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Features of West Hackberry SPR Caverns and Internal Structure Of the Salt Dome

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FEATURES OF WEST HACKBERRY SPR CAVERNS AND INTERNAL STRUCTURE OF THE SALT DOME

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ABSTRACT

The intent of this report is to examine the internal structure of the West Hackberry salt dome utilizing the information from the geometric configuration of the internal cavern surfaces obtained from graphical representations of sonar survey data. In a general sense, the caverns of West Hackberry are remarkable in the symmetry of their shapes. There are only rather moderate deviations from what would be considered an ideal cylindrical solution mining geometry in these caverns. This finding is in marked contrast to the directional solutioning found in the elliptical cross sectioned, sometimes winged, caverns of Big Hill. None of the persistent lineaments prevalent in Big Hill caverns are evident in West Hackberry caverns. Irregularities of the West Hackberry caverns are restricted to preferential solution formed pits and protuberances with moderate dimensions. In fact, the principal characteristic of West Hackberry caverns is the often large sections of smooth and cylindrical cavern wall. Differences in the cavern characteristics between West Hackberry and Big Hill suggest that the former dome is quite homogeneous, while the latter still retains strong remnants of the interbeds of the original bedded Louann salt. One possible explanation is that the source of the two domes, while both from the Louann mother salt, differs. While the source of the Big Hill dome is directly from the mother salt bed, it appears that the West Hackberry arises from a laterally extruded sill of the mother salt. Consequently, the amount of deformation, and hence, mixing of the salt and interbed material in the extruded sill is significantly greater than would be the case for the directly formed diapir. In West Hackberry, remnants of interbeds apparently no longer exist.

An important aspect of the construction of the West Hackberry caverns is the evidence of an attempt to use a uniform solutioning construction practice. This uniformity involved the utilization of single well solutioning and the consistent physical location of the inlet/outlet

tubing in each solutioning stage, although the process did evolve with time as would be expected in a large construction project. In this study of the construction of the West Hackberry caverns, it was possible to examine the apparent effects of flow rate (solutioning rate) and salt removal quantities during each of the solutioning stages of construction. Interestingly, there appeared to be no real influence of these factors on the details of the cavern characteristics. Any of the flow rates or removal quantities could produce significant irregularities at discrete cavern wall locations, whether or not these irregularities influence the cavern behavior remains unclear. It seems that subsequent solutioning stages could either remove irregularities from earlier stages or generate irregularities of their own. In the study, no apparent influence of the material factors of creep resistance or impurity content of the salt could be found. As has been previously speculated from the earlier study of Big Hill caverns, some irregularities of the cavern wall are thought to be the formation sites of potential salt falls, this thought pertains to the West Hackberry caverns, as well.

Considering the extent of the West Hackberry cavern facility, the relative uniformity of the solution mined caverns throughout the facility is impressive. This uniformity is certainly the result of homogeneity of the salt dome, and the uniformity of the solutioning practice in these single well caverns.

ACKNOWLEDGEMENTS

The author is indebted to David Borns, manager of the Geotechnology and Engineering Department, for his continued support of this work. Brian Ehgartner is the Sandia Laboratories scientist in charge of the analysis effort reported here. His interest and effort, including many helpful discussions, in developing this project is greatly appreciated. The technical inputs of Joshua Stein and Anna Snider Lord in the original three-dimensional cavern graphical representations using the MVS code made the analysis presented here possible. Their inputs were critical. Anna Snider Lord also provided many helpful comments in her review of the manuscript. As usual, support of W.S. Elias of the SPR Project Office has been greatly appreciated.

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1.0 INTRODUCTION

The massive salt domes that occur along the Gulf Coast have been used for decades for commercial storage of crude oil, refined products, and industrial chemicals, typically in large solution mined caverns. Virtually every accessible dome contains caverns used currently or previously for storage. For this current study of solution mined storage caverns and dome stratigraphy, extensive use is made of the database generated from the caverns of the Strategic Petroleum Reserve (SPR) as developed under the auspices 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. Storage sites are located at West Hackberry and Bayou Choctaw in Louisiana and Big Hill and Bryan Mound in Texas. The reserve is held by the United States to reduce the impact of possible energy supply interruptions and to fulfill United States obligations under the International Energy Program [1].

While one might believe the extensive, decades-long development of storage facilities in salt domes would have provided detailed knowledge of the internal structure of the domes, this has not been the case. Most significant studies involve the determination of the dome surfaces, i.e., the top of salt and the extent of the dome flanks. 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 through drill core taken from solution mining wells, brine disposal wells, and other special purpose drilling, 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.

Based on the limitations of the typical sampling methods, it appeared that our knowledge of the internal dome structure would always be meager. Recently, however, a confluence of two different technologies have provided a powerful method of examining relatively large portions of the internal dome structure based on the internal surface features of caverns. The combination of advanced graphics, as incorporated into a specialized Mining Visualization System (MVS) [2], 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 [3], while still leaving unanswered questions, 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 purpose of the current study is to examine the internal structure of West Hackberry dome, another of the SPR storage sites, using the same methodology developed during the analysis of the Big Hill site. In addition to the surface features of the West Hackberry caverns, several aspects of the general dome geometry and possible peculiarities in the dome formation are examined. These lead to a general assessment of the internal dome structure.

