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Darrell E. Munson, Consultant
Geotechnology and Engineeriing Department
Sandia National Laboratories
P. O,. Box 5800
Albuquerque, New Mexico 87185-0706

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Darrell E. Munson, Consultant
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ABSTRACT

The intent of this study is to examine the internal structure of the Bayou Choctaw salt dome utilizing the information obtained from graphical representations of sonar survey data of the internal cavern surfaces. Many of the Bayou Choctaw caverns have been abandoned. Some existing caverns were purchased by the Strategic Petroleum Reserve (SPR) program and have rather convoluted histories and complex cavern geometries. In fact, these caverns are typically poorly documented and are not particularly constructive to this study. Only two Bayou Choctaw caverns, 101 and 102, which were constructed using well-controlled solutioning methods, are well documented. One of these was constructed by the SPR for their use while the other was constructed and traded for another existing cavern. Consequently, compared to the SPR caverns of the West Hackberry and Big Hill domes, it is more difficult to obtain a general impression of the stratigraphy of the dome. Indeed, caverns of Bayou Choctaw show features significantly different than those encountered in the other two SPR facilities. In the number of abandoned caverns, and some of those existing caverns purchased by the SPR, extremely irregular solutioning has occurred. The two SPR constructed caverns suggest that some sections of the caverns may have undergone very regular solutioning to form uniform cylindrical shapes. Although it is not usually productive to speculate, some suggestions that point to the behavior of the Bayou Choctaw dome are examined. Also the primary differences in the Bayou Choctaw dome and the other SPR domes are noted.

The configurations of the Bayou Choctaw caverns reflect the changes in construction and drilling technology over time. Many of the caverns were constructed in the 1930's when the use of caverns to provide hydrocarbon and petrochemical product storage and to produce industrial brine was limited. When the principal use of solutioning was to produce brine, the development and utilization of these early caverns proceeded with little understanding of solutioning control. These early caverns were essentially shallow, above the -2000 ft depth elevation in the dome, probably reflecting the state of drilling practice at the time. After World War II, technology of drilling advanced significantly resulting in deeper caverns, and the utilization of cavern storage increased markedly. Eventually, the two most recent Bayou Choctaw caverns were constructed to depths typical of other modern caverns. Certainly, over the decades, the ability to measure cavern dimensions using sonar surveys has advanced and become an essential tool in controlling the configuration and size of the caverns. Although few conclusions can be drawn, it is interesting that the range of construction practices and resultant cavern configurations can be examined at the Bayou Choctaw facility.

Recent events have led to the authorization for expansion of the total capacity of the SPR, perhaps involving a total expansion of some 700 MMb (million barrels) or construction of about 70 new caverns. Certainly, if the additional expansion is funded, an extensive search for domes with significant cavern space would have to be made, this has resulted in the identification of potential expansion of existing facilities and of a new site. Any knowledge that can be obtained about the internal structure of salt domes from studies such as the one presented here, has the potential to make new cavern site selection and construction a more informed process.

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1.0 INTRODUCTION

As with the earlier reports on the internal cavern geometry and structure of Big Hill [1] and West Hackberry [2] caverns that help to reveal the stratigraphy of the salt domes containing these caverns, this report brings together the same kinds of information for the Bayou Choctaw caverns and dome. As is well known, solution mined caverns in the salt domes of the Gulf Coast have been used over the decades for sources of industrial brine and commercial storage of crude oil, refined products, and industrial chemicals. Caverns, either previously or currently in use for storage, exist in nearly every salt dome along the coast. In this current analysis, extensive use is again made of the database generated from the caverns of the Strategic Petroleum Reserve (SPR) program of the Department of Energy (DOE). SPR involves the storage of some 700 MMb (million barrels) of crude oil in 62 large caverns at four sites along the Gulf Coast. Sites are located at Bayou Choctaw and West Hackberry in Louisiana and Big Hill and Bryan Mound in Texas. The reserve is intended to mitigate any impact of a potential energy supply interruption and is within the obligations of the United States under the International Energy Program [3].

There is some worth in restating the motivation for a study of cavern straigraphy. It is difficult to understand that the decades-long development of storage facilities in salt has not provided detailed knowledge of the internal structure of the domes. Most studies involve the determination of the top of salt and the extent of the dome flanks, i.e., the dome surfaces. As stated in the earlier report [1]: "The technical data comes from drilling into the dome and along the flanks or from geophysical surveys. Even here, because the domes are relatively large bodies, some several miles in diameter, the quantity of data per square foot of surface is frankly minimal. In comparison, the details of the cap rock and the rock and soil beds surrounding the dome are relatively well known and reported. In some contrast, the available information of the internal structure of domes is extremely limited, almost non-existent. The sampling of the interior of salt domes is typically from core samples taken during drilling of solution mining wells, brine disposal wells, and other special purpose wells, and through direct observation in the relatively shallow salt mines developed in a few domes. Drilling contractors may or may not choose to extract core samples, and, when core is extracted, the core is normally limited to a few tens of feet from perhaps two or three discrete depths in the well, essentially yielding a sample that is an insignificantly small fraction of the dome volume. Even in mines the total drift or shaft lengths are small compared to the vertical or horizontal extent of the dome. When one calculates the total relative sampling volume even under the best of circumstances, it amounts to much less than a thousandth of a percent of the potentially accessible dome volume."

Although it appeared that knowledge of the internal dome structure would always be extremely limited, the combination of advanced graphics, as incorporated into a specialized Mining Visualization System (MVS) software [4], and the reexamination of either normal or high resolution sonar surveys using the MVS system have produced images of cavern interiors of incredible detail. This methodology has been used to examine the interior conditions of the Big Hill caverns of the Strategic Petroleum Reserve (SPR), after a massive salt fall occurred in Big Hill Cavern 103. The resulting

analysis [1] lent considerable insight into the generation of salt falls, the relationship of caverns to larger scale material differences in the dome, and possible spine locations. The analysis of the West Hackberry caverns and dome using the same improved graphics and higher resolution sonar data [2] provided further insight into the potential role of homogeneity of the salt. Differences in internal stratigraphy between the Big Hill and West Hackberry domes appear to correlate to possible differences in local pre-diapir extrusion history of the Louann bedded mother salt. Evidence suggests that the West Hackberry diapir formed only after extensive initial lateral displacement of the Louann salt bed, while the Big Hill diapir formed directly from the original bedded salt location.

As stated for all of these studies, the purpose of the current study is to examine the internal structure of Bayou Choctaw dome, another of the SPR storage sites, using the same methodology developed during the analysis of the Big Hill and West Hackberry sites. In addition to the surface features of the Bayou Choctaw caverns, several aspects of the general dome geometry and possible peculiarities in the dome formation are examined. These lead to a general, but limited, assessment of the internal dome structure. The assessment is made considerably more difficult because of the construction age difference and documentation variance among the caverns, with only a few recent, fully documented cavern histories available.

Although not specifically relevant to our current study of dome stratigraphy, recent events have caused increased interest in expansion of the SPR capacity. Consequently, the possibility of both increasing storage in existing sites and the possible acquisition of new sites have prompted the reexamination of a number of sites. Bayou Choctaw naturally is considered within this reexamination. The earliest of these studies at Bayou Choctaw was in 1980 [5] and with intervening studies since that time. In this regard, Lord and Ehgartner [6] are the most recent to examine in detail the development criteria with respect to the available space at Bayou Choctaw. The conclusion of this most recent evaluation suggested the two new caverns required by the DOE could be accommodated within the SPR area of the dome, but with the potential to accommodate perhaps as many as five caverns. However, more possibilities may be available provided the criteria are viewed on an available volume basis as a function of depth into the dome and with acquisition of sites from adjacent holdings. As noted, even though, this work is limited to the study of the internal structure of the Bayou Choctaw dome, parallels from this study to the utilization of dome volume for caverns occur naturally.

2.0 DOME CONFIGURATION AND GEOLOGY

Bayou Choctaw is located in south-central Louisiana, on the western bank of the Mississippi River, some 13 miles southwest of Baton Rouge. It is in a low-lying area with the backswamps of the Atchafalaya Basin to the south and west. The site is subject to inundation during storms. The geological characteristics related to the Bayou Choctaw site were first described by Hogan [7] in 1981. Neal et al. [8] utilized the earlier work, together with additional information on dome geology, surrounding stratigraphy, and relevant environmental information, to update the dome characterization in 1993. This work resulted in the detailed plan view of Figure 1, which includes the location of the
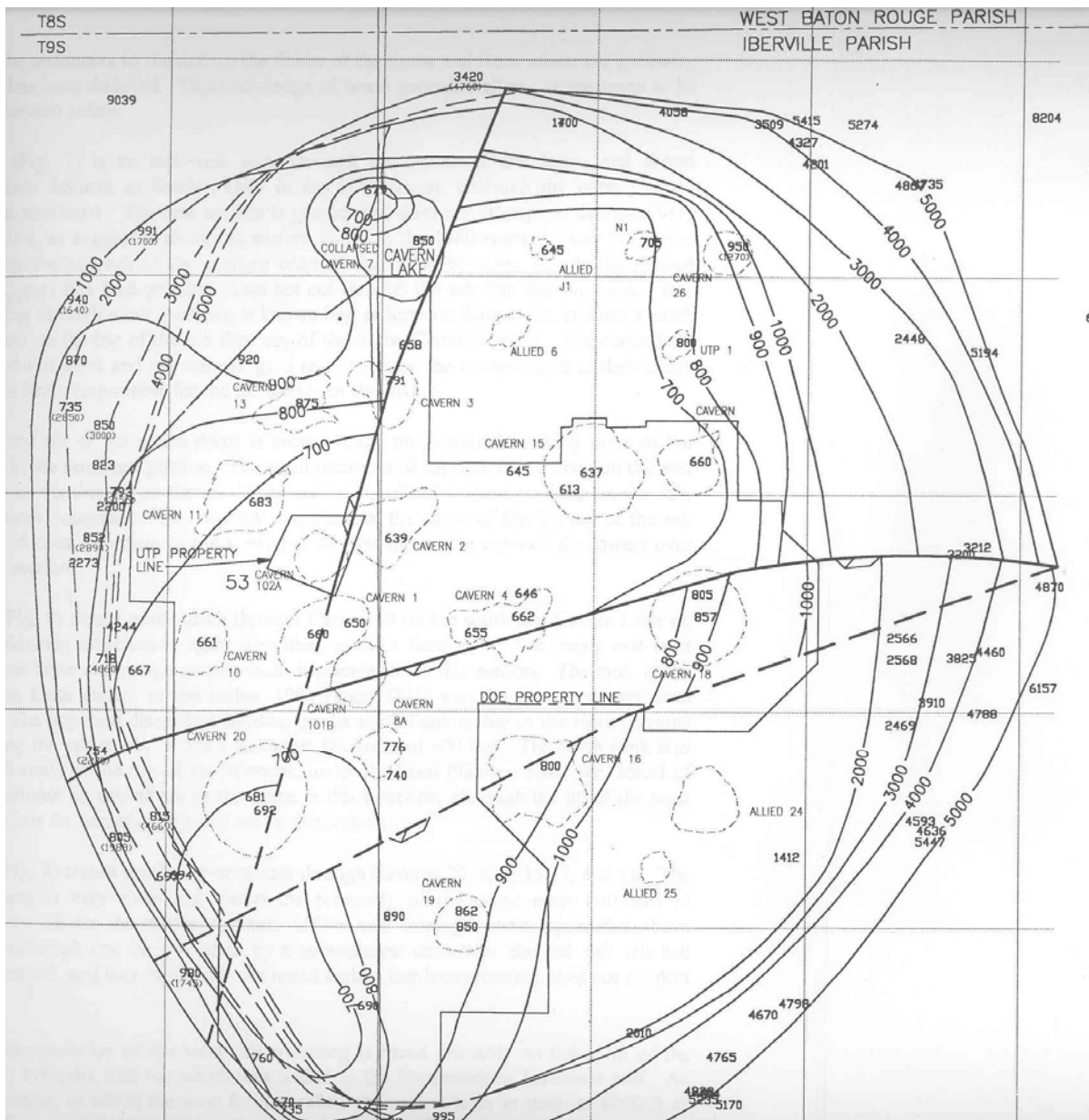
Figure 1. Plan of Bayou Choctaw with Cavern and Well Locations [8].

caverns and brine disposal wells. Also shown are the locations of the dominant faults in the caprock. A construction of the dome surface from this same report, given in Figure 2, shows the dome to be a well defined oblate cylinder.
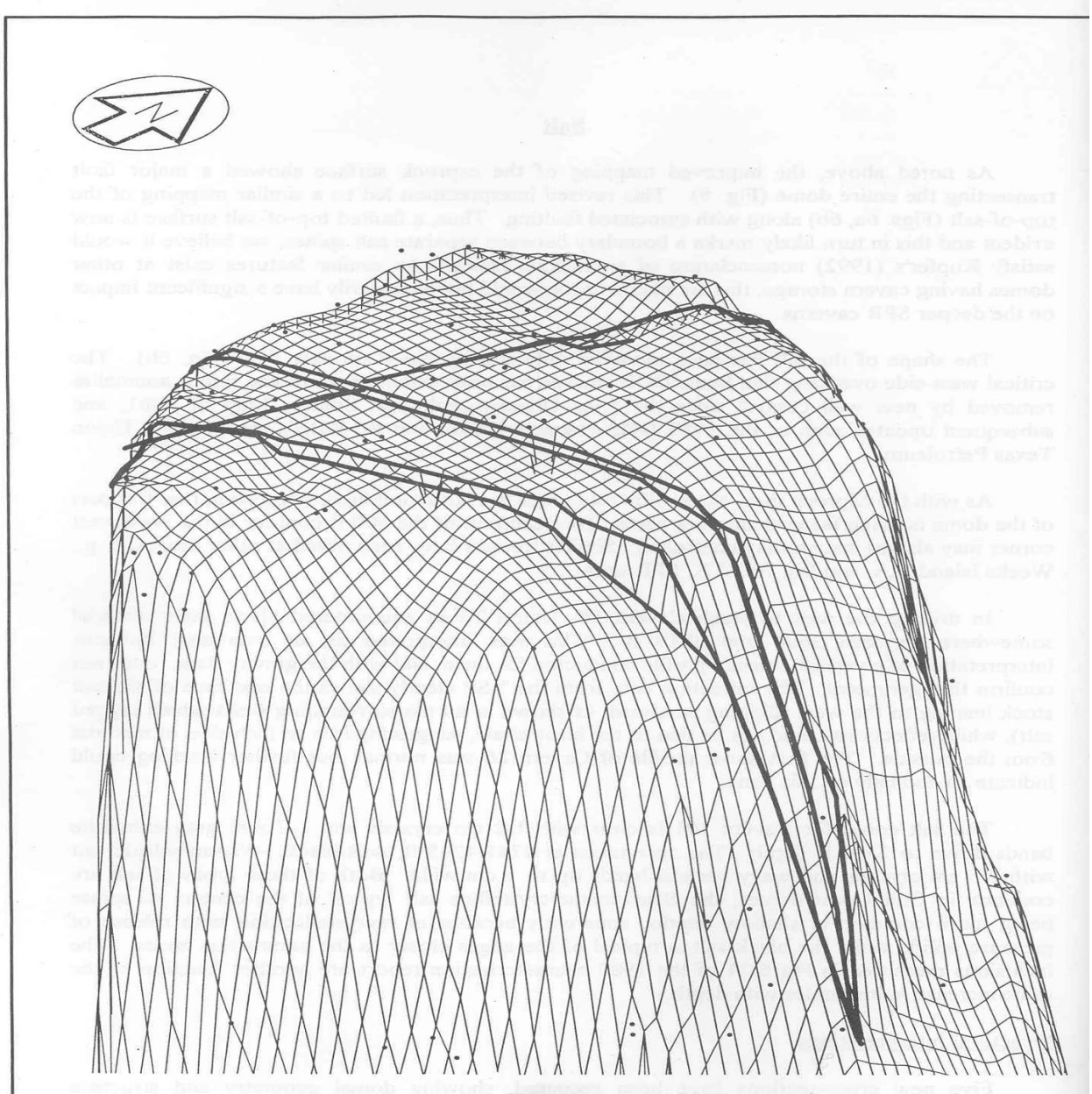
Figure 2. Three Dimensional Representation of Bayou Choctaw [8].

