE ESTIMATION

Frequently it is desirable to estimate subsidence effects in advance of actual cavern development, given the large investment in such operations. Approximations of the potential subsidence pattern was estimated for a 200 MMB generic cavern field [Fig. 6]. The estimate of about 1.5 m maximum subsidence over 30 yrs is based on a rule-of-thumb for volume loss used in SPR (10% in 30 yrs), comparisons with domes having caverns at similar depths (Bayou Choctaw), similar group patterns observed in the cavern field at West Hackberry dome, and knowledge of creep principles obtained from numerical calculations (Segalman, 1989; Heffelfinger, 1990) [Figs. 4 & 5]. The estimate appears reasonable based on experience observed elsewhere, but there is no material property data or salt core to substantiate it.

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REFERENCES

Biffle, J. H. (1984) JAC - A two-dimensional finite element computer program for the non-linear quasistatic response of solids with the conjugate gradient method. SAND81-0998. Sandia Nat'l. Labs., Albuquerque, NM. Note: the users manual for JAC-3D has not yet been formally documented.

Chow, R. (1974) Long term creep closure of solution cavity system. Proc. 4th Int. Symp. on Salt, 119-127, Northern Ohio Geol. Soc. Cleveland, OH.

Deere, D. U. (1961) Subsidence due to mining - a case history from the Gulf Coast region of Texas. Proc. 4th Symp. on Rock Mech. 59-64.

Goin, K. L. & Neal, J. T. (1988) Analysis of surface subsidence of the Strategic Petroleum Reserve crude oil storage sites from December 1982 to January 1988. SAND88-1309, 39 pp. Sandia Nat'l. Labs., Albuquerque, NM.

Heffelfinger, G. S. (1990) Creep closure modelling of the U. S. DOE Strategic Petroleum Reserve caverns (abs). EOS, Trans. Am. Geophys. Un., 71, No. 17, p. 627.

Kelsall, P. C. & Nelson, J. W. (1983) Geologic and engineering characteristics of Gulf region salt domes applied to underground storage and mining. Proc. 6th Int Symp. on Salt, vol. I, 519-544. Salt Institute, Alexandria, VA.

Nelson, J. W. & Kelsall, P. C. (1984) Prediction of long-term creep closure in salt. 25th Symp. on Rock Mech., preprint. Northwestern Univ., Evanston, IL.

Preece, D. S. & Sutherland, H. J. (1986) Physical and numerical simulations of fluid-filled cavities in a creeping material. SAND86-0694, 40 pp. Sandia Nat'l. Labs., Albuquerque, NM.

Russell, J. E. (1980) A creep model for salt. Proc. 5th Int. Symp. on Salt, 349-353. Cleveland, OH.

Segalman, D. R. (1989) Informal communication of calculational results. Sandia Nat'l. Labs., Albuquerque, NM.

Thoms, R. L. & Gehle, R. M. (1983) Borehole tests to predict cavern performanse. Proc. 6th Int. Symp. on Salt, vol. II, 27-33. Salt Inst., Alexandria, VA.

Todd, J. L. (1989) Informal communication of calculational results. Sandia Nat'l. Labs., Albuquerque, NM.

Wawersik, W. R. & Zeuch, D. H. (1984) Creep and creep modeling of three domal salts - a comprehensive update. SAND84-0586, Sandia Nat'l. Labs., Albuquerque, NM.