2.0 DOME CONFIGURATION AND GEOLOGY

West Hackberry is located in the extreme southwestern corner of Louisiana, some 15 miles from the Louisiana/Texas border to the west and the Gulf of Mexico to the south. Surface manifestation of West Hackberry dome is a small island rising only a few feet above the Gulf water level. Black Lake impinges on the SPR site on the north and Lake Calcasieu is somewhat removed to the east. The site is subject to inundation during storms and from a gradual subsidence of the site. The geological characteristics related to the West Hackberry site were first described by Whiting [4] in 1980. Magorian et al. [5] utilized the earlier work, together with additional information on dome geology, surrounding stratigraphy, and relevant environmental information, to update the dome characterization in 1991. Conversion of the two-dimensional databases from these earlier characterization reports formed the basis for the most recent reexamination by Rautman et al. [6] using modern three-dimensional methods for representation of the dome and its surroundings. While major aspects of the dome, caprock and surrounding strata defined by the earlier characterizations remain unchanged, the updated three-dimensional models of Rautman et al. [6] used more refined analysis of the data and produced models of the dome that differed slightly from the earlier models. The three-dimensional models also achieve a level of visualization clarity and graphical manipulation previously impossible.

The extensive geometric and geologic description of the West Hackberry dome was developed by Magorian et al. [5] under the auspices of the SPR. This description includes the boundaries of the SPR site, the location of the existing wells and caverns in the dome, and the contours of the salt dome, as shown in Figure 1. Further, the description also includes the stratigraphy of the rock and soil formations pierced by the dome, the hydrology, and a number of other important aspects related to the dome environment.

The West Hackberry dome consists of the more-or-less typical geologic sequence of rocks. With increasing depth below the ground surface, initially there is roughly 1500 ft of soil and unconsolidated gravel, sand, and mud, followed by approximately 400 ft of caprock, consisting of anhydrite and carbonate (a conversion product of anhydrite). Generally, the upper portions of the caprock consist of the anhydrite conversion products of gypsum and dolomite, while the lower portion of the caprock is the initial anhydrite residue from the solution of the original domal material. The caprock is generally lens shaped with the thickest part of the lens over the central portion of the dome, tapering to thin edges toward the periphery of the dome; however, some portions of the caprock, even at the dome edge, are quite thick. In the updated model, the caprock even laps over the dome edge in several locations. The caprock is in contact with the top of the domal salt body. Beneath the caprock, the domal salt body extends to considerable depth, potentially to the original Louann bedded salt source.

The most recent geological representations or models of the dome [6], as noted, were based on the extensive databases of the two previous geological descriptions or characterizations. The updated model incorporated all available well logs, geophysical surveys, and physical observations, both from the earlier characterizations or models and from relevant new data generated after those models were published. The updated model utilized the MVS software and modern analysis techniques to generate the greatly detailed representation of the West

Hackberry site. This detail can be seen in the dome model which gives the shape of the dome and the SPR cavern locations, as shown in Figure 2. This updated representation essentially supports the earlier site description work. However, there are some minor differences in the dome shape and contour configurations, especially with a general smoothing of the dome flanks. The specific detail of the “top of salt” and the caprock thickness also are updated. In general, these differences, while making our understanding of the dome more precise, do not alter significantly the utility of the dome, the geometry, or stratigraphy. The MVS software also permits greater detail of the geometry of the storage caverns, but there is no change, of course, in the location of the caverns within the dome.