Conversion of the two-dimensional databases from these earlier characterization reports formed the basis for the most recent reexamination by Rautman et al. [4] using modern three-dimensional graphics methods for representation of the dome and its surroundings. It should be noted that the major aspects of the dome, caprock and surrounding strata defined by the earlier characterizations remain largely unchanged. However, the updated three-dimensional models of Rautman et al. [4] differed slightly from the earlier models

because of the more refined analysis of the data. The most recent visualization of the Bayou Choctaw dome is shown in Figure 3 based on the MVS graphics [4]. This visualization includes all of the existing caverns in the dome, both active and inactive caverns. It is evident that there is a distinct separation between the group of caverns with bottom elevations above -2000 ft, consisting of primarily the earlier, abandoned, inactive caverns, and the group of more recent deeper caverns, most of which are active.

Figure 3. View of Bayou Choctaw Dome from South, Tilted Forward 14° [4].

The roughly cylindrical dome is relatively small, with a diameter of about 4500 ft. This can be seen in Figure 1 where the grid lines are at 1000 ft intervals. There is a slight tilt of about 5° toward the west which is exaggerated toward the top of the dome to produce a slight overhang. Beyond the suggestion of a more rapidly moving portion of the dome to cause a structural high point in the northwest corner of the dome [8], the configuration is unremarkable. More importantly, Neal et al. [8] noted that the sequence of rocks adjacent to the Louann mother bed at depth suggest the salt was displaced to the north from its original position. Indicating it was possibly extruded as a sill into the existing sequence of rocks. The identical type of horizontal displacement was suggested for the West Hackberry salt [9]. Salt deformation during the sill development is thought, at least

in part, to consequently destroy the original bedded structure and to homogenize the impurities and second phase particles through out the salt body [2].   Potential for further homogenization occurs later when the salt diapir is formed. The potential for the homogenization of the Bayou Choctaw and West Hackberry domes thorough the initial lateral extrusion prior to diapir formation must be contrasted to the direct extrusion into the diapir formation found for Big Hill. Big Hill would be expected to retain more of the original bedded structure where the previously undeformed original bed would become a deformed cylindrical feature through the self-mandreled diapir extrusion. Any partially homogenized salt from a previous deformation, such as found for Bayou Choctaw and West Hackberry would naturally show considerably less, if anything, of the Louann bedding.

The dome is overlain by layers of alluvial sand and clay originating from channels and backswamp depositions. These alluvial materials are stated to be about 400 ft in depth, but may approach 600 ft in depth. Beneath these loosely consolidated materials, is the caprock covering of the dome. The caprock is composed of two generic layers, the uppermost layer is a mixture of clay and gypsum and the lower layer is massive gypsum-anhydrite. The thickness of these layers varies considerably, depending upon location. Again, there is a local high in the caprock in the southwest quadrant that is attributed to a more rapid rise (a possible spine) in the salt in this part of the dome. According to Neal et al. [8] several faults occur in the caprock. While these faults are common features in the caprock, but it is not clear whether they penetrate into the body of the dome or merely terminate at the salt surface. One fault transverses the caprock, running generally west-southwest to east-northeast that potentially marks a boundary of an anomalous zone in the dome. This fault crosses near Cavern 4, and may have influenced the solutioning response of this cavern. It appears that Cavern 4 was unintentionally solutioned well into the caprock, a situation that is being closely monitored to assure that it does not lead eventually to collapse of the cavern. Another major fault runs diagonally from the southwest to the northeast traverses the dome very near Cavern 7, which collapsed to form Cavern Lake in 1957.

3.0 CAVERN CONSTRUCTION AND HISTORY

As noted previously, although it is not necessarily obvious, examination of storage caverns for indications of the internal structure of the salt dome provides a huge sampling volume compared to the infinitesimal sampling volume of drilled wells and retrieved salt core. Such a large sampling volume of salt surfaces presents up to 2000 ft in height with diameters of about 200 ft. It is critical to take advantage of this new source of potential understanding of cavern behavior. The caverns of this dome offer a collection of caverns of significantly different ages, and hence, construction practices and histories.

3.1 Locations of Caverns and Relevant Drill Holes in Bayou Choctaw

The salt dome and the region immediately surrounding it is penetrated by a number of drill holes, primarily for the discovery and production of hydrocarbons found along the flank of the dome. In addition to the wells drilled into the dome for commercial exploitation involving brine production and product storage, a number of wells were also drilled into the salt dome that were never leached to produce caverns. Also, there are a number of drill penetrations over and around the dome for the disposal of brine from the solution mining which produced the storage caverns.

A schematic of the location of all of the caverns, and the three deep wells, is shown in Figure 4. The schematic also shows the approximate location of the two principal faults noted by Neal et al. [8]. Here the active SPR caverns are shown in light blue, the active UTP caverns are shown in red, the abandoned caverns are shown in green, the collapsed Cavern 7 which formed Cavern Lake is shown in black, and the simple numbers indicate the approximate location of the deep drill holes. The implication of the schematic is that the utilization of the dome area is comprehensive. However, it is of interest to examine the configuration of the dome and caverns in somewhat greater detail. When this is done, the utilization of the vertical extent, or volume, of the dome may not be as extensive as the simple plan view indicates.

3.2 Utilization History of Bayou Choctaw

Currently, there are 15 active and 10 abandoned caverns in the dome. A number of these caverns were initially developed and owned by Allied Chemical. Of the active caverns, Union Texas Petroleum (UTP) acquired nine of these existing caverns, and then exchanged one existing cavern for a newly constructed cavern by the SPR [8]. While UTP initially operated these seven caverns for hydrocarbon storage, with the two other caverns used for brine production, they are now operated by PetroLogistics. They continue to carry the UTP designation. Of the remaining active caverns, four were purchased by the SPR from Allied Chemical, one resulted from the UTP exchange, and finally one was newly constructed specifically for the SPR program.

The caverns are separated into four categories: inactive or abandoned caverns constructed above the -2000 ft elevation in the dome, abandoned deep caverns (including deep wells never leached into substantial caverns), active UTP caverns, and active SPR caverns.
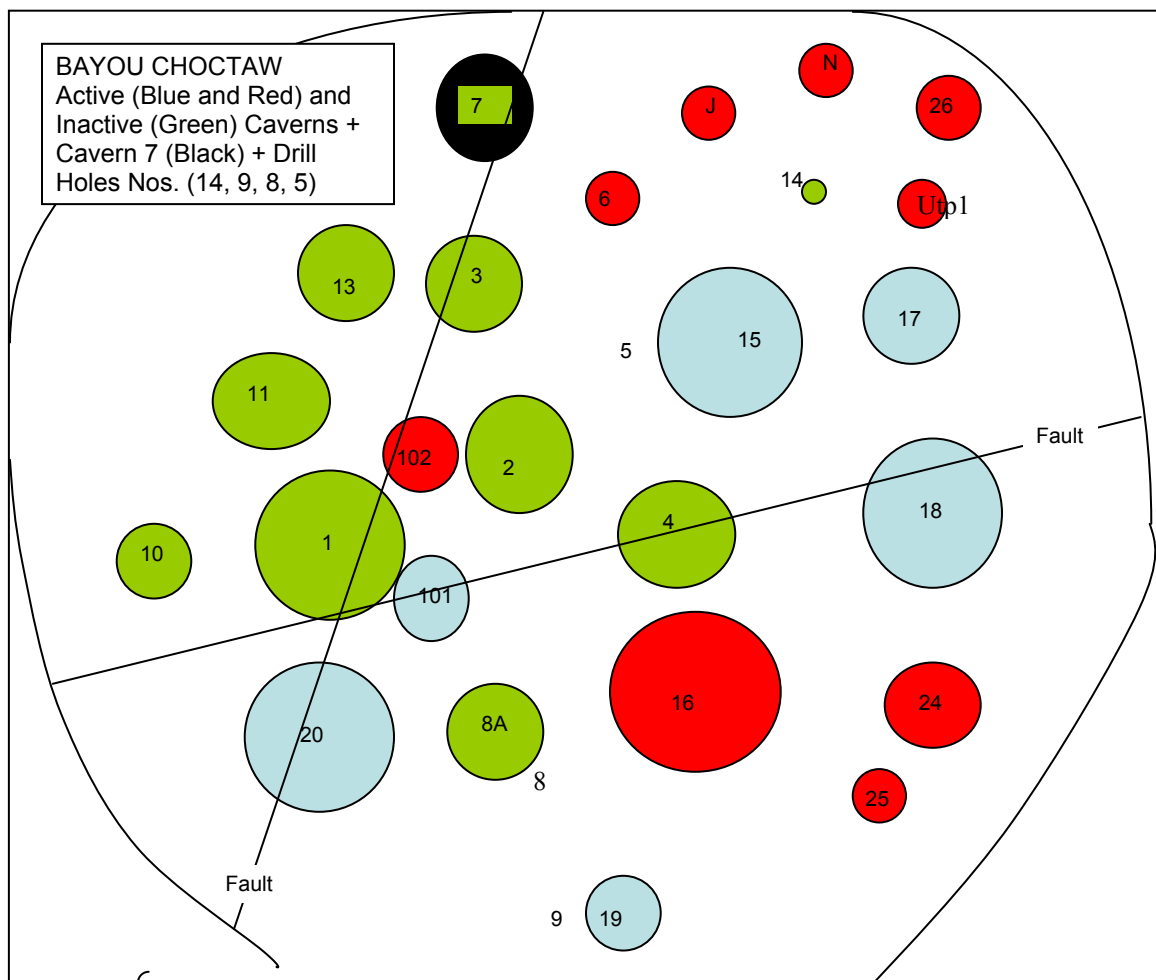
Figure 4. Schematic of Cavern and Well Locations in Bayou Choctaw Dome.

A closer examination of the history and utilization of those wells and caverns is of considerable interest. As a result, the appropriate wells and caverns, together with the approximate thickness of the salt roof over the cavern, the top of salt, the approximate depth of the cavern top and bottom, and related comments, are specified in a series of tables. As noted above, division of the caverns into several categories occurs naturally. First we examine the wells and caverns that have been abandoned, located above -2000 ft elevation. As shown in Table I, some nine caverns are included in this category.

It is not accidental that all of these caverns were constructed from the mid 1930's to the late 1940's, that is, either in the period of the depression or the immediate post-war period. These can be designated as first generation technology caverns. Little development activity occurred during World War II. At the time, it seems that drilling or pumping technology was somewhat limited to depths considered moderate by today's standards. Hence the -2000 ft bottom elevations. Depth of salt over the caverns was correspondingly thin. In fact, two of the caverns have essentially failed, with Cavern 4 showing an apparent breech of the salt barrier and penetration into the caprock, and

Table I. Bayou Choctaw Abandoned Caverns (Bottom Elevation above -2000 ft).

Cavern	Year	Sonar	Salt Roof Thickness (ft)	Cavern Depths (ft) Top	Bottom	Comments
				Shallow Caverns		
1	1937	1977	371	950	1988	Lower casing seal leak
2	1934	1977	100	~700	1846	Thin roof
3	1934	1977	100	860	2000	Communicates to 11 and 13
4	1935	1980	(-40)	620	1990	Leached into caprock
8A	1944	1980	460	1235	2007	Leak in casing
10	1947		300	990	1942	Potential leach through salt
11	1947	1980	350	1030	1928	Enlarged to west, see 3
13	1948	1977	190	1103	1915	See 3
7	1942		(-??)		1951	Collapsed, Cavern Lake

Cavern 7 having completely breeched the overlying material to form Cavern Lake in 1954. Perhaps coincidentally, both Caverns 4 and 7 are beneath faults in the caprock [8].

Although records of the abandonment dates were not found, the caverns were obviously in service for several years. The reasons for the abandoning the caverns are somewhat vague, but usually seemed to be based on apparent failures of seals and leaks or loss of pressure, as noted in the table. In some cases there appeared to be communication between caverns.

The schematic position of these caverns in the salt dome is given in the plan view of Figure 5. In terms of general description, these caverns dominate the western and north-western portion of the dome.

An important aspect of these caverns is their vertical location, with bottom elevations above -2000 ft. As a consequence, a relatively large volume of salt beneath them appears to be unusable. Never-the-less, because they are quite shallow, they would have little if any influence on caverns constructed between -3000 and -5000 ft. Even though they would undoubtedly continue to deteriorate with time, they would not affect a suitable thickness of salt separating them from caverns below. Although not fully explored in the previous studies of expansion activities, these locations may be of future importance. Of course, care would have to be taken to assure that the access wells into the deeper caverns were not affected by the abandoned caverns behavior. Clearly, new entry wells to such deep caverns would be best placed at positions of calculated neutral lateral displacement, i.e., the midpoint between same sized caverns. It is also necessary to assure the deep caverns will not cause instabilities in the shallow caverns or adversely impact any neighboring caverns.