note: illustrations are being redrafted

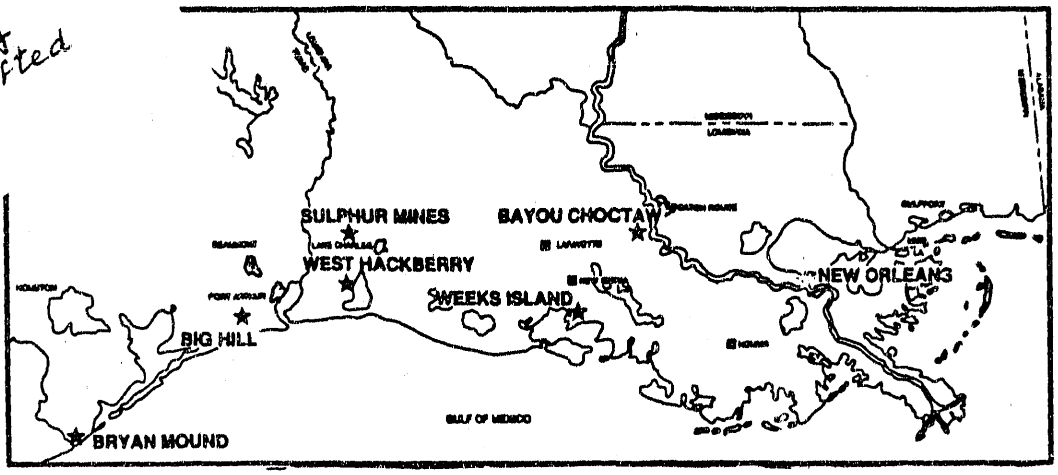


FIG. 1 The six Strategic Petroleum Reserve sites (star) are operated by the ~~system~~ project management office in New Orleans.

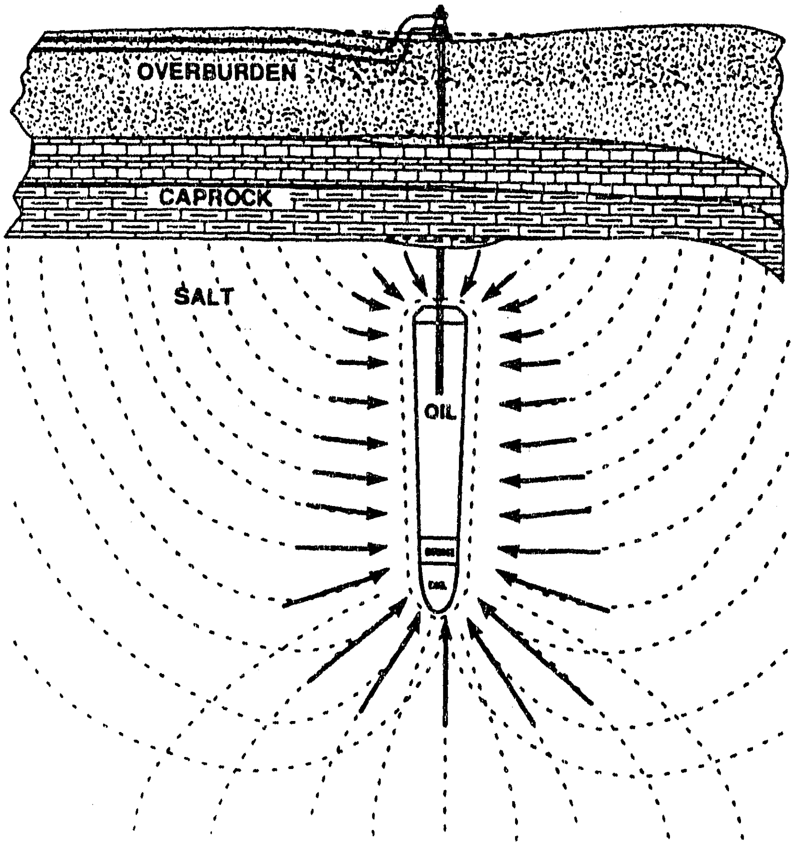


FIG. 2 Creep closure and subsidence associated with caverns in salt. Arrows show vector quantities of relative closure; dashed lines are flow patterns in salt. Some 10% of cavern volume is lost by this process in 30 years.