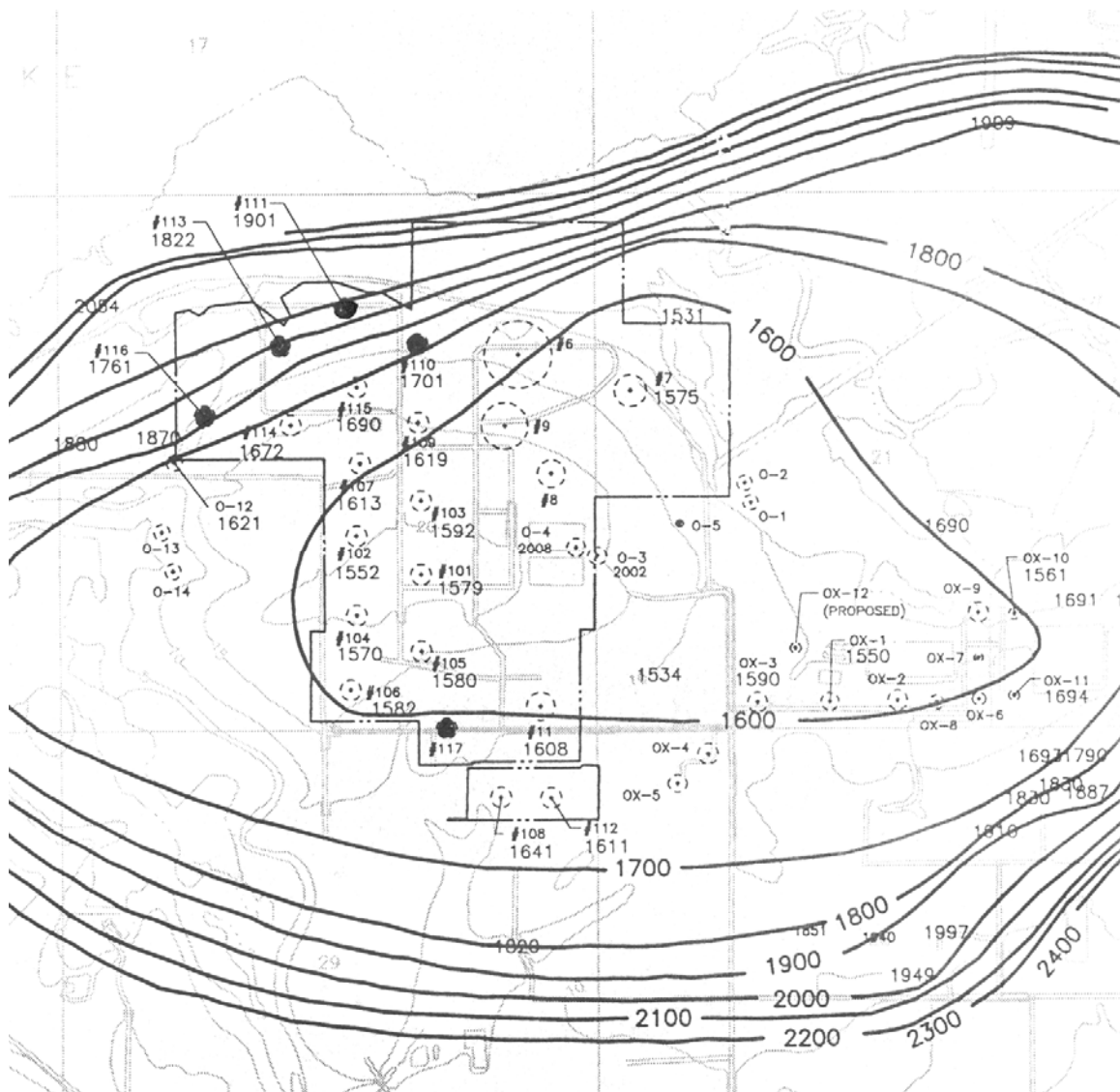


Figure 1. West Hackberry Dome and SPR Facility (after Magorian et al. [5]).

While there is no typical shape for any of the Gulf Coast salt domes, they are often of a general cylindrical configuration at depth, with the possibility of tilts and overhangs at the top of the dome. West Hackberry differs from many of the domes in that it is distinct ellipsoidal cylinder crudely elongated by a factor of two in the west-east direction with a northerly trend on the eastern portion of the dome, as shown in Figure 2. At a 2000 ft depth, the dome measures about 3.9 miles east-west by 1.6 miles north-south.

Magorian et al. [5] have postulated that the West Hackberry dome is related to a ridge defined between the West and East Hackberry domes. Such ridges can potentially produce a line sequence of domes. Further, they indicate that salt flow in West Hackberry “likely originates as separated spines.” One spine center is in the southwest quadrant of the dome and the other is in the northeast quadrant. While not explicitly stated, there could be conceivably two independent spine sources closely-spaced at depth, which converge to produce the dome. The ellipsoidal dome mass is tilted somewhat toward the north. This tilt produces an apparent overhang, in this case manifested as a slightly recumbent dome flank, on the north. This feature is clearly shown in the D view of the MVS representation of the dome in Figure 2, where the dome is being observed essentially from the north (note the axis indication), to show the north face of the dome. The other views clearly illustrate the shape of the dome. The point source lighting is from the viewer’s position and results in the back portion of each view of the dome being somewhat in shadow.

The source of the West Hackberry dome has some unusual aspects related to the rock formations immediately overlying the Louann salt. The rock formations immediately overlying the Louann are Jurassic, represented by the Buckner anhydrite and the Smackover dolomite. Above these are the Cotton Valley limestone sequence and bituminous shale. However, the sequence of overlying formations appears to be different at the West Hackberry dome, with oceanic basalts younger than the Jurassic being deposited here, even though the salt is Jurassic. Consequently, Magorian et al. [5] have proposed that the Jurassic Louann salt has migrated southward and upward from the original Louann bedded salt body to form a sill, at depths of three to seven miles. This lateral migration is perhaps associated with the southern periphery of the original Louann deposit. Such a lateral migration, which is really a horizontal extrusion of the original Louann bedded salt, could prove to be very important to the nature of the salt in the West Hackberry dome. It implies the source salt for this dome has potentially undergone considerably more deformation compared to those domes formed directly above the original Louann source.

The SPR facility at the West Hackberry site contains 17 DOE constructed caverns and five previously existing commercial caverns purchased by the DOE for the reserve from the Olin Corporation. The locations of these 21 SPR caverns in the dome are shown schematically in Figure 3. In addition, Magorian et al. [5] included other, non-SPR, caverns in the characterization report of 1990. In summary, east of the SPR site there are three Olin Corporation commercial caverns in the dome originally used for brine production, and another five Olin wells (possibly caverns) to the west of the SPR caverns, not then or now in use. There are 12 Oxy USA caverns, all to the east of the SPR caverns, of which in 1990, 11 stored liquified petroleum gases (LPG) products and one of which was originally for production of brine. While use of these relatively small commercial caverns was known in 1990; the history of these caverns and whether or not they are still in service is beyond the scope of this report.