The next category of caverns and wells are those that are abandoned but which are deeper than -2000 ft. As detailed in Table II, only one abandoned well (cavern) is in the
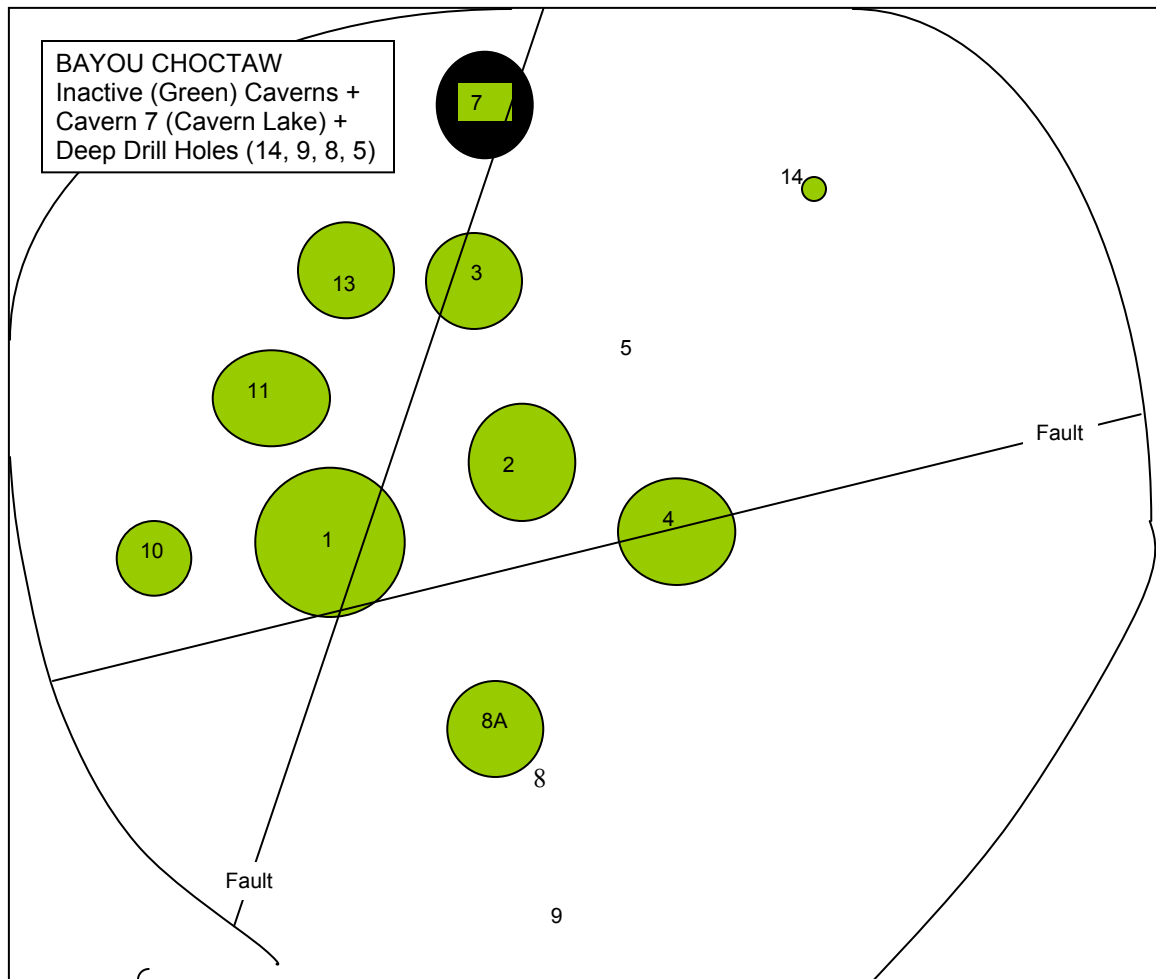
Figure 5. Schematic of Abandoned Shallow and Deep Caverns and Deep Wells.

category of having a bottom elevation deeper than -2000 ft. This not an actual cavern because only minimal solutioning of about 100,000 bbl occurred; the brine from this well contained quantities of magnesium. Several deep wells or intended caverns were constructed which were either never leached or which were minimally leached. Of the unleached wells, the stated reasons for discontinuing the leaching process and the abandonment of the wells was local subsidence and collapse. All of the locations are shown in Hogan [7] (Figure 5.3). Because the wells were scattered through out the dome, it is difficult to know the origin or meaning of the subsidence. Potentially it may have been just problems in drilling practice. However, in the instance of Cavern 14 (Well 14) which may have been intended as a brine source, presence of high magnesium content seems to have been a factor in abandonment.

These deep wells are listed in Table II and are also shown in Figure 5. Shown in the figure is the deep Well 8, which is nearly collocated with Cavern 8A. The abandoned deep wells are almost on a north-south diameter of the dome, widely spread from north to south. The later Cavern 14 (Well 14) is just west of the adjacent earlier first generation

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Table II. Bayou Choctaw Abandoned Caverns (Bottom Elevation below -2000 ft).

Cavern	Year	Sonar	Salt Roof Thickness (ft)	Cavern Depths (ft) Top	Bottom	Comments
			Deep (Well) Cavern			
14	1953				3058	100K bbl, high Mg content
			Unleached Wells			
5	1943				775	No leaching, subsidence
8	1944					Subsidence, replaced by 8A
9	1944				2013	No leaching, well collapsed

Note deep Well 8 is essentially collocated with Cavern 8A.

Cavern 6, one of the early caverns above the -2000 ft bottom elevation was also noted to have a high magnesium component. Cavern 14 (Well 14) is in the northeast quadrant of the dome, reasonably removed from the SPR property. In the Hogan [7] plan view representation of the dome, there is a Well 6 shown, see Figure 1, which does not appear in the written record. Apparently it was never developed. Another possibility is that the well eventually became Cavern 6. Regardless, the well is not shown in a critical location.

The next category considered is the active UTP storage caverns at Bayou Choctaw. Theses caverns are those primarily constructed between the late 1960's and the early 1990's. Only Cavern 6 from 1943 remains active. As shown in Table III, Cavern 6 is less than 2000 ft deep, while the remaining eight cavern bottoms range between 3228 and

Table III. Active UTP Caverns of Bayou Choctaw.

Cavern	Year	Sonar	Salt Roof Thickness (ft)	Cavern Depths (ft) Top	Bottom	Comments
			Cavern Less Than 2000 ft Deep			
6	1943	1990	519	1195	1562	Propylene, high Mg content
			Caverns Greater Than 2000 ft Deep			
UTP-1	1967	1989	1660	2360	3502	Ethylene
16	1954	1989('76)	1763	2612	3228	Ethylene
J	1972	1989	2054	2854	3945	Ethane/Propane
N	1972	1987	1870	2670	3590	Ethylene
24	1979	1987	2245	3100	4337	Natural Gas
25	1979	1992	2721	3575	5790	Brine
26	1990	1991	2176	3076	3470	Brine
102	1981	1984	1968	2640	5339	Ethane, constructed by DOE

Figure 6. Active UTP and SPR Caverns, with Shallow Cavern 6 and Deep Wells.

5790 ft deep. The active UTP caverns are shown in Figure 6 in red, except for shallow Cavern 6 which is in orange. In general these cavern locations are found in two groups both in the eastern portion of the dome. While one UTP cavern group traces a gentle arc in the far northeastern quadrant of the dome and the other group in located in the south-southeastern dome. The centrally located Cavern 102 seems somewhat alone, but actually is located generally near to Cavern 101. The criteria that governed the selection of these cavern sites are not readily available.

The active caverns of the SPR are shown in Table IV, and their locations are illustrated in the schematic of Figure 7. Note that the active SPR caverns are also shown in Figure 6 in order to give a complete picture of the active cavern field. The active SPR caverns all involved the second generation, or more advanced technology, cavern construction, with the most recent cavern, Cavern 101, being constructed in 1990. Some operational concerns have developed for Caverns 15 and 17 and Cavern 20. Apparently the web of salt separating Cavern 15 and 17 is sufficiently thin and flexible that it transmits the effects of pressure changes from one cavern to the other. As a result, the caverns are

Table IV. Active SPR Caverns of Bayou Choctaw.

Cavern	Year	Sonar	Salt Roof Thickness (ft)	Cavern Depths (ft)		Comments
				Top	Bottom	
Caverns Greater Than 2000 ft Deep						
15	1953	1992('74)	1960	2605	3296	Pressure communicates to 17
17	1955	1992('76)	1900	2600	4023	See 15
18	1967	1992('78)	1200	2125	4219	
19	1967	1992('77)	2100	2935	4228	
20	1979	1993('78)	3200	3830	4425	Close to dome flank
101	1990	1992	1824	2550	4830	SPR constructed

operated as a single unit. The separation of Cavern 20 from the dome flank is suspected to be quite small, thus causing concern about the cavern integrity during any future drawdowns.

As in the case of the active UTP caverns, the SPR caverns occupy a well-defined portion of the dome. Specifically, they are all located south and east of a diagonal southwest-north-east line which crudely occupies about 65 % of the eastern side of the dome for the caverns, as indicated in Figure 7. This line of separation coincides very well to the southwestern to northeastern fault line noted by Neal et al. [8]. Interestingly, three potential unutilized areas of reasonable size can be immediately identified within the area occupied by the group of active caverns. Also, the relatively large area to the north and west of the fault line may be considered as an unutilized area of the dome. Such areas have been the subject of investigation for possible reserve expansion [6].

Bayou Choctaw caverns development histories are by and large difficult to trace. Certainly both construction practice and documentation were considerably less rigorous for the first generation caverns. This generation encompassed the years beginning prior to World War II up to the immediate post-war period. During this period, solutioning practice was largely uncontrolled and the means to monitor or measure the development of a cavern were very limited or non-existent. Rather spectacular failures and operational difficulties in some of the earliest, pre-World War II caverns, caused changes to solutioning practices and regulations, including use of blanket oil to protect the cavern roof during solutioning. Also, some major technical advances provided for better measurement and control of cavern dimensions through increasingly accurate sonar surveys.

Only one of the active UTP caverns which utilized the first generation technology remains in service. The majority of the active caverns, both UTP and SPR, are related to a second generation technology. With the rapid development of the post-war oil industry, drilling to greater depths became possible and seismic methods for defining the subsurface advanced. These, together with the increasing demand for petrochemical products, forced advances in solution mining and storage.

3.3 Available Construction Histories of Two Most Recent Caverns

As one would imagine, construction documentation for the caverns constructed in the early years, 1930's and 1940's, is very difficult to find. A summary of these caverns [7] is indeed limited. In fact, sonar surveys of these caverns only occurred in the late 1970's
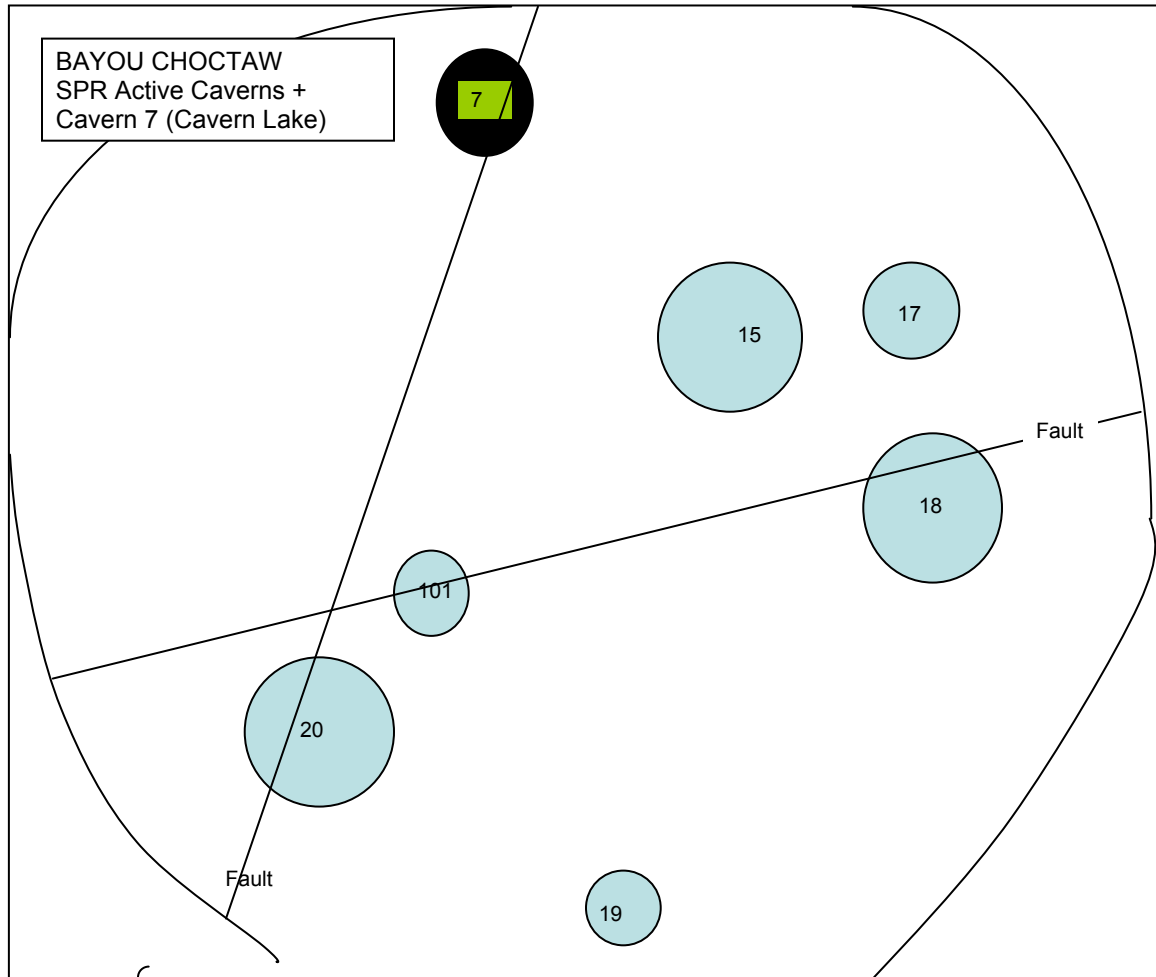
Figure 7. Schematic showing Active SPR Caverns and Cavern Lake.

and early 1980's. The very limited resolution of some of the survey data is apparent, as shall be discussed later. Even most of the later caverns, which were developed using better technology, are not well documented; however, the sonar survey data are quite contemporary, being obtained between 1987 and 1992. Some multiple, time separated, surveys of caverns are available.

The two most recent caverns, constructed in 1990 and 1981, can certainly be considered as second generation caverns, but with even more advanced solution mining technology and cavern formation control. While the two most recent caverns can be discussed in some detail, they provide, unfortunately, only limited, localized data and not a broad

insight into the entire dome stratigraphy and how this might influence cavern solutioning at Bayou Choctaw, as one would hope.