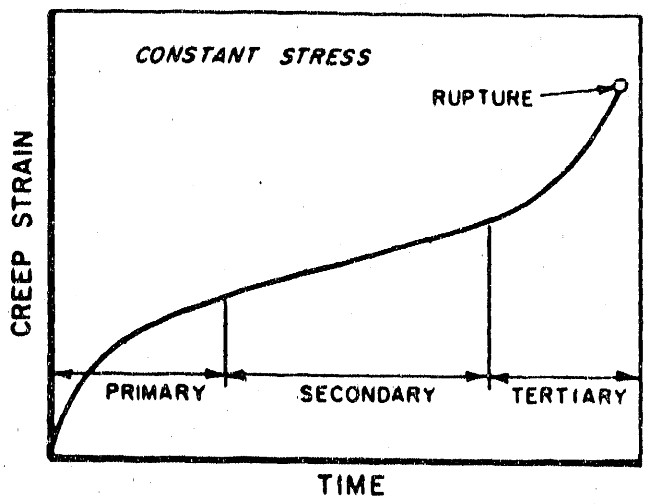


FIG. 3 Phases of creep deformation in salt.

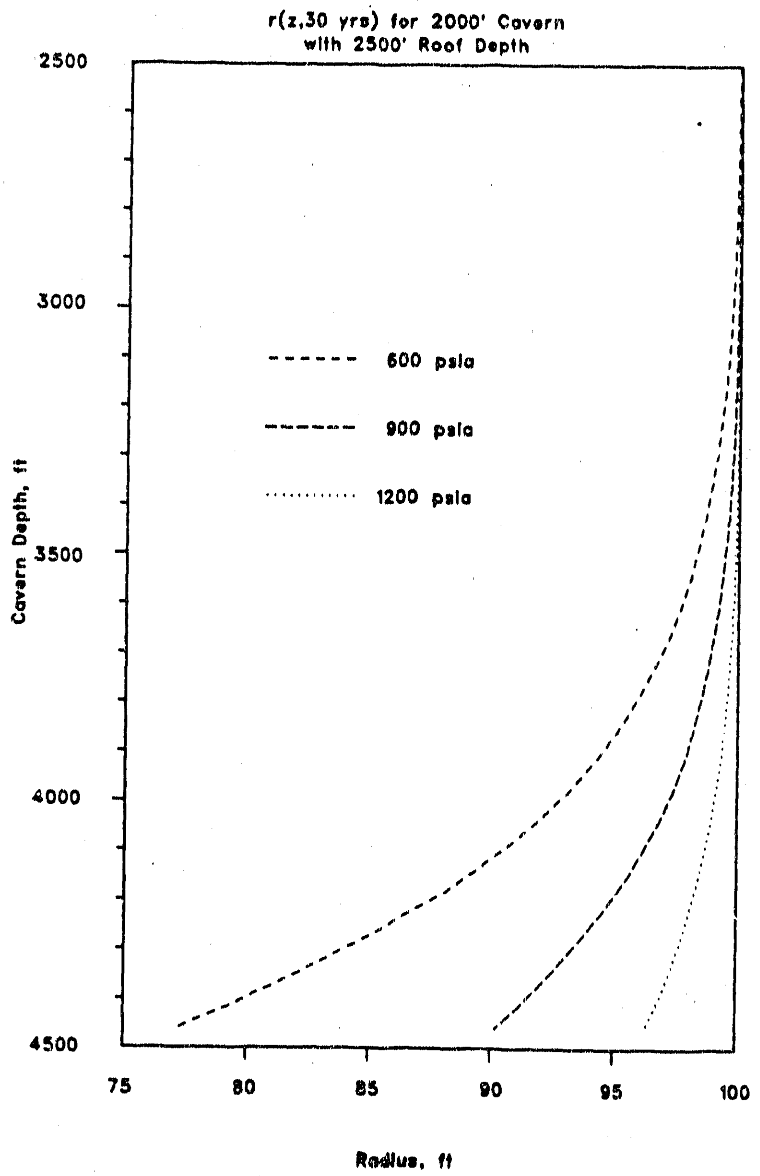


FIG. 4 Calculated effects of differential pressure at 600, 900, & 1200 psi (4.1, 6.1, 8.2 MPa), plotting cavern diameter ~~loss~~ vs depth at 30 years. From Heffelfinger, 1990.