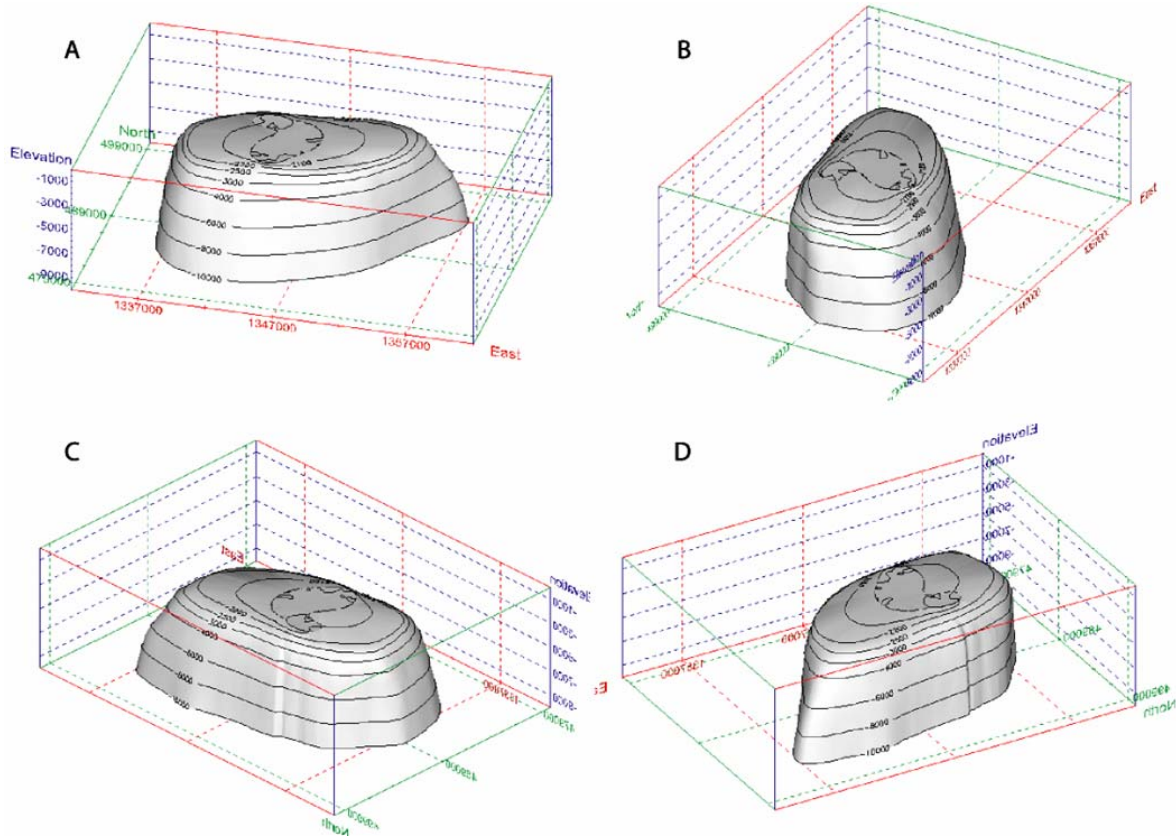


Figure 2. MVS Views of West Hackberry Dome [6].

The schematic of the SPR cavern layout in Figure 3 gives a better visualization of the site. Magorian et al. [5] and Neal et al. [7] have proposed that anomalous zones occur in salt domes. These zones are based largely upon the formation of faults in the caprock, and sometimes, in other domes, upon evidence from salt mines. The two suggested probable shear zones in West Hackberry appear in Figure 3 as traversing the dome in positions that could potentially influence some caverns. Apparently, only Caverns WH106, WH108, WH112, and WH117 are within the probable shear zone running northwest to southeast on the southern edge of the SPR site. WH101 and WH105 could possibly be influenced by the probable shear zone running southwest to northeast roughly at the center of the dome. Based on studies of other salt domes, Magorian and Neal [8] advanced the supposition that these anomalous shear zones found in the caprock extend into the dome itself and may delineate distinct spines within the dome. However, some evidence indicates the faults are only in the caprock and terminate at the caprock-salt interface [7]. Also included in Figure 3 are the relative creep resistances of the salt, ranging from very soft to normal salt, which are derived from the closure rates of the caverns, as determined by Ehgartner [9], as will be discussed later in detail.

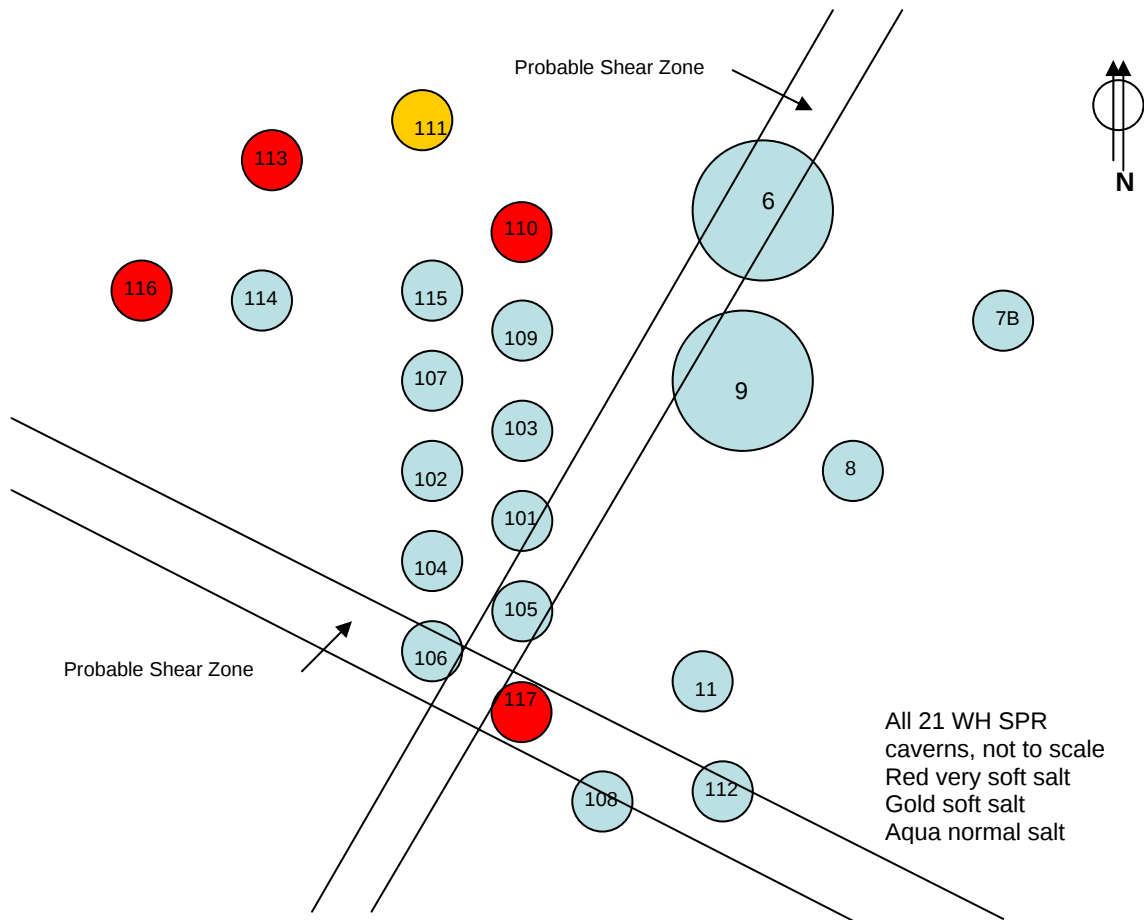


Figure 3. Schematic of the Location of the SPR Caverns at West Hackberry.