Cavern 101 construction [10] began with the completion of two wells in 1985. These wells have 13 3/8" O.D. cemented casings with a 10 ¾" O.D. outer tubing and a 7" O.D. inner tubing in each well. Solutioning commenced in late 1987 when the inner tubing of each well was removed and one well acted as the raw water inlet and the other well was the brine outlet for the Chimney/Sump leaching stage. Inlet water in Well B was at -5042 ft elevation and outlet brine was produced from Well A at -4749 ft. Sump development required four months, and removed a rather small amount of salt, 311,400 bbl. The sonar surveys indicate a relatively small diameter sump, about 25 ft, and a long very narrow chimney. The two wells were coalesced over major portions of their length [11]. Next, the Chimney development had the inlet water in Well B at -4828 ft elevation and outlet brine was produced from Well A at -2904 ft, which removed 2,089,624 bbl of salt (varying between 12,641 bbl/day and 17,412 bbl/day). Sonars taken at completion of Chimney development show an enlargement of the sump with variable diameters of 100 to 210 ft. Above the sump the cavern had a smaller but relatively uniform diameter. The two wells were completely coalesced below -3800 ft. The First Reverse stage of leaching actually was primarily direct leaching because it was determined that the sump formation was undersized. When reverse leaching was reinstated, water injection was at -2904 ft and brine production at -4828 ft. At the completion of the First Reverse Stage the cavern had a significant sump with a diameter of about 210 ft with an extended chimney of much smaller diameter [12]. The development proceeded to the Second Reverse Stage. For both of the Second stages the configuration of Well B was at a 4828 ft elevation and Well A was at a -3898 ft elevation with the reverse flow. The Second Reverse stage took place over nine months. During four months some 2,979,663 bbl of salt were removed (19,529 bbl/day). The average diameter was about 140 ft, but tapered from top to bottom to about 116 ft. However, the cavern was undersized. As a result, the final stage was noted as a continuation of the Second Stage leaching without changing the elevation of the inlet and outlet tubing, removing a total of some 4,183,795 bbl of salt (15,498 bbl/day). At this point the upper portion of the cavern had been enlarged significantly with diameters around 150 ft [13]. While all of the features of the cavern were developed at this point, the cavern shape details separating the direct from the reverse leach can not be established. Finally, the leaching was completed using a two month direct leaching period with inlet water tubing at a -4819 ft elevation in Well A and the outlet brine tubing at a -2651 ft elevation in Well B. Salt removal was 649,068 bbl (10,815 bbl/day). These removal rates are plotted in Figure 8, with some uncertainty in the agreement of dates between sonar surveys and the construction report.

The solid line for Cavern 101 in Figure 8 connects the leaching stages in chronological sequence, beginning with the direct Sump Development stage at the lower left corner of the graph. Following the line to the next stage leads to the 1st Reverse Leaching stage which in actuality was primarily a direct leaching stage to increase the sump/chimney volume. The line then goes to the 2nd Reverse Leaching stage, followed by the 3rd Reverse Leaching stage. Finally the cavern construction ended with an extra Direct Leaching stage.

Cavern 102, which was constructed by the SPR and traded to UTP for Cavern 17, was constructed before Cavern 101. The two wells [19] of Cavern 102 were completed in a 10 month period in mid-1981 and were cased at 14", with 10 ¾" O.D. outer tubing and 7" O.D. inner tubing. At completion of the wells, the inner 7" O.D. tubing reached to 5446 ft and the 10 ¾" O.D. tubing was emplaced to -2988 ft. It is not clear how the two wells were used in the solutioning process. According to the records, the leaching of the Chimney/Sump stage was completed by direct leaching on December 15, 1982 [20].
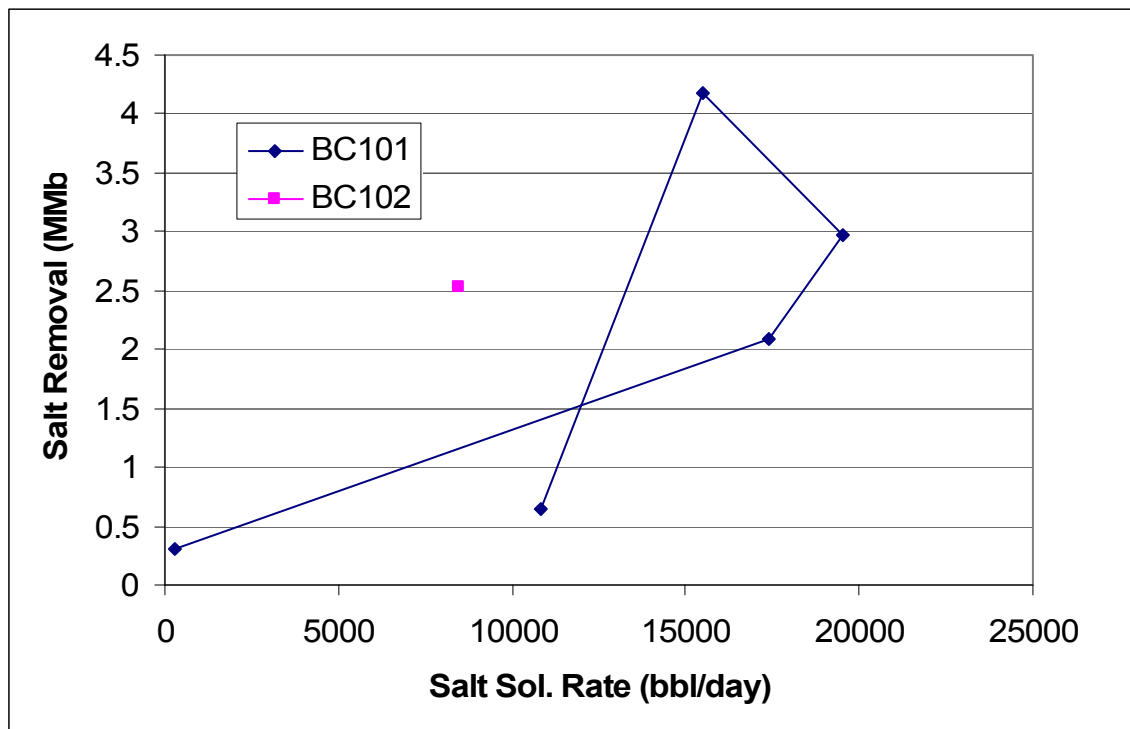
Figure 8. Salt Removal and Solutioning Rates for Caverns 101 and 102.

This was followed by a reverse leaching stage completed on September 8, 1983 [21]. However, prior to this time the cavern apparently had a complex leaching history. It appears that before December 1982, the cavern was leached in the direct leaching mode. Because the cavern diameters and volume were not sufficient, between December 1982 and October 1983 the cavern was leached in two reverse configurations, first with the brine output tube at -5000 ft for 19 weeks and then with the brine output tube at -4300 ft for 11 weeks. While a total cavern volume is available from the September 1983 sonar, no record can be found for the December 1982 sonar. The last Reverse Leaching stage utilized raw water input at -3162 ft with brine production from a depth of -3400 ft. Leaching ended just prior to the October 1984 survey, with a calendar time of 13 months. The calculated solutioning rate of 8,457 bbl/day of salt seems low, indicating perhaps that leaching was not active during all of the 13 months. At this time the cavern portion below -3460 ft was a cylindrical bulb. Above bulb the cavern was still cylindrical but with a diameter of only 57 ft, this diameter increased to about 180 ft at an elevation of

3280 ft. The top of the cavern was again bulbous, with diameters ranging from178 to 226 ft [20]. Again the limited solutioning rate data, a single point, is shown in Figure 8.

While the quantity of solution rate data for the construction of Caverns 101 and 102 is limited, the construction solutioning rates the two caverns are generally within and consistent with those rates used for the West Hackberry caverns [2] (Figures 7 through 10 of that report), as one would expect. Again the only rate that could be determined for BC102 was low. As in the case with West Hackberry, no conclusion on the affect of these rates on cavern geometry is possible.

It must be noted that recreating the history of both Cavern 101 and Cavern 102 is often confusing, sometimes because the records are incomplete and at others because the solutioning events changed within what was defined as a specific stage. Correspondence of dates and the actions within a given stage apparently was not always possible. It is possible that improvement in this situation could be gained by more intense study; the author believes the account given is adequate for the purposes of this study.

3.4 Evolution of Cavern Solutioning Design

Because of the large number of caverns being constructed for the SPR, it is possible to follow the evolution of the construction practice with time. This interesting history is as follows:

1. Bryan Mound   March 1980 – July 1984 (Initially 2 and 3 well caverns, but from '82 forward all 2 wells caverns.)
2. West Hackberry April 1981- June 1985 (All single well caverns, except for last cavern constructed which had 2 wells.)
3. Bayou Choctaw   May 1986 – March 1990 (Only Cavern 101 with 2 wells.) November 1981- October 1984 (Only Cavern 102 with 2 wells.)
4. Big Hill   October 1987- September 1991 (All were 2 well caverns.)

The history shows the progression from the mixed two and three well configuration at Bryan Mound, followed by the large scale effort using a predominantly single well configuration at West Hackberry. However, the last West Hackberry cavern was of a two well design. At Bayou Choctaw, the two well configuration was continued for the only two caverns constructed by the SPR. The two well design then persisted through the construction of the Big Hill cavern field. Munson [2] considered the single well West Hackberry caverns to have the best solutioning control based on the final geometry of the caverns. Whereas the Bryan Mound caverns exhibited multiple problems with geometry control, i.e., salt remnants between wells, blind volumes, ledges, etc. Whether this was more a coincidence resulting from other factors at Bryan Mound than well design or not is unknown. Stratigraphy and leaching preference was thought to play an important role at Big Hill. Whereas the material homogeneity of the dome is thought to be important, at West Hackberry. Indeed, at West Hackberry it was speculated that the control of cavern geometry was influenced by the details of the dome stratigraphy as well as the single well

configuration of construction. Never-the-less, the single well configuration was not used again, but neither was the three-well design.

Construction of Cavern 102 is essentially contemporary with the construction of the caverns of West Hackberry. The two well Bayou Choctaw Cavern 102, which shares the same well/tubing configuration, was constructed just prior to the two well West Hackberry Cavern 117. Further the two well caverns of Big Hill were constructed in the same configuration just after the West Hackberry Cavern 117. Bayou Choctaw 101 was constructed concurrently with the later West Hackberry caverns. Just to complete the evolution of the SPR cavern construction design, the earliest caverns were those of Bryan Mound, two and three well caverns constructed between 1980 and 1984. As a general comment, the three well configuration at Bryan Mound resulted in very irregular cavern geometries, which may have contributed to the large number of salt falls in these caverns [17]. The two well cavern configuration eventually predominated at Bryan Mound. Apparently the design of caverns evolved from uncertainty between two and three well configurations, to single well design, and then became established at a two well design. However, it appeared that the large casing of the single well configuration was subject to higher occurrence of casing leaks than the smaller casing of the two well configuration. While the three well design was cumbersome and apparently difficult to control during solutioning, the choice between the single well and two well designs is apparently based on the propensity for leaks in the large diameter casing.

At this point, it was not possible to reconstruct the thinking that led to the various well configurations. Perhaps it was a combination of well size – flow rate considerations, economics, maintenance, and well duplication for safety.

3.5 Salt Materials

It is important to include all known aspects of the dome material response which may relate to the response of the caverns. This includes mechanical behavior as determined from both laboratory and field observations.

As described by Neal et al. [8], the salt core taken from a drill hole at Cavern 101, the salt of the dome has some distinguishing features. At the higher elevations, i.e., above -2390 ft, the salt is clear with 1-2 cm diameter crystals which contained 1-2 mm wide gray anhydrite bands. At deeper elevations, in the five feet of core take at about -4741 ft, the 5 mm diameter salt crystals appear black. The color is the result of a distribution of about 5% of anhydrite. Anhydrite is also found in wavy bands some as much as 10 mm wide. The authors suggest this occurrence of different salt is common in the Gulf Coast domes. They state the clear salt is typical of the center of spines, while the black, anhydrite containing salt is thought to be associated with anomalous zones. While the analysis method is not specified, typically it would have been from the insoluble residue of dissolved core samples.

Recently, Fredrich et al. [18] have analyzed the composition of a number of salt specimens from both deep water and coastal salt domes and structures using x-ray

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techniques. This work included samples from the Bayou Choctaw core described by Neal et al. [8]. The only second component was anhydrite. Two samples at roughly 1129 ft measured 4.3% anhydrite, and two at roughly -2388 ft were 3.4 - 6.7% anhydrite, correspond to the earlier core descriptions by Neal et al. [8] of clean salt. Two samples taken at roughly -4743 ft were 1.3 – 2.4% anhydrite, and correspond to the visual description of the black 5.0% anhydritic salt. Clearly, these later analyses are not supportive of the earlier descriptions. It suggests that the x-ray samples may have selectively eliminated some of the anhydrite in the black salt, and in fact may not have taken into account the anhydrite bands. Clearly the two methods of analysis could lead to such discrepancies.

Although the mineralogical composition of the salt is not quite clear at this point, the earlier descriptions of the core samples by Neal et al. [8] are probably more indicative of the bulk condition of the domal salt. Never-the-less, the implication is that above -2300 ft the salt is different in some manner from the salt deeper into the dome. In explaining the cavern solutioning, and perhaps other aspects of cavern behavior and stability, this difference may have some significance.

The amount of creep information on Bayou Choctaw is extremely limited, consisting of only one multistage creep test [19, 20] on a core taken from Well 19A at 2577 ft depth. However when this test was analyzed, according to the concepts of the M-D creep model, the results are compatible. The sample was noted to be clean salt with a medium, 1 to 2 cm, grain size.

In this effort, Munson [19] analyzed the laboratory creep tests of a number of domal salts. From this study it was determined that the mechanical response was divided roughly into those salts that are more (hard) or less (soft) creep resistant. Both West Hackberry and Big Hill salts are considered soft, whereas Bayou Choctaw is a hard salt, as is the Bryan Mound salt. These results, together with those for other domal salts, are shown in Table VI. On occasion, it appears that the hard and soft salts may occupy different portions of a dome, perhaps associated with different spines.

Table VI. Structure Factor Multiplication from WIPP 25°C Pure Salt [19].

Temp.	Factor	Clean	Soft Salt					Hard Salt		
		WIPP	AI*	WI	MB	WH	BH	BM	BC	JD
25°C	Multiply by	1.0	0.71	0.59	1.0	1.23	1.29	0.17	0.17	0.17
	Log$_{10}$ Differ.	0.00	-0.14	-0.23	0.00	+0.09	+0.11	-0.76	-0.77	-0.77

* The multiplication factor applies to A2 of the undefined mechanism. Because A_1 could not be evaluated, this factor is applied to the dislocation climb mechanism [21]. Here, AI=Avery Island, WI=Weeks Island, MB=Moss Bluff, WH=West Hackberry, BH=Big Hill, BM=Bryan Mound, BC=Bayou Choctaw, and JD=Jennings Dome.
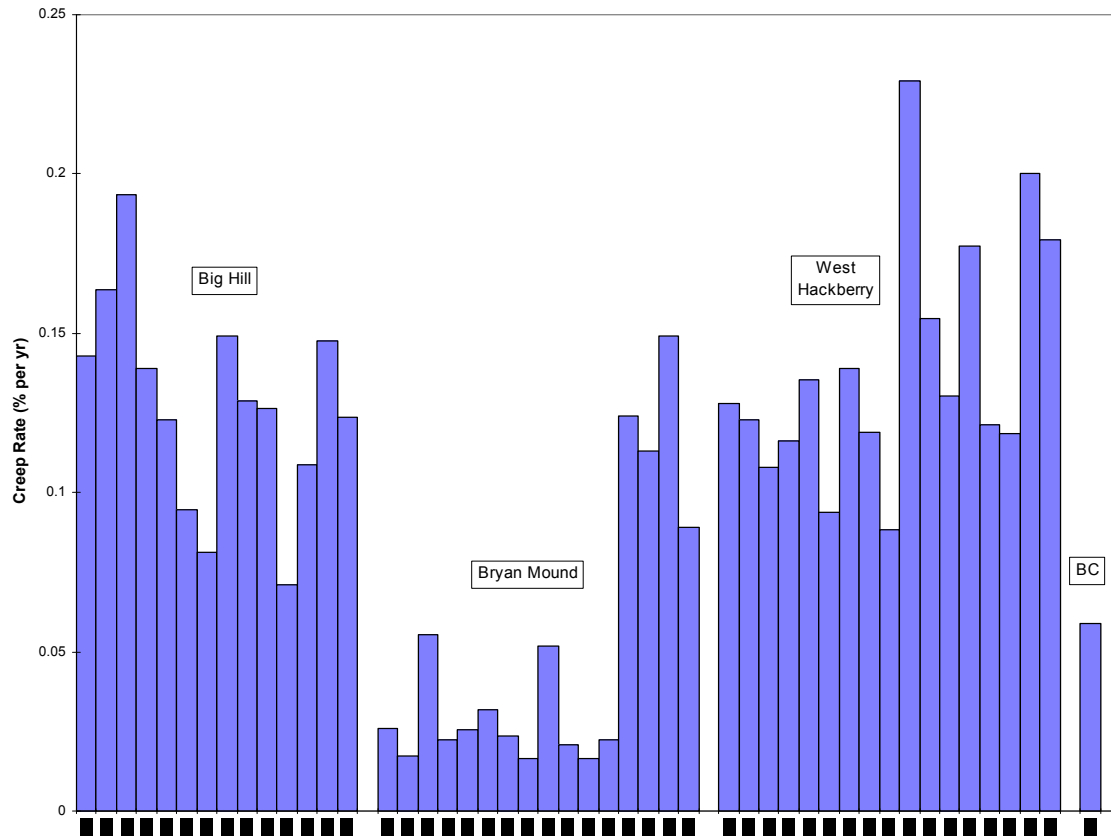
Figure 9. SPR Cavern Closure Rates for Individual Caverns [22].