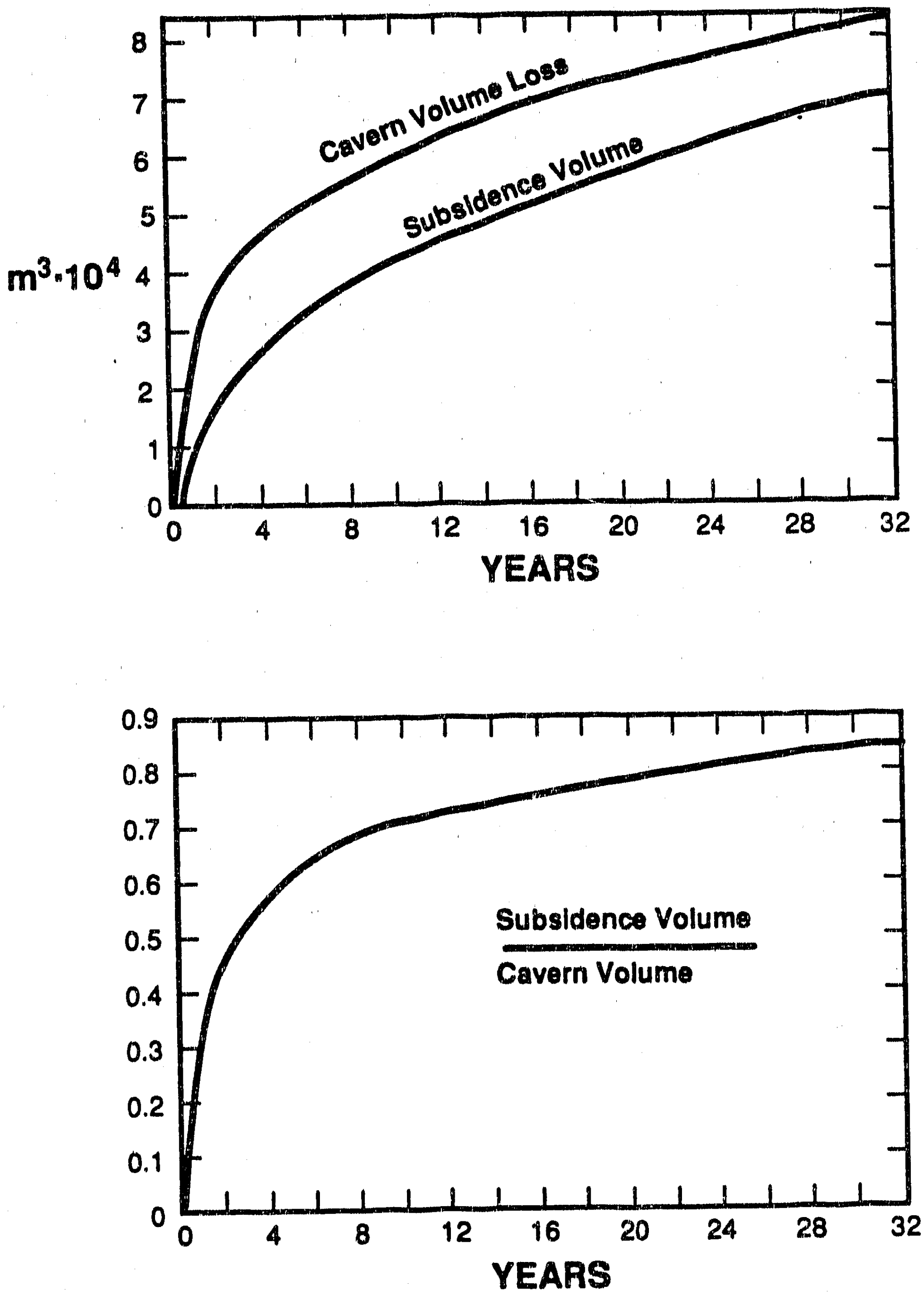
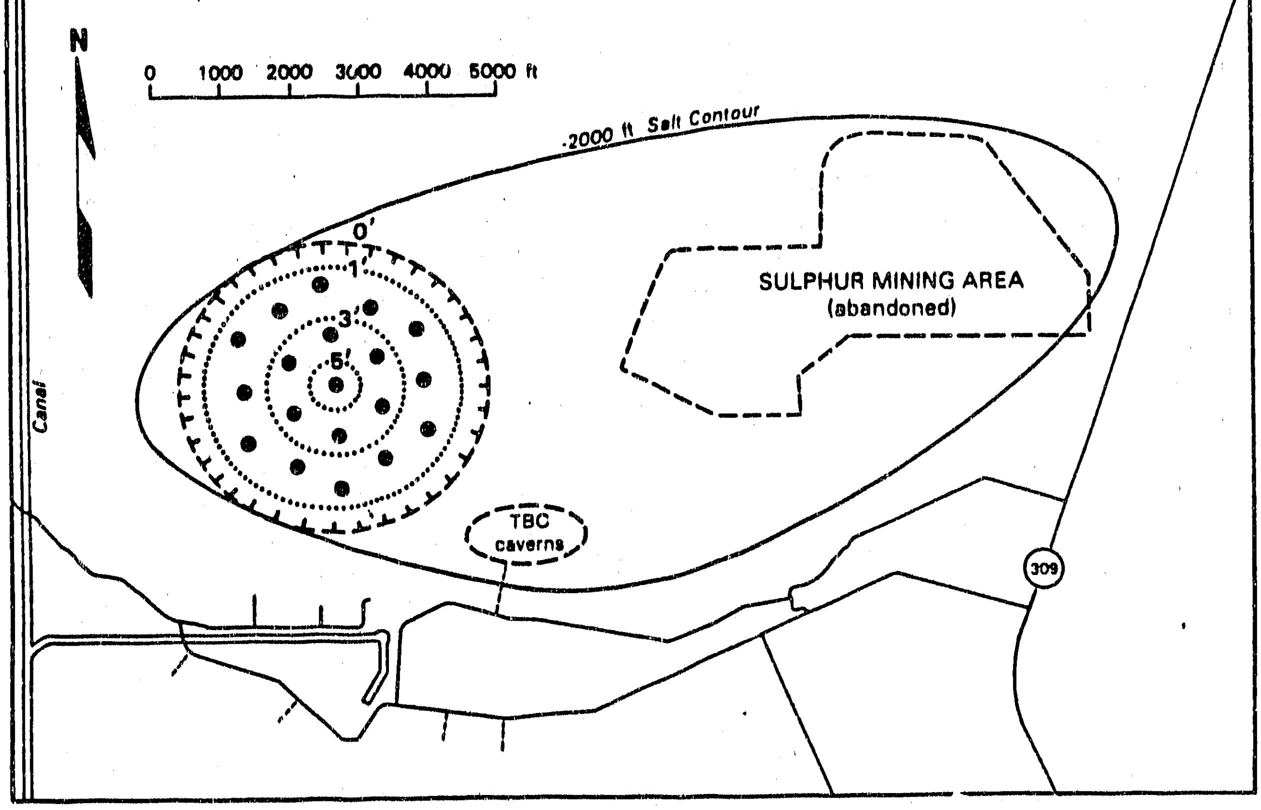


FIG. 5 Top: Calculated creep closure and associated subsidence for a generic West Hackberry Cavern. Initial rapid closure (primary creep) gives way to longer-term (secondary) creep. Bottom: Ratio of subsidence to cavern closure, showing some 80% of closure is manifested in subsidence in 30 years. From Segalman, 1989.

FIGURE 6 PROBABLE 30 YR. SUBSIDENCE PATTERN FROM 200 MMB CAVERN FIELD



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