As is often the case, the core sampling of the initial wells drilled for the construction of the caverns was limited, compounded in part because all the caverns were single well except for a two well cavern, WH117. The salt core recovered all exhibited relatively fine grained, dark salt specimens where the included anhydrite was well disseminated, or in other words uniformly distributed [5]. There apparently were no steeply dipping bands of higher anhydrite concentrations equivalent to those observed in the salt core of Big Hill [8], for example. These bands of anhydrite are thought to be the traces of the original interbeds typically found in bedded salt deposits when these interbeds are tilted vertically and thinned as the dome is extruded upward. While the vertical extrusion thins and tends to disperse the interbed material, it still retains some identity and relationship to the salt bedding. However, the history of the West Hackberry salt appears to be quite different. As noted earlier, the lateral extrusion of the West Hackberry salt away from the original Louann deposit to form sills, serves to also disrupt the bedded structure, particularly the interbeds. This horizontal extrusion will tend to homogenize the salt, distributing the anhydrite and other impurities more evenly in the salt mass before the vertical extrusion occurs and further disrupts remnants of the bedded structure.

3.0 CAVERN CONSTRUCTION AND HISTORY

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 of depth with diameters of about 200 ft. It is critical to take advantage of this new source of potential understanding of cavern behavior.

As noted previously, of the SPR caverns at West Hackberry, five were commercial solution mined caverns purchased by the SPR and 17 were constructed by solution mining solely for the SPR. The locations of these caverns are given roughly by the schematic of Figure 3. Caverns 6, 7B, 8, 9, and 11 are those existing commercial caverns purchased by the SPR. Caverns 101 through 117 are purpose built caverns for the SPR.

Construction and use history of the purpose built SPR caverns is well documented [10]. The West Hackberry site was essentially the second of the SPR facilities constructed and the first to use single well solutioning. It is possible the development may even have benefited from difficulties in the development of an earlier facility. In fact, the West Hackberry cavern geometries suggest that the solutioning process was, for the most part, very well controlled. These caverns are very consistent in general shape and size, with diameters of essentially 200 ft. and heights of 2000 ft. In contrast, the construction and use history of the purchased caverns is very poorly documented but the evidence suggests that solutioning was mostly uncontrolled. Cavern shapes of the former commercial caverns are essentially as they were at the time of purchase and vary considerably.

Except for WH117 which has two wells, the West Hackberry caverns are all single-well caverns with a 20 inch O.D. (outside diameter) cemented casing through the overburden and caprock into the salt, the casing string within the cemented casing consists of a 16 inch O.D. outer tubing for leaching which in turn contains a 10 $\frac{3}{4}$ inch O.D. tubing. The latter two serve as the input and output tubing for the solutioning process, with the specific configuration depending upon construction or operational requirements for each solutioning stage, at the time. Each of the Cavern WH117 wells consisted of 13 $\frac{3}{8}$ inch cemented casing, with 10 $\frac{3}{4}$ inch outer tubing and 7 inch inner tubing. The reason for the unique, and rather abrupt, change in configuration for WH117 was not explained in the construction summary.

Although individual cavern development often deviated somewhat to accommodate specific operational and local variations, the basic solutioning or leaching technique for the West Hackberry caverns was recognizably the same, even though the technique evolved somewhat with time. Typically, solutioning occurred in discrete stages, with the function and placement of the tubing adjusted between stages. In construction of the single-well caverns, initially four stages were used for the first four caverns constructed, and then for the remainder of the single-well caverns three stages were used. In the Sump/Chimney Leach Stage solutioning, the outer tubing end was positioned for brine removal about 100 ft. below the planned top of the resultant cavern. An oil blanket, to protect the roof was placed above this tubing location. The inner tubing open end was placed deep into the well, very near the total drilling depth. For this stage, **direct** flow was used, e.g. the raw water was injected through the inner tubing into the cavern bottom, near the total drilling depth, to develop the cavern sump. Direct flow

corresponds to the normal drilling configuration where the water is injected at the drill bit at the bottom of the drill hole. The solutioning produces an inverted conical shaped volume, expanding upward as the solutioning continues. The sump collects the insolubles as they are released from the salt matrix during dissolution. Insolubles contents in West Hackberry range from 2.34 % (WH116) to 5.68% (WH102) by volume [11]. As the sump was developed, the insolubles often enveloped and then may eventually have plugged the 10 ¾ inch tubing, stopping raw water input flow. The water input level was then raised to above the insolubles level by explosively cutting off the bottom portion of the tubing or by a workover to remove and then reinstall the tubing. When this Sump/Chimney stage was terminated, a chimney on the order of 10 to 20 ft. in diameter was formed and a sump diameter in excess of 100 ft was established to eventually accommodate the 12 to 40 ft. depth of insolubles.