As is clear, laboratory testing information concerning the mechanical behavior of the caverns of Bayou Choctaw is quite limited. However, there is another important source of information on the creep of the salt dome, in situ. This information comes from the rather detailed data on the closure of the SPR caverns with time. Ehgartner [22] analyzed the creep closure rates based on the shut-in pressure increases in the SPR caverns. These results are shown in Figure 9. While Ehgartner [23] has reanalyzed the cavern closure rates in the light of more recent and complete data, the basic relationship remains the same. Unfortunately, only Cavern 101 of Bayou Choctaw could be analyzed. From these results, the closure rate of BC 101 was found to be quite low. Although not the lowest, it was considerably less than most of the West Hackberry and Big Hill caverns, and somewhat more than the Bryan Mound caverns. And of even greater interest, the laboratory response of the various domal salts is directly linked to the creep deformation or closure of the caverns in a dome, and this is shown in Figure 9. A low closure rate implies a more creep resistant behavior. Thus the measured field creep closure resistance is consistent with the relative creep resistance measured in the laboratory.

3.6 Mechanical Behavior Aspects

We want to examine all aspects of the behavior of the caverns of a particular dome to see if they can contribute to the general knowledge of the dome. Loss of portions of the brine hanging string over time in a cavern is usually ascribed to damage done by salt falls [24,

25]. At Bayou Choctaw these events are recorded only for the SPR caverns. As Table V shows, the events in the purchased existing caverns are rare, in fact only Cavern 20 has indicated possible damage of a hanging string. Unfortunately, the exact details of this event could not be established. In the more recent constructed, SPR Cavern 101, at the time of this report, there were two events, one of which occurred during the construction leaching and the other shortly thereafter. However, in a recent update of hanging string failures, Mansure [26] has noted four additional events. From limited observations, it appears that Cavern 101 was initially stable but has become more active with time. Based on the concept of progressive development of spalls and hence salt falls, this seems reasonable. Mansure [26] reports no new events in the other Bayou Choctaw caverns. Thus, it would appear the purchased caverns of the SPR are stable. There is no available information on the mechanical stability of the active UTP caverns nor, as one would expect, on the abandoned caverns. However, one would expect these caverns to be relatively stable, reflecting the observed behavior of those caverns that have been monitored.

The apparent mechanical stability of the Bayou Choctaw caverns is somewhat surprising because of the many regions of "blocky ledges." These regions are profound in Cavern 101, for example, and may be responsible for the increase in hanging string failures. In

Table V.   Bayou Choctaw Site Hanging String Events [17].

No.(Wells) Typ.	Start-End (year)	Salt. Cover (ft.)	Depth to Roof (ft.)	Cavern Height (ft.)	Diam. (ft.)	Casing No.	Failure Date	Casing Loss (ft.)	Depth (ft.)	Notes
BC 15A (2)Sour	53(80)	1979	2695	691	412					
BC 17 (2)Sour	55(85)	1952	2600	1423	238					
BC 18 (2)Swt	67(78)	1320	2125	2094	244					
BC 19 (2)Sour	70(78)	2078	2935	1257	380					
BC 20A (2)Swt	79(78)	3130	3830	395	514	20*"	??/81	Damg.		
						20A*"	??/81	Damg.		
						20*"	??/83	?		
BC 101 (2)Sour	87-90	1824	2550	2290	201	101B*'	12/87	118	4838	LUC
						101A*'	03/90	1445	3874	BSF

" [1988]Taken from D506-1788-09, author unknown, February 1988.
' [1991]Taken from Boeing Petroleum Services, Inc., DOE SPR Constructed Cavern History,
        Rev. 2, January 1991.
* [1996]New events reported by individual cavern reports, private communication Harry
        Lombard.
G [1980]Gas reported in one or more of the brining wells, Strategic Petroleum Reserve (SPR)
        Geological Site Characterization Report Bryan Mound Salt Dome, Ed. R. G. Hogan,
        SAND80-7111.

B = Brine solutioning   SF = Salt fall
L = Loss of pipe   UC = Unknown cause

fact the cavern has the appearance of having a lace collar of ledges around a central core. It seems that these ledges are associated with the reverse leaching state of cavern development. Such regions could be considered as prime areas for the formation of spalls, the source of salt falls. There may be some suspicion that the blocky appearance is an artifact of the sonic techniques, but this appears to be a remote possibility because the feature is so prevalent. It is also difficult to accept that these features are the result of the solutioning process. If solutioning alone were involved formation of such blocks would seem to be impossible because solutioning is not really preferential on such an apparent regular, repeating scale. If the spall process occurs during leaching, the blocks would fall to the cavern bottom, but would still be subject to dissolution. As in the case of normal solutioning, only the insolubles would remain. Certainly, it would be helpful to confirm the continued existence of these features though new sonar surveys.

There are several peculiar aspects of the Bayou Choctaw caverns that will be treated during the following discussion. Clearly the implications of the blocky appearance in Cavern 101, together with the far reaching fan-like preferential solutioning apparently found in some of the abandoned caverns, require additional comments.

4. DISCUSSION OF CAVERN GEOMETRIES

At the onset of this discussion, we must admit that the caverns of Bayou Choctaw present some unusual and challenging features; this is combined with limited information about their construction and history. Against this background, never-the-less, an attempt will be made to interpret the structure of the caverns and use this information to develop an understanding of the dome stratigraphy.

The primary tool to determine the shape of the cavern internal surfaces is the sonar survey. A sonar transducer is lowered into a brine filled cavern through an appropriate well. At each station, typically at intervals about 10 to 25 ft, the transducer vertical elevation is held constant while the azimuth direction of the sonar beam is changed in a stepwise fashion, in recent practice this is normally 128 steps, with sonar reflections recorded at each azimuth angle. This is repeated at every vertical station. The result is the generation of a surface based on the sonar survey points which define the interior surface of the cavern. The resolution is related to the number of points recorded and the sonar beam characteristics. However, the sonar surveys of the Bayou Choctaw caverns were affected by the status of early sonar developments, where the technology and methods were either undeveloped or cost prohibitive resulting in survey detail of a lower standard, with subsequent lower resolution. In many of the older Bayou Choctaw caverns, this inadequacy in the sonar surveys is apparent.

The observation of the maximum outline shapes of the caverns in the case of Big Hill suggested directions of preferential solutioning which was taken as a sign of internal dome stratigraphy [1]. The plan view outlines of the caverns of Bayou Choctaw [4] are shown in Figure 10. Not all caverns appear in this figure, especially Cavern Lake, some UTP caverns in the upper northeastern portion, and Cavern 16 and 24, because sonar survey data for these caverns are not available. Unfortunately, this figure is somewhat complicated, so it is essential to focus on the individual plan view shapes of the caverns, from both the irregularities of the individual cavern aspects and how these irregularities fit into the overall dome aspect. When this is done, it becomes clear that even though some of the caverns clearly show directional features, there is no unifying trend suggesting the dome itself has preferential or directional features. Most of these directional features appear as a "fan" that extends away from the main cavern outline. Specifically, both Cavern 1 and 2 have fan features extending toward the west, and Cavern 4 has an elongated east and west fan. Typically these features are associated with the early, abandoned caverns, in which the feature may be an artifact rather than real, as will be discussed later. There are also a few of the early abandoned caverns with sharp angular features which are the result of insufficient resolution of the sonar records. For those caverns where the sonar resolution is better, more features are defined. However, the remaining caverns, which include all of the active caverns, are in many aspects generally cylindrical in shape. Certainly, there is no indication from the assemblage of caverns that there is any significant overall preferential dome stratigraphy.

There are many features of individual caverns that can be examined in detail. The features themselves tend to categorize in to potential causes. However, as will become
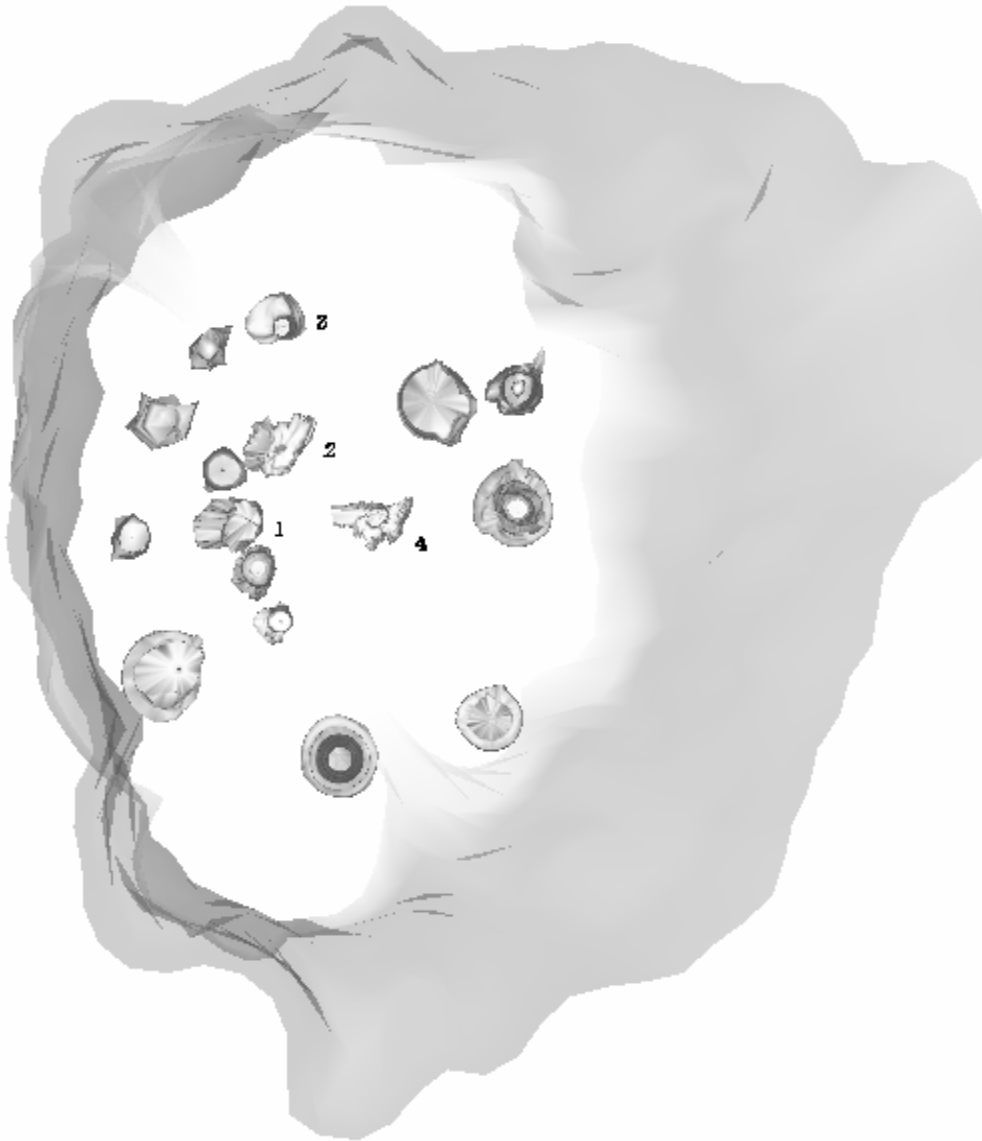
Figure 10. Bayou Choctaw Plan View of Cavern Shapes (Partial) [4].

apparent, not all of these features are, or can be, the result of inherent characteristics of the salt or the result of solutioning.

4.1 Insufficient Sonar Survey Resolution

The sonar of Caverns 10, see Figure 11 (and Appendix A) and Cavern 11 (see Appendix A) indicate very distinct and sharp angles related to simple geometries, which can be attributed to a lack of resolution, where too few survey stations are used around the azimuth. It appears only a limited number of azimuth stations, perhaps as few as six, were used at any given vertical station. Consequently connecting these azimuth readings

Figure 11. BC10-270°cw-45° – Opaque, Insufficient Sonar Resolution.

give rise to flat surfaces of a hexagonal prism. Even though these sonar surveys lack resolution and do not adequately reflect the true cavern shape, they remain useful in estimations of the cavern volume. It is not known if the insufficient resolution was because of limitations in the technique or was intentional to save time or cost.

4.2 Apparently Highly Irregular Solutioning

Examination of the shapes of caverns in some detail may provide more insight not only into the domal characteristics but also into the sonar methodology. While apparently

susceptible to irregular solutioning, early abandoned caverns are very difficult to characterize. The history of these caverns is that they were apparently used as brining caverns with little control on the brining process. The cavern shapes are quite irregular, with sharp changes in diameter and apparently marked preferential dissolution features, such as channels and ledges as shown for Caverns 1 and 4. Cavern 1 is illustrated in Figure 12 and Cavern 4 is in Figure 13. The detailed shapes of Caverns 1 and 4 illustrate that the "fans" noted previously are marked changes in diameter, with steps and ledges. These two caverns are somewhat unique in the size of these fans. Cavern 1 shows a broad fan shape over a portion of the cavern. Cavern 4 is crudely cylindrical in the lower half,
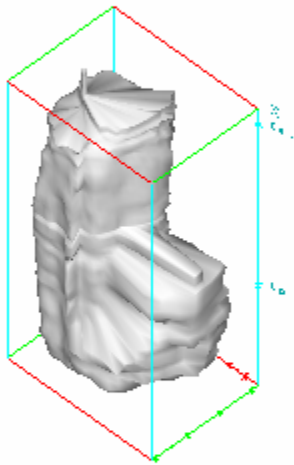

Figure 12. BC01-315°cw-45° – Opaque,
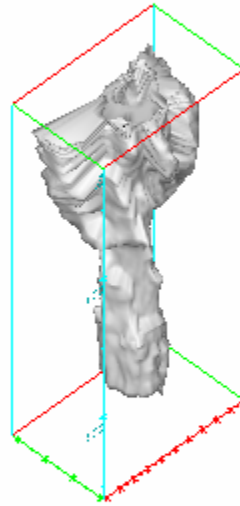Highly Irregular Solutioning.

Figure 13. BC04-225°cw-45° – Opaque,
Highly Irregular Solutioning.

but has the distinctive double fan shape in the upper portion of the cavern. Here the fan is very directional and seems to be separated in distinct horizontal elements, as in the separate blades of a fan. While the initial impression is that the solutioning has occurred from a strong preferentially directed jet of water, this must be examined closely.

The question must consider from two potential aspects, one based on location and direction of the inlet water stream and the other based on the maximum diameter that a jet velocity could be expected to be unattenuated and still effective. Upon examination, both of these seem unfavorable:

First, the direction of the inlet tubing is normally vertically downward not horizontal, a situation that can be changed only slightly by the details of any irregularity in the tubing opening (such as from explosive cutting, for example).

Second, the typical cavern diameter approximates some 250 ft (maximum diameter of perhaps 500 ft in the case of Cavern 4), a radius which seems large enough that any pressurized jet, even horizontally directed, would be dispersed and attenuated in the surrounding brine. Perhaps the description of the brining of Cavern 4 may offer some insight. It was noted that with the loss of cavern pressure, the brining operation then proceeded using an "air lift." The details of this operation are not specified. Cavern 4 was at some point solutioned upward into the cap rock and has been watched closely since for potential collapse. While it appears that the formation of fans will remain a mystery, a potentially more acceptable explanation is that the sonar data and analysis is perhaps questionable. One possible speculation involves the operation of the sonar azimuth stepping system. Although certainly unlikely, a defective stepping system that allowed only a small range, or segment, of azimuth to be interrogated, without indicating this to the operator, could produce a directional fan. Moreover as the vertical station changes, the segment of the azimuth interrogated would logically migrate slightly to simulate a fan even more. If one examines the fans in Figure 13, such migration can be envisioned.

Even though the caverns with markedly irregular shapes are of interest, most of the Bayou Choctaw caverns have certain features in common. These common features however still lead to apparently mixed solutioning shapes.

4.3 Apparently Mixed Solutioning Shapes.

From the available sonar survey data, it is possible to examine nearly all of the currently active caverns. This is true for the SPR caverns, and somewhat less so for the UTP caverns. These caverns suggest a very interesting development that seems common to them in general. They all have some elements of a cylindrical cavern development, with other features added. The caverns are Cavern 15, 17, 18, 19, 20, 101, and 102 (graphical representations of these caverns are found in Appendix A). Let us examine Cavern 15 first. Cavern 15, as seen in Figure 14a, is a relatively shallow cavern, with a very large diameter of some 412 ft. While there are some irregularities, the cavern can be imagined as a relatively uniform cylinder, with a vertically extended solutioning protuberance to

one side. The cross-section view of Figure 14b confirms the cylindrical shape. Because of the very large diameter, it would appear that any preferential direction of the incoming water would be both greatly mitigated and velocity attenuated. Moreover, the likelihood of the jet forming a vertical trough of such height seems unlikely, if not impossible. It appears most likely those sites are regions of salt that are susceptible to an increased solutioning rate. If this is so, the region of affected salt is quite pervasive, possibly extending vertically several hundred feet. It seems unlikely the region waits until the cylindrical shape has formed before it forms. It is more likely that they form simultaneously. It is possible that the leaching rates around the cavern wall is continuous
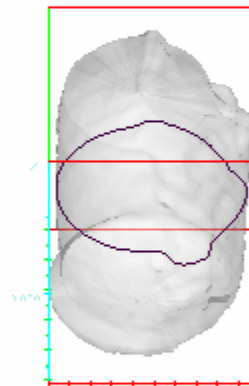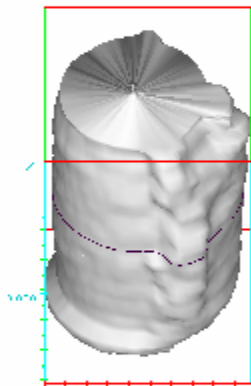

Figure 14a. BC15-180°cw-45°- Opaque Sonar June 1999.

Figure 14b. BC15-180°cw-45°-Sections

and uniform, except at the region where the salt is susceptible to more rapid leaching rate. Certainly, the idea that the solutioning process is continuous and occurs everywhere over the cavern surface is appealing. Then the only variable is the localized solutioning rate as determined by the unique characteristics of salt, which can be variable. The sequence of fluid injection into this cavern to form the final shape is unknown, but the period when the cylindrical cavern portion was formed might suggest that only direct solutioning was in play. The current state of knowledge, at this time, of the flow characteristics of the raw water injected into the cavern bottom are not well specified, but the less dense unsaturated injected water would rise, certainly diluting the existing brine but increasing density as it rises. It seems unlikely that the fluid contacting the cavern surface would be turbulent. Certainly this question is not fully resolved and would benefit from additional study.

While Cavern 15 is predominantly cylindrical, it appears to be toward one end of a range of cavern shapes. These features can be called mixed solutioning shapes. Further examples are found in Caverns 17 and 101, as shown in Figures 15 and 16.

Perhaps these two caverns, 17 and 101, which represent an older purchased cavern and a recently developed cavern, respectively, can best illustrate the cylindrical development effect. In Cavern 17, as shown in Figure 15, there are some apparent irregularities, even perhaps suggestive of the highly irregular caverns discussed previously. However if the cavern is examined closely, there is a better conclusion to be reached. A shape of a cylinder can be readily seen in the top half of the cavern, with the cylindrical shape essentially complete. While portions of the cylinder extend into the bottom half of the cavern, a vertical segment of the cylinder develops an increased diameter which extends from about midheight to the cavern bottom. Interestingly this segment seems to have a definite thickness, almost as if it were a shell about the central cylindrical cavity. At the bottom of the cavern, another small tongue region of preferential solutioning forms.

Cavern 101, as shown in Figure 16, exhibits the same general features as Cavern 17. First, there appears to be a central core of the cavern that is a relatively uniform cylinder. One can speculate that this was formed during the direct solutioning phase. Based on visual estimation from Figure 16, the volume of the central core seems consistent with the calculated volume of about 2 MMb for that leaching stage [11]. The First Reverse Stage water input was at an elevation of -2904 ft which is essentially the level of a dominant feature of the cavern. This suggests that the reverse solutioning phases caused the features on the west wall of the cavern which wrap about half way around the cavern like a shell. This shell is shown clearly in Figure 17, which is a view looking directly down on the cavern. During the first reverse stage there was a brief period where the solutioning reverted to a direct mode to enlarge the sump. Clearly the sump area of the cavern appears to be significantly enlarged. The Second Reverse Stage, with in input water elevation was changed to -3898 ft which corresponds to the elevation where the shell essentially becomes complete to extend around the central core. The complete shell extends to the bottom of the cavern. The elevation of brine removal tubing throughout the reverse solutioning stages remained at -4828 ft. Prior to the completion of the cavern, there was again a significant period of direct leaching to bring the cavern to the correct

volume. In this solutioning phase the inlet tubing was at -4819 ft and the brine removal tubing was at -2651 ft. Undoubtedly, this further increased the size of the rather bulbous foot at the cavern bottom. There is directionality in the shape of the foot, with elongation toward the south. The formation of directional feet during sump formation is quite common. Foot formation is perhaps related to the inflow of water against the insoluble sump layer with the potential of this layer to preferentially direct the flow sideways. Consequently, a sump foot can have a direction unrelated to preferential solutioning. We want to look for features in these caverns which help define the solutioning process, especially those features that conform to a general trend. Perhaps the single feature that
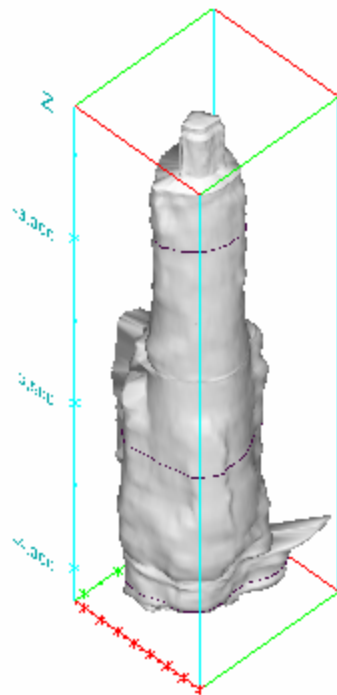

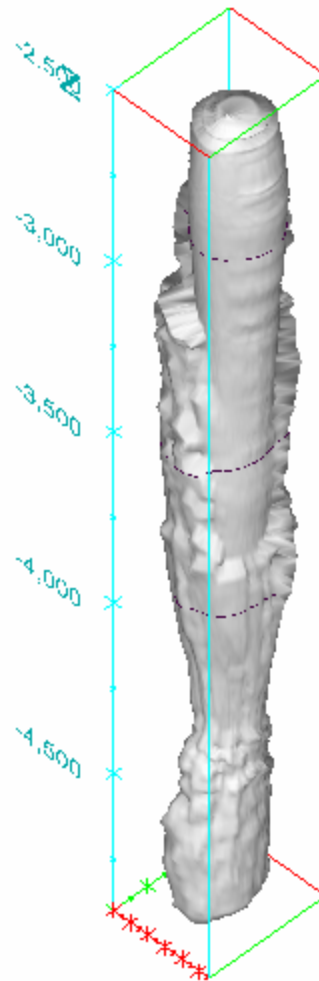Figure 15. BC17-135°cw-45° – Opaque, Mixed Solutioning Results.

Figure 16. BC101B-135°cw-45° – Opaque, Constructed SPR Cavern.

defines the general trend is the cylindrical central shape. The general trend toward a central cylindrical shape occurs in some early abandoned caverns, and also in the newer active, deep caverns. One must look carefully for this central cylinder, because, indeed, there are many irregularities in the features of these caverns. The question of interest is whether this cylindrical shape is the result of the direct solutioning, and whether the irregular features develop from reverse solutioning stages.
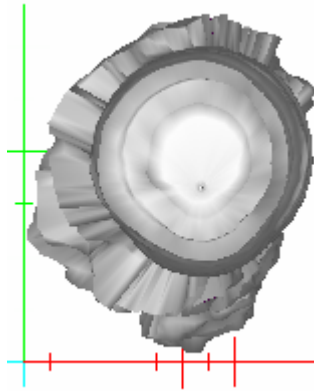

Figure 17. BC101-Top View, North is Up, Sonar from Well A – Shows Shells.

Cavern 18 is another of the deep caverns (See Appendix A) which initially one might suggest is completely irregular. However, one can envision a central cylindrical core to this cavern as well, with subsequent beginnings of the shell like structure at several locations in the cavern.

Of the other deep caverns, Cavern 102, which is one of the recent SPR constructed caverns, later traded to UTP, illustrates a very interesting shape (See Appendix A). The cavern is quite uniform and nearly cylindrical. There is some irregularity in the bottom third of the cavern, but not markedly so. The top third of the cavern is enlarged, but still is very cylindrical except for a small region of preferential solutioning. This region appears to be the initial step in the formation of shell like features such as in Cavern 101.

4.4 Blocky Solutioning

In a number of the caverns the solutioning forms regions of blocky ledges in addition to the appearance of fans. A perfect example of this is Cavern 101, where the ledges almost appear as a lace draped around the cavern, as shown in Figure 16. The question of how these irregular shapes could form is difficult to answer. One would expect a solutioning process to be relatively continuous, varying only slowly and smoothly over the entire solutioning front, even in the case of a small percentage of anhydrite provided it is uniformly distributed. Moreover in Cavern 101, the formation of these ledges can be ascribed to a particular solutioning stage, following a stage where the solutioning was smooth. While the former stage was by direct solutioning whereas the latter stage was by

41

reverse solutioning, it is difficult to imagine why this would radically change the physical mechanism of solutioning. Moreover, there is no indication that the water inlet elevation was altered during the solutioning stage in which the blocky ledges were formed. It is not clear if any differences existed in the salt or in the solutioning fluid.

The shell-like features thought to be produced by the reverse leaching are extremely unusual. Initially, it appears that the solutioning is completely asymmetric with respect to the elevation of the inlet water. The shell forms over a limited portion of the cavern wall, and then changes in the extent of the portion with increased depth. The effect is to produce a drapery appearance. The mechanism of solutioning that causes this is difficult to envision. One would assume that the dissolutioning process from a point injection of water would be uniform with depth even if it was asymmetric because of the eccentricity of the reverse leaching injection point with respect to the initial direct solutioning injection point. In addition, the drapery portion of the cavern wall has distinct ledges with a series of blocky steps.

As noted, the ledges of the blocky steps could logically act as sites for the creation of salt falls, as might be expected [25]. Certainly, recent hanging string failures in Cavern 101 appear to have increased. Possibly the salt is sufficiently creep resistant that it delays the onset of salt falls. As noted previously, if salt falls do occur, the solutioning process on these blocks of salt continue so that eventually they will dissolve leaving only the insolubles behind. This process however could potentially be very lengthy, with salt blocks remaining in the sump debris for long periods of time. A careful analysis of the amount of sump material accumulated during the solutioning process compared to the expected insoluble content might shed some light on the Cavern 101 circumstance. While such an analysis has been performed for Bryan Mound caverns [27], it was not extended to the other SPR caverns.

Another possible speculation involves the origin of these blocky appearances of cavern surfaces. The analysis of the sonar data involves the numerical smoothing of the discrete data taken at each azimuth angle to form a smooth surface. If this smoothing is improperly implemented so that it carries the same level of the point sonar value throughout the angular range of that azimuth station and then changes abruptly to the succeeding azimuth station sonar value, it could produce the step-like appearance. Such an analysis error could result in a blocky appearance of the cavern surface which is not real. While such a numerical procedure error seems very unlikely to survive quality control, a single sonar survey might possibly show these effects without detection. Again additional new surveys potentially would resolve the problem, if it exists. However, in fact, a number of the Bayou Choctaw caverns do seem to show this effect, perhaps demonstrating that it is a real effect.

Unfortunately, the questions posed by the some features of the Bayou Choctaw caverns do not presently have answers. Although very difficult to imagine, some of these features indeed may be just artifacts of the measurement or analysis process. Other features, while apparently real, stretch our understanding of the solutioning of salt as a smooth, continuous process.