The Sump/Chimney Stage was followed by one or more Reverse Leaching Stages in which the raw water input was higher in the cavern than the output location, giving a **reverse** flow as compared to direct flow. In reverse flow, the water is injected near the top of the cavern and removed from the bottom of the cavern. In the First Reverse and Roof Construction Stage, the raw water input was within a few hundred feet of the anticipated top of the cavern, often retaining the same tubing location as that used for the previous stage, just with a reverse in water flow. The brine output was near the bottom of the cavern. In the Second Reverse Stage, which was a cavern development stage, the water input was lowered to about cavern midheight, while the brine output tubing remained near the bottom of the cavern. In the Third Reverse Stage, a continuation of the cavern development process, the water input tubing was lowered further into the cavern to about 200 ft. above the brine output tubing location, which remained essentially unchanged throughout the leaching operations.

The leaching operations were carefully controlled. In the Sump/Chimney Stage the salt solutioning rate averaging approximately 11,400 bbl/day of salt. Note, the rates quoted here are the *salt solutioning* rates and not the quantity of raw water input required to dissolve that amount of salt. About six bbl of raw water are required to dissolve one bbl of salt. The average amount of salt removed was 2.75 MMb. While the salt solutioning rate average is relatively modest, i.e., being neither aggressive nor cautious, the range of rates was quite large, going from a very aggressive 21,330 bbl/day to a very low 4,140 bbl/day of salt. The range of salt removed was from about 3.80 MMb to 1.45 MMb. During the First Reverse Stage, the raw water input flow rate was often relatively high, with an equivalent average salt solutioning rate of approximately 18,300 bbl/day of salt. Salt removal amounted to about 3.15 MMb, on average. Again, the range of salt solutioning rates was quite large, ranging from the very aggressive 28,600 bbl/day to a very cautious 8,900 bbl/day of salt. The amount of salt removal ranged from about 5.15 MMb to 1.34 MMb. During the Second Reverse Stage, the flow rate was usually decreased to yield an average salt solutioning rate of about 14,000 bbl/day of salt. Salt solutioning rates, although generally with the tightest distribution of any of the stages, ranged from a very aggressive 23,400 bbl/day to a modest 10,000 bbl/day of salt. The amount of salt removal on average was the highest of any of the stages, being about 5.00 MMb, ranging from a very large 8.44 MMb to 2.29 MMb. The Third Reverse Stage, which involved only four caverns, had an average salt solutioning rate of 12,200 bbl/day, ranging from 15,300 bbl/day to 8,000 bbl/day of salt. The amount of salt removal was relatively small ranging from 2.29 MMb to 1.27 MMb. As will be shown later, the flow rate may have affected the cavern features or shape, although not as greatly as one would

suppose. Roof development with the high flow rate appears to produce a more irregular cavern surface, perhaps associated only with the high flow rate but also potentially with a less uniform salt in this region of the dome. In contrast, the second and third reverse stages, generally, but not always, result in a nearly cylindrical, uniform cavern shape. In fact, the entire SPR cavern field encompasses a general trend toward nearly cylindrical caverns, with about 75% of the caverns displaying some portion of cylindrical geometry. This uniform cylindrical shape is especially evident in the lower portion of the caverns, as achieved during the last reverse stage.

The dissolution history of the Olin caverns is not available, but as brining caverns they are leached more or less continuously by inflow of raw water and the removal of brine. In 1980 the sonar survey revealed that the caverns were in the shape of inverted clubs, i.e., the large end was at the bottom of the cavern. The cavern tapers toward a smaller diameter at the top. The bottom of the Olin caverns is essentially at the same elevation as the SPR caverns, with cavern heights nearly the same, at about 2000 ft. Future plans in 1990 indicated that Olin would continue to draw brine from these caverns, with changes in leaching to enlarge and potentially change the cavern shape. The current disposition of these caverns is unknown, and not particularly relevant to this study. However, under some conditions they may be considered as possible future reserve expansion caverns.

The Oxy USA cavern leaching history also is not available. In 1990, the sonar surveys showed these caverns to be in general smaller than the SPR caverns. Their roofs are all at an elevation of 2300 ft. below the ground surface. Only two of the caverns approach a cavern height of 1000 ft., with the remaining cavern heights considerably less than 1000 ft. Because these caverns were used for petrochemical storage, the cavern configurations were not expected to change significantly with use. Again, the current disposition of these caverns is unknown.

4.0 ANALYSIS OF CAVERN FEATURES

In the analysis of the West Hackberry caverns, selected examples will be used to illustrate potential salt dome features. Some examples will be more-or-less typical cavern configurations, whereas others will be extreme examples that suggest unusual features or potential problem situations. As appropriate, comparisons will be made between the West Hackberry structures and features analyzed here and the previous analysis of the Big Hill structural features [3].

4.1 General Cavern Features and Solutioning Conditions

As previously noted, a feature, or lack thereof, that perhaps most distinguishes the West Hackberry SPR caverns is that they tend to be very cylindrical, especially in the lower portions of the caverns. This type of cavern represents, in some degree, about 75 % of the cavern surfaces. However, there is another, less frequent, cavern type which has marked solutioning features along the entire cavern surface. Using tools provided by the MVS software, the features and geometry of the caverns can be examined in considerable detail, as is readily illustrated in Figures 4 and 5. In the figure captions, the degrees of clockwise (cw) rotation of the caverns from the north view is indicated.

In Figure 4, Cavern WH112 (number 13 in order of construction) is more-or-less typical of a smooth cavern. Here the lower $\frac{3}{4}$ of the cavern is a well defined smooth cylinder. The upper $\frac{1}{4}$ of the cavern is a rough bulbous enlargement, with indistinct horizontal features. This cavern is located at the extreme southeastern corner of the SPR cavern array. Cavern WH108 (number 8 in order of construction), as shown in Figure 5, is perhaps an extreme example of the cavern with rough surface features over nearly all of the cavern length. This rough appearance is probably the consequence of preferential solutioning which results in protrusions and pits in the cavern wall. Whether or not this preferential solutioning is caused by material variations or by hydrological flow variations remains a question. The orientation of WH108 is chosen to show the most prominent features. These include indistinct vertical wavy linear features running vertically for several hundred feet, and prominent solution features, protuberances or pits, with radial heights of up to 20 ft and vertical lengths of more than a 100 ft. Interestingly, WH108 is adjacent to WH112 in the extreme southeastern corner of the SPR facility.

It is worthwhile to note that the resolution of the sonar surveys is sufficient to assure that the distinct cavern features observed are not artifacts. The sonar data are taken at discrete vertical elevations over the cavern depth, with 10 to 20 ft separation between elevations. At each depth station individual data points, varying from eight to 72 discrete locations, depending upon operator discretion and instrument capabilities, are taken around the azimuth. Thus, errors in any individual data point or in any given station are on the order of tens of ft, much smaller than the sizes of the perturbations observed in the cavern wall.

The cavern shape is the end product of the solutioning process. For example, the leaching operation for WH112 began with the inlet/outlet tubes configured for the **Direct Sump/Chimney Development** Leaching Stage. As noted previously, the input raw water was through the inner tubing with a vertical location of 4942 ft, near the end of the drill hole for

the initial well. Brine withdrawal was from the outer tubing located at 2865 ft, near the cavern top at the planned roof elevation. In this stage the salt solutioning rate was roughly 8,480 bbl/day of salt, or about 50,880 bbl/day of water. As will be shown later, this is a relatively slow rate in comparison to other direct solutioning rates. After establishing the sump and the small diameter chimney by direct leaching (solutioning), the raw water input and output tubing functions were reversed in preparation for the main leaching stages. Consequently, in the **First Reverse/Roof Construction** Stage of leaching, the 16 inch diameter outer tubing becomes the raw water input, and it slightly repositioned to a depth of 2903 ft, essentially just beneath what will become the top ¼ portion of the irregular cavern top.

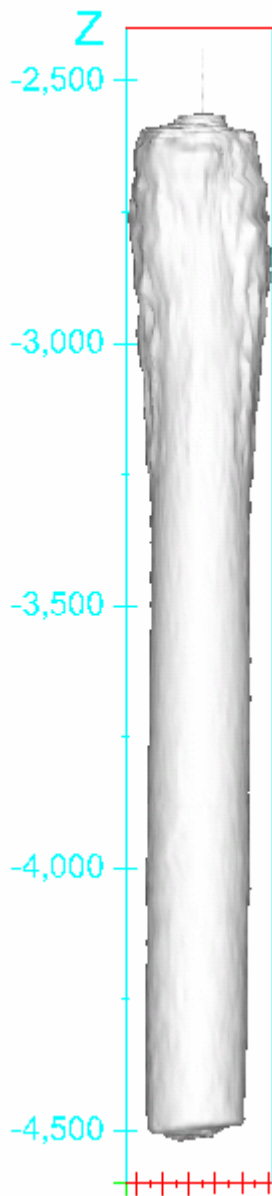


Figure 4. WH112-180°cw, 75% Smooth.

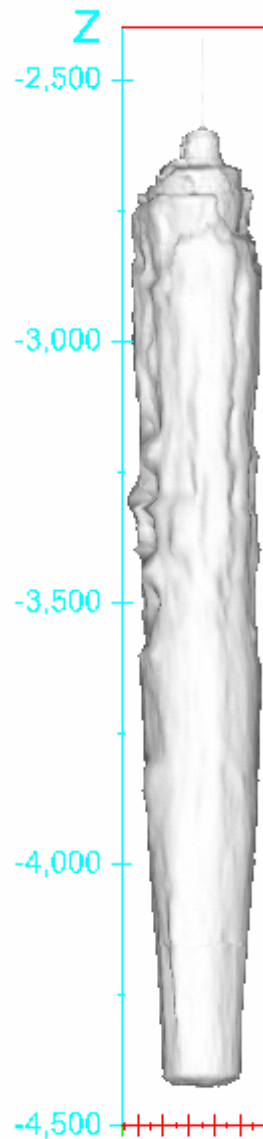


Figure 5. WH108-180°cw, All Irregular.

The brine output was through the 10 ¾ inch diameter inner tubing relocated to a depth of 4659 ft. During the First Reverse/Roof Development leaching stage, the solutioning rate is roughly 25,530 bbl/day of salt, or a flow rate of roughly 153,200 bbl/day of water. This was a significantly greater flow rate than the earlier leaching stage. As noted, this leaching stage was planned to form the roof of the cavern. The Second Reverse leaching stage, and any subsequent stages, were planned to form the lower portions of the cavern. In WH112, the Second Reverse leaching stage input tubing was relocated to 3950 ft, and the output brine tube was placed at 4559 ft. Interruptions for site use and a leaching moratorium of unknown duration cause some uncertainty in the solutioning duration. Never-the-less, the solutioning rate was crudely estimated to be 13,440 bbl/day of salt, or 80,640 bbl/day of water. The flow rate during the second leaching stage was markedly slower than that of the previous stage. No third stage of leaching was used in WH112.

Cavern specific tube end depths or locations, solutioning beginning dates, salt solutioning rates, and salt removal quantities for each solutioning stage of every cavern are given in Table II-B in Appendix B. These quantities are either as defined or as derived from the construction details and histories documented by the DOE [10].