4.4 Speculative Comments

The sonar survey results of a number of the Bayou Choctaw caverns present some unusual, and perhaps paradoxical, features. In some cases there are horizontal fans formed apparently by either strong jet action or by highly preferential solutioning in the salt. While these possibilities seen unlikely, if not impossible, they should be considered. Cavern BC 4, Figure 12, has such an appearance. It is also speculated that problems with the sonar survey azimuth control could produce the false appearance of a fan shaped feature.

As noted previously, the drapery solutioning of Cavern 101, together with the blocky formations also are difficult to explain with the expected response of salt to the solutioning process. However, Cavern 101 observations offer some potential insights into the solutioning process and the influence on the cavern shape. In the solutioning sequence, initially Well B was the deep well and the inlet water well for direct solutioning. During the direct solutioning, the well defined cylindrical portion of the cavern was developed, with Well B at the central axis of the cylinder. The well location is not shown in Figure 16, but the initial cylindrical shape is evident. It is believed that this Well B is north of Well A, the location of which appears in the view of Figure 16.

After the direct solutioning stage, subsequent reverse stages utilized Well A as the water inlet, with two inlet elevations – first reverse at -2904 ft and second reverse at -3898 ft. As noted earlier, the brine was withdrawn at the bottom of the cavern. It appears from the view of Figure 16 that reverse solutioning achieved a very crude cylindrical cavity centered on the location of Well A. Certainly the lateral boundaries of this cylinder are not well defined. The reason for the uncertainty may be some limitation of the sonar technique or analysis. The first reverse stage apparently could not produce the complete cylinder, leaving the far side from Well A with the cavern wall at the original direct solutioning stage boundary. The second reverse stage, however, was successful in establishing a new somewhat cylindrical boundary below the elevation of the water inlet. The general tapering of the cavern obscures the lower cylindrical shape in Figure 16. The final solutioning to increase the cavern capacity to the specified value was a direct solutioning through Well A with the elevation of the inlet water at -4819 ft, essentially the cavern bottom, and the brine withdrawal through Well B at a -2651 ft elevation.

It almost seems that the initial nearly cylindrical core has a solution resistant boundary. This boundary can be penetrated locally during the following reverse solutioning stages, which then forms a new solution boundary encompassing only part of the initial cylindrical boundary. This can continue down the length of the initial cylinder to form the drapery effect. It was also noted earlier that the smoothing operation of the discrete sonar data points could also produce a blocky appearance, but this again seems unlikely.

In summarizing the speculation about solutioning, we adopt the following line of thought, which admittedly is highly speculative. Cavern BC 15 shows the strong trend to form a cylindrical cavern; however, a nearly uniform, relatively narrow, slot is solutioned concurrently over the entire height of the cavern. If the dome is formed from a self-

mandereled extrusion of initial layers of the bedded salt, then the dome consists of cylindrical shells (like a Russian doll). This can suggest a cylinder of salt of one solubility constant that comes into contact with a salt of higher solubility over a portion of the shells. This could form the natural slot of BC 15.

Although the geometry and structure of Caverns BC 17 and BC 101 are more complex, the same line of thought can be used. These caverns show a relatively well defined central core which is nearly cylindrical. This core is identified probably with the direct solutioning stage. Apparently, no slot was able to form because the higher solubility salt cylinder was not yet encountered. When the reverse stages are initiated, discrete points along the initial cylinder were, however, locations of greater solubility, just as in BC 15. These points instead of forming a slot, widened around the central cylindrical cavity, progressively working around the circumference. In BC 101, the widening during the first reverse stage did not completely work itself around the cavern. However, the second reverse stage of solutioning further down in the cavern was capable in taking the same process to completion to widen entirely around the original cylindrical shape. In BC 17, the widening of the reverse stage never completed itself around the central initial cylindrical cavern. Thus, the shape of a cavern is determined by the solubility constant of a given body of salt, how this body is encountered by the solutioning front, and the time of solutioning.

4.6 Cylindrical Aspects

The apparent cylindrical nature of many of the caverns, whether it is the final shape or the central core, is compelling. This formation appears to occur during direct solutioning. Again being speculative, the propensity to form such a uniform shape suggests that the domal salt is quite homogeneous.

5.0 SUMMARY

The Bayou Choctaw dome is quite small. As in the case of West Hackberry, the stratigraphy at depth suggests that the salt sill from which the Bayou Choctaw diapir formed was initially deformed laterally from the Louann bedded salt formation. This additional salt deformation to form the sill and then the diapir is thought to disperse and homogenize any non-salt materials of the original bedded salt layers.

Although the initial impression is that the caverns of Bayou Choctaw are irregular seems accurate, there are some underlying features that are contrary to this observation. If the highly irregular, and somewhat questionable, older cavern geometries are not considered, then perhaps the principal nature of the cavern configurations can be determined. This dominant feature that many of the caverns exhibit is development of a nearly cylindrical central core, thought to be the result of the direct leaching stage. Later stages involving reverse solutioning tend to be less regular and to obscure the central feature. It is not clear why the reverse solutioning produces such interesting features as a blocky or veil-like structure. Various speculative postulates are advanced, none of which appear to really present a creditable interpretation.

While there are numerous cavern features that might indicate solutioning directionality, these features appear to be local to a given cavern. There is no apparent directionality which extends over the dome.

Perhaps the only apparent conclusion is that the design and construction of any future caverns at Bayou Choctaw must be closely monitored through sonar surveys throughout the construction. The irregularities of the existing caverns indicate the same possibility for any new cavern, with the danger of inadvertently violating the criteria for intra-cavern spacing.

APPENDIX A

THREE DIMENSIONAL REPRESENTATIONS OF
BAYOU CHOCTAW CAVERNS

The Figures in this appendix are all grey scale, three-dimensional representations of the SPR caverns in the West Hackberry dome facility, using the most recent sonars available at the time of the preparation of the West Hackberry database [2]. The graphics program used to create these representations was the Mining Visualization System (MVS). The representations include first an opaque (opacity 100 %) view of the cavern and next a partially transparent (opacity 30 %) view with superimposed highlighted cross-sections. These cross-sections are always at the same three constant elevations regardless of cavern elevations, picked arbitrarily to detail the large, deep cavens. These elevations are at depths of approximately -2900, -3550, and -3950 ft. Consequently, in short caverns some, or all, of the cross-sections will not appear.

The Figure title contains significant information about the representation, beginning with:

(1) The cavern number is actually the numerical portion of the well number; however, because these caverns may involve more than one well, the well is distinguished by an additional letter. For these caverns, such as Cavern 101, a large letter designation indicates the well through which the sonar survey was obtained.

(2) The cavern number is followed by the orientation of the cavern view, which is the viewing direction of an observer stationed outside of the cavern as measured in degrees clock-wise from North. Thus, from the 0°North view is looking directly at the north face of the cavern. Therefore, it follows that 90°cw is looking at the East face, 180°cw is looking at the South face, and 270°cw is looking at the West face.

(3) The next designator, if included, is the tilt of the cavern view, which is in degrees of tilt about a horizontal axis, normal to the viewing angle, with positive angles showing a tilt of the top of the cavern toward the viewer. This tilt tends to aid in visual definition of irregularities in the cavern surface.

(4) The final indicator defines special attributes of the representation. Here, the first graph is defined as "opaque" where the opacity of the image is set at 100%. The second image is normally a transparent view with opacity at 30% and containing several traces of cross-section planes on the cavern surface.

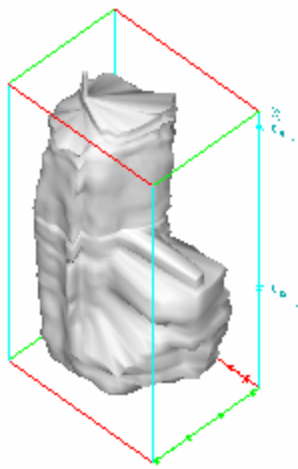(5) Any other special aspects of a representation will be explained in the figure title, as necessary.

Figure A1. BC01-315°cw-45° – Opaque
Sonar May 1980.

Figure A2. BC02-225°cw-45° – Opaque
Sonar July 1983.

Cavern BC01 is abandoned.
1980 Cavern diameter ~250 ft.

Cavern BC02 is abandoned.
1993 Cavern diameter estimated ~ 250 ft.

Cross sections are not shown because these relatively short caverns are high in the dome, and above the elevation chosen for the first cross section.
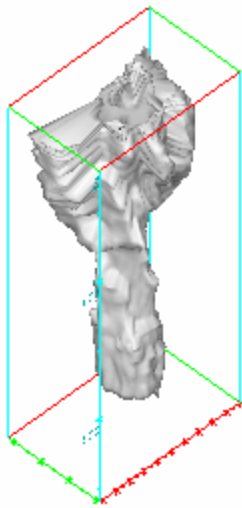
Figure A3. BC04-225°cw-45° - Opaque Sonar April 1997.

Figure A4. BC08A-North0°-45° – Opaque Sonar May 1980.

Cavern BC04 is inactive due to apparent breach through the salt into the caprock.

Cavern BC08A is abandoned.

Cross sections are not shown because these relatively short caverns are high in the dome and above the elevation chosen for first cross section.

Figure A5. BC10-270°cw-45° – Opaque Sonar September 1973.

Figure A6. BC11-135°cw-45° – Opaque Sonar March 1978.

Caverns BC10 is abandoned.

Cavern BC11 is abandoned.

Cross sections are not shown because these relatively short caverns are high in the dome and above the elevation chosen for first cross section.
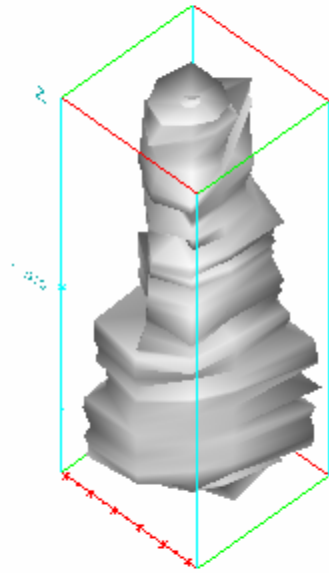
Figure A7. BC13-135°cw-45° – Opaque   Figure A8.   BC07 (Blank)
               Sonar August 1977.   Sonar – None.

Cavern BC13 is abandoned.   Cavern BC07 collapsed to form Crater Lake.

Cross sections are not shown because this relatively short cavern is high in the dome and above the elevation chosen for first cross section.
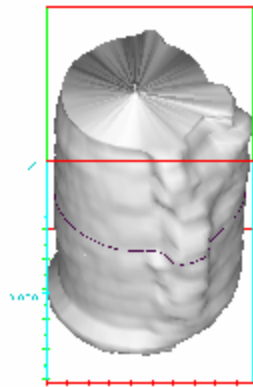
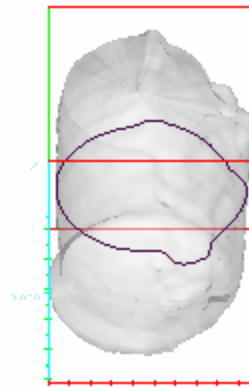Figure A9a. BC15-180°cw-45°- Opaque
          Sonar June 1999.

Figure A9b. BC15-180°cw-45°- Sections

Cavern BC15 was an existing cavern purchased for use by the SPR.

Cavern BC15, which is a relatively short, is also comparatively deep in the dome and therefore the upper elevation cross section appears.
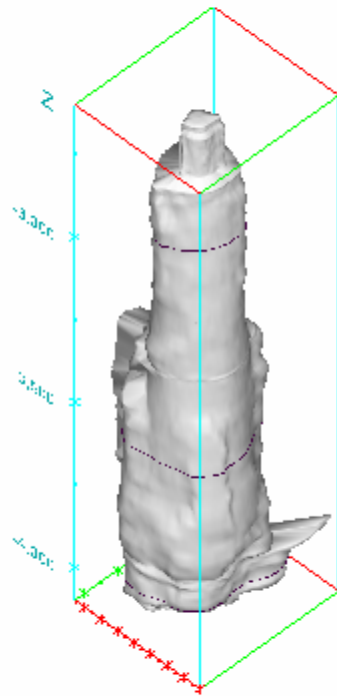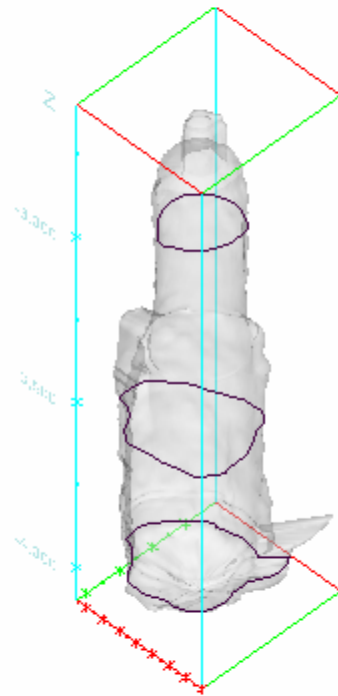
Fig. A10a. BC17-135°cw-45° – Opaque   Fig. A10b. BC17-135°cw-45° – Sections
            Sonar July 1999.

Cavern BC17 was an existing cavern exchanged for Cavern 102 for use by the SPR.

Cavern BC17, while relatively short, is comparatively deep in the dome and all cross sections appear.
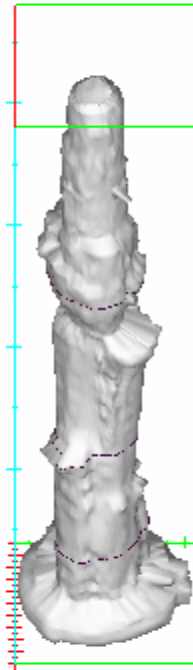
Figure A11a. BC18-90°cw-45° – Opaque   Figure A11b. BC18-90°cw-45° - Sections
Sonar October 1991.

Cavern BC18 was an existing cavern purchased for use by the SPR.

Cavern BC18, while relatively short, is comparatively deep in the dome and all cross sections appear.
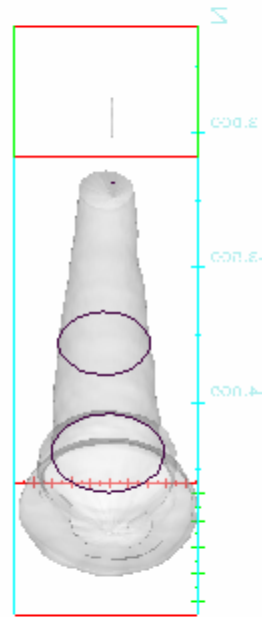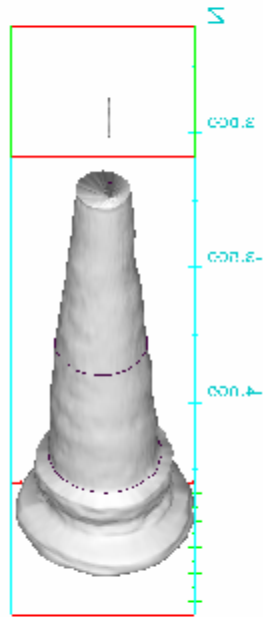
Fig. A12a. BC19A-0°North-45° – Opaque
Sonar June 1999.

Fig. A12b. BC19A-0°North-45° – Sections

Cavern BC19 was an existing cavern purchased for use by the SPR.

Cavern BC19, while relatively short, is comparatively deep in the dome and two of the cross sections appear.
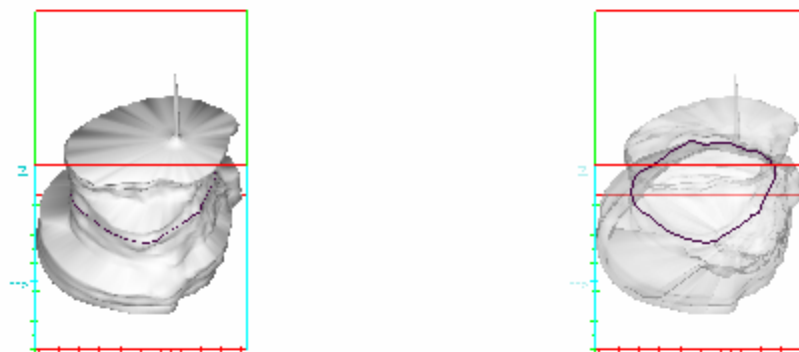
Figure A13a. BC20A-180°cw-45°– Opaque Figure A13b. BC20A-180°cw-45° - Sections
              Sonar November 2002.

Cavern BC20 was an existing cavern purchased for use by the SPR.

Cavern BC20, which is quite short, is also quite deep in the dome and just one of the
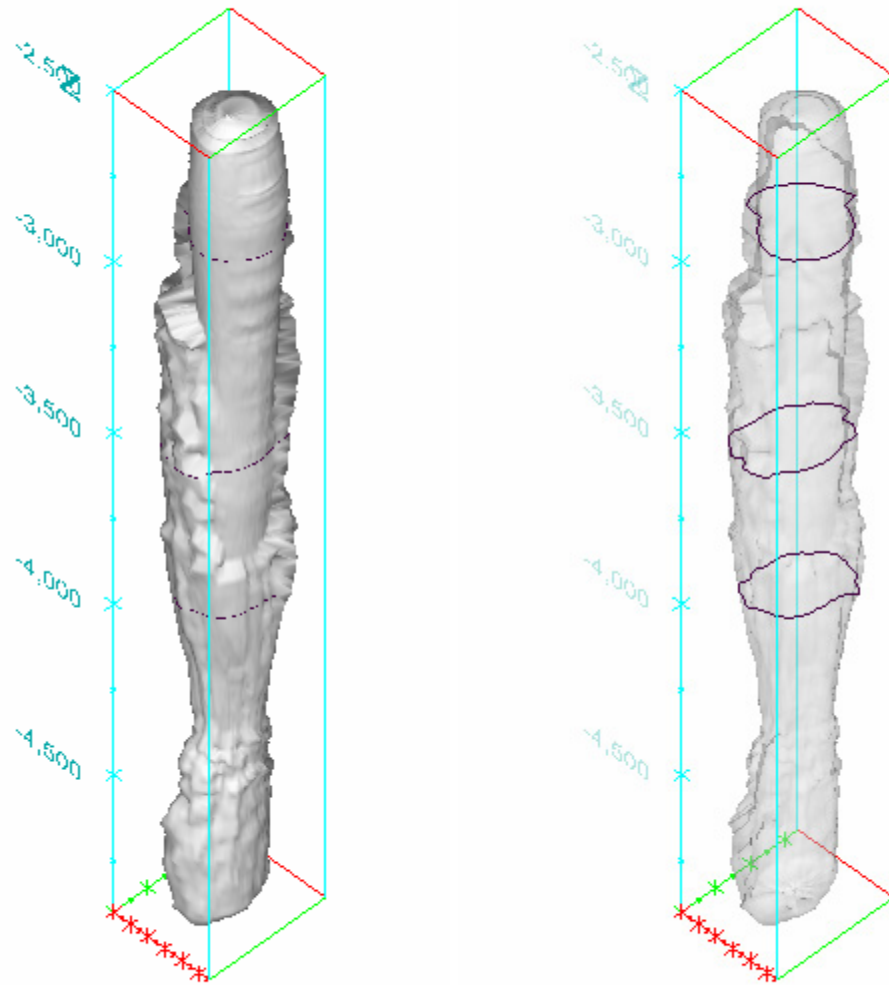cross sections appears.

Fig. A14a. BC101B-135°cw-45° – Opaque   Fig. A14b. BC101B-135°cw-45° – Sections
Sonar July 1995.

Cavern 101 was constructed by the SPR in beginning in 1985 and completed in 1990.

Cavern 101 has dimensions comparable to all other SPR constructed caverns.
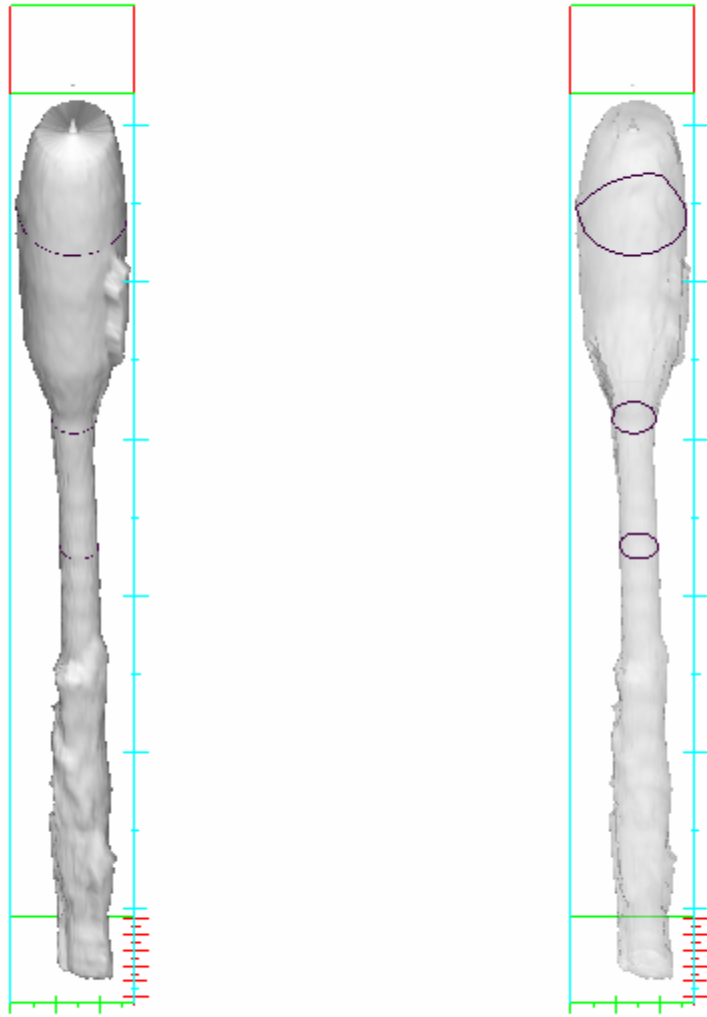
Fig. A15a.BC^{UTP}102A-270°cw-45°–Opaque Fig.A 15b.BC^{UTP}102A-270°cw-45°–Sections
Sonar September 1994.

Cavern 102 was constructed by the SPR, and then exchanged to UTP for existing Cavern 17.

Cavern 102 has dimensions comparable to all other SPR constructed caverns.

Fig. A16a. BC^{UTP}25-0°North-45° – Opaque   Fig. A16b. BC^{UTP}25-0°North-45° - Sections
            Sonar December 1996.

Cavern ^{UTP}25 was constructed by others, but had an available sonar.

Cavern ^{UTP}25 has dimensions comparable to the SPR constructed caverns.
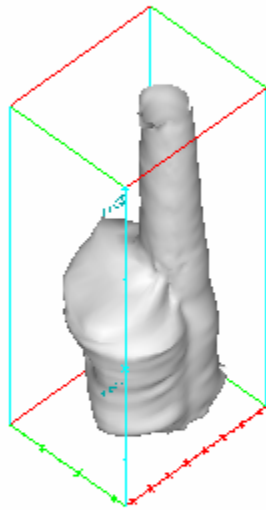
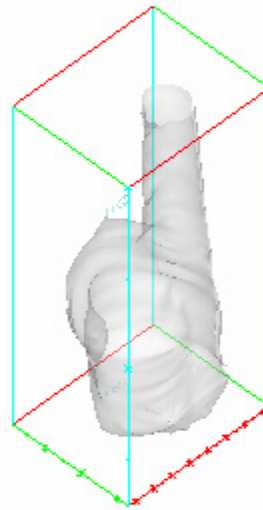Fig. A17a. BC 3-225°cw-45° - Opaque   Fig. A17b. BC 3-225°cw-45° – Section
          Sonar July 1977.

Cavern BC 3 is owned by others, but had an available sonar.

Cavern BC 3 is quite short and is high in the dome, consequently no cross sections appear.

REFERENCES

[1]   Munson, D.E., S.J. Bauer, C.A. Rautman, B.L. Ehgartner, and A.R.Sattler, 2000. Analysis of the Massive Salt Fall in Big Hill Cavern 103, SAND2003-0703, Sandia National Laboratories, Albuquerque, NM.

[2]   Munson, D.E., 2006. Features of West Hackberry SPR Caverns and Internal Structure of the Salt Dome, SAND2006-5409, Sandia National Laboratories, Albuquerque, NM.

[3]   DOE, 1995. *Strategic Petroleum Reserve Annual/Quarterly Report*. Washington, D.C., U.S. Strategic Petroleum Reserve, Report DOE/EE-0055, 15 Feb 95.

[4]   Rautman, C.A., and J.S. Stein, 2003. Conversion of the Bayou Choctaw Geological Site Characterization Report to a Three-Dimensional Model, SAND2003-3299, Sandia National Laboratories, Albuquerque, NM.

[5]   Ney, J.F., 1980. Recommendations on New Cavern Locations at Bayou Choctaw SPR Site, Sandia Letter Report to R.F. Mazurkiewicz, DOE/SPR, July 10, 1980.

[6]   Lord, A., and B.L. Ehgartner, 2005. Memorandum "Potential New Cavern Locations at Bayou Choctaw, Compatible with Existing Caverns" to W. Elias, DOE, dtd November 22, 2005, from 6312, Sandia National Laboratories, Albuquerque, NM.

[7]   Hogan, R.G., (Editor), 1980. Strategic Petroleum Reserve (SPR) Geological Site Characterization Report Bayou Choctaw Salt Dome, SAND80-7140, Sandia National Laboratories, Albuquerque, NM.

[8]   Neal, J.T., T.R. Magorian, K.O. Byrne, and S. Denzier, 1992. Strategic Petroleum Reserve (SPR) Additional Geologic Site Characterization Studies Bayou Choctaw Salt Dome, Louisiana, SAND92-2284, Sandia National Laboratories, Albuquerque, NM.

[9]   Magorian, T.R., J.T. Neal, S. Perkins, Q.J. Xiao, and K.O. Byrne, 1990. Strategic Petroleum Reserve (SPR) Additional Geologic Site Characterization Studies West Hackberry Salt Dome, Louisiana, SAND90-0224, Sandia National Laboratories, Albuquerque, NM.

[10] DOE, 1991. DOE SPR Constructed Cavern History, Publication D506-01644-09, Rev. 2, Prepared by Boeing Petroleum Services, Inc., New Orleans, LA.

[11] DOE, 1987 DOE SPR Sonar Caliper Report Bayou Choctaw Well 101 A, October 26, 1987, Prepared by Sonar and Well Testing Services, Inc., for PB-KBB, New Orleans, LA.

[12] DOE, 1988. DOE SPR Sonar Caliper Report Bayou Choctaw Well 101 A, April 15, 1988, Prepared by Sonarwire for PB-KBB, New Orleans, LA.

[13] DOE, 1990. DOE SPR Sonar Caliper Report Bayou Choctaw Well 101 B, January 23, 1990, Prepared by Sonarwire for Boeing Petroleum Services, New Orleans, LA

[14] DOE, 1981. DOE SPR Well History Well 102A, Bayou Choctaw, April 31, 1981, Prepared by Williams-Fenix & Scisson, New Orleans, LA.

[15] DOE, 1984. Sonar Caliper Report Bayou Choctaw Well 102 A, October 29, 1984. Prepared by Dowell Schlumberger for PB-KBB, New Orleans, LA.

[16] DOE, 1983. Sonar Caliper Report Bayou Choctaw Well 102, September 8, 1983, Prepared by Dowell for PB-KBB, New Orleans, LA.

[17] Munson, D.E., M.A. Molecke, J. T. Neal, A. R. Sattler, and R.E. Myers, 1998. Strategic Petroleum Reserve Caverns Casing Damage Update 1997, SAND98-0090, Sandia National Laboratories, Albuquerque, NM.

[18] Fredrich, J.T., A.F. Fossum, and R.J Hickman, 2007. Mineralology of Deepwater Gulf of Mexico Salt Formations and Implications for Constitutive Behavior, *J. Petrol. Sci. Eng.*, **10**, 1016-1037.

[19] Munson, D.E., 1998. Analysis of Multistage and Other Creep Data for Domal Salts, SAND98-2276, Sandia National Laboratories, Albuquerque, NM.

[20] Munson, D. E., 1999. Multimechanism-Deformation Parameters of Domal Salts using Transient Creep Analysis, SAND99-2104, Sandia National Laboratories, Albuquerque, NM.

[21] D. E. Munson, 1997. "Constitutive Model of the Creep of Rock Salt Applied to Underground Room Closure," Int'l. J. Rock Mech. and Min. Sci. & Geomech. Abstr., **34** (2), 233-248.

[22] Ehgartner, B.L., 1997. SPR Ullage Study, in Memo J.K. Linn to R.E. Myers, SPR/DOE, November, 25, 1997, Sandia National Laboratories, Albuquerque, NM.

[23] Ehgartner, B.L., 2004. Ullage Study 2004, Memo B.L. Ehgartner to R.E. Myers, SPR/DOE, October 1, 2004, Sandia National Laboratories, Albuquerque, NM.

[24] Munson, D.E., 2004. Update of Casing Damage Survey – 2004, Memorandum from Darrell Munson (Consultant 6113) dtd October 22, 2004 to Robert Myers, DOE/SPR FE 4421, Sandia National Laboratories, Albuquerque, NM.

[25] Munson, D.E., 2000. Spall Formation in Solution Mined Storage Caverns Based on Creep and Fracture Analysis. Proc. 4th N. Am. Rock Mech. Symp., A.A. Balkema, Rotterdam, Netherlands. pp. 901-908.

[26] Mansure, A.J., 2007. Update on Hanging String Failures Statistics, Memo A.J. Mansure to R.E. Myers, SPR/DOE, May 25, 2007, Sandia National Laboratories, Albuquerque, NM.

[27] Munson, D.E., M.A. Molecke, J.T. Neal, A.R. Sattler, and R.E. Myer, 1998. Strategic Petroleum Reserve Caverns Casing Damage Update 1997, SAND98-0090, Sandia National Laboratories, Albuquerque, NM.

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