While examining the construction narratives is illustrative, a better method of describing the solutioning variables is necessary for any analytic discussion. Cavern solutioning involves a number of important variables, which for such large operations as the SPR, may indicate important trends. However, even here, the range of solutioning conditions possible even with a limited number of caverns can overshadow the ability to clearly define the trends. In general there are two types of considerations that must be examined: first is the physical solutioning conditions of input/output locations and fluid flows imposed by the operators and second is the solutioning effects caused by the variations in domal materials and geology.

Some of the imposed conditions can be examined directly. Intuitively, the positioning of the inlet and outlet tubes must have some effect on the cavern geometry, and as such are important variables in solutioning. From the construction history, it is possible to obtain the locations of the bottoms of the tubes and to determine the separation distance between the raw water inlet and the brine outlet. These separation distances for the initial Direct, 1st Reverse/Roof, 2nd Reverse, and 3rd Reverse (if applicable) solutioning stages are shown in Figure 6. In the graph, the separation distances are plotted against the starting date of the given solutioning stage. Although there is a general consistency in the separation distances for the single well caverns for each of the stages, the separation distance of the Reverse Stages tends to decrease progressively with start time. For whatever reason, the operators, over time, must have found a reason for this well defined progression in tube positioning to decrease the separation distance. In the two-well cavern WH117, tube configuration is considerably different, as might be expected. Disregarding WH117 for the moment, the general consistency in tube placement and separation distances throughout the construction of the single well caverns strongly suggests that these do not contribute to the observed differences in cavern shape. These must have developed because of other factors, such as fluid flow or material variation.

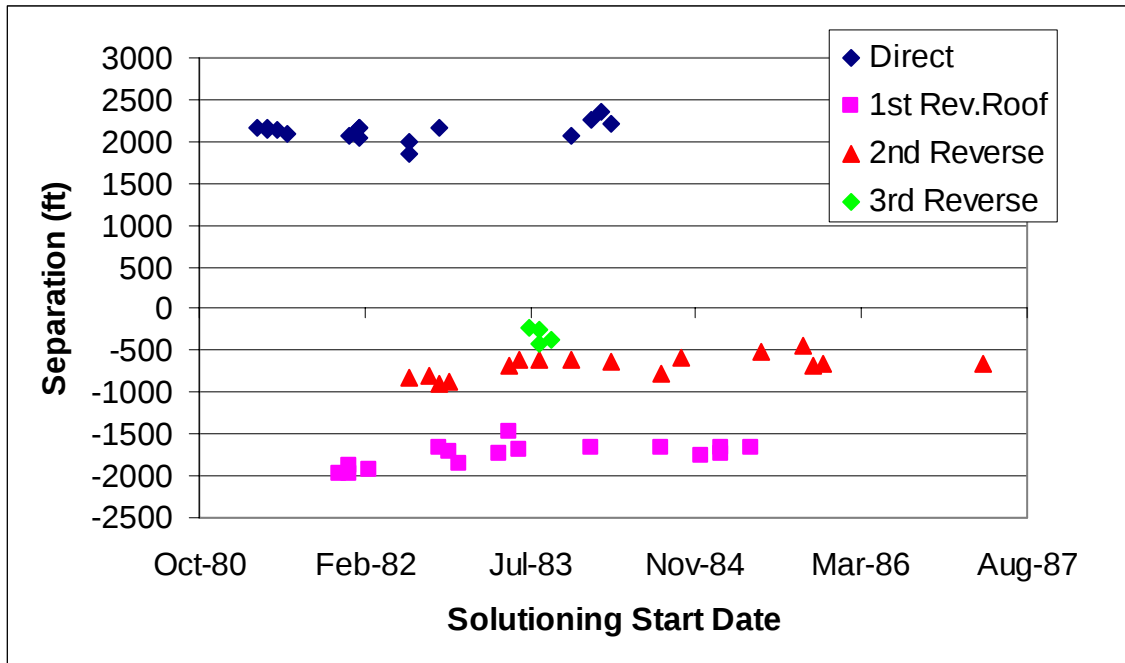


Figure 6. Input and Output Tube Separation Distances for Each Cavern and Stage.

For Cavern WH112, the start date for direct solutioning was November 1983, toward the end of the site construction activities. The subsequent two stages started on December 1984 and June 1985. From Figure 6, at the time this corresponded to the somewhat reduced separation of the input and output locations. While physical locations of the well tubing are relatively easy to obtain, defining the fluid flow conditions during solutioning is significantly more challenging. At the very least, the solutioning may depend upon the rate of raw water input as well as the duration of that input. Analysis of any other variations, such as the instantaneous cavern diameter associated with a given raw water input rate, etc., are beyond this study. Nevertheless, proceeding apace, the apparent salt solutioning rate (which, as noted previously, is a direct substitute for the raw water flow rate) for each cavern and solutioning stage are plotted against the amount of salt removed for that stage, where the salt volume differences are obtained from integration of the sonar survey results after each stage of solutioning [10]. These results are shown in Figure 7 for the Direct, in Figure 8 for the 1st Reverse/Roof, in Figure 9 for the 2nd Reverse, and in Figure 10 for the 3rd Reverse stages.

Even though the graphs of salt solutioning rates show the marked degree of operational variation permitted during construction of the SPR caverns, it is not entirely random. In general, the direct solutioning stage utilized relatively intermediate solutioning rates, along with relatively small salt removal quantities. The solutioning rates for the 1st Reverse/Roof stages were generally greater than the other stages, with a larger variation, and exhibited the highest extremes in rates. Also, salt removal quantities of the 1st Reverse/Roof stages tended to be larger than in any other stages, again showing the upper extremes in variation. The 2nd Reverse (and 3rd Reverse if applicable) stage solutioning rates were considerably lower than those of earlier stages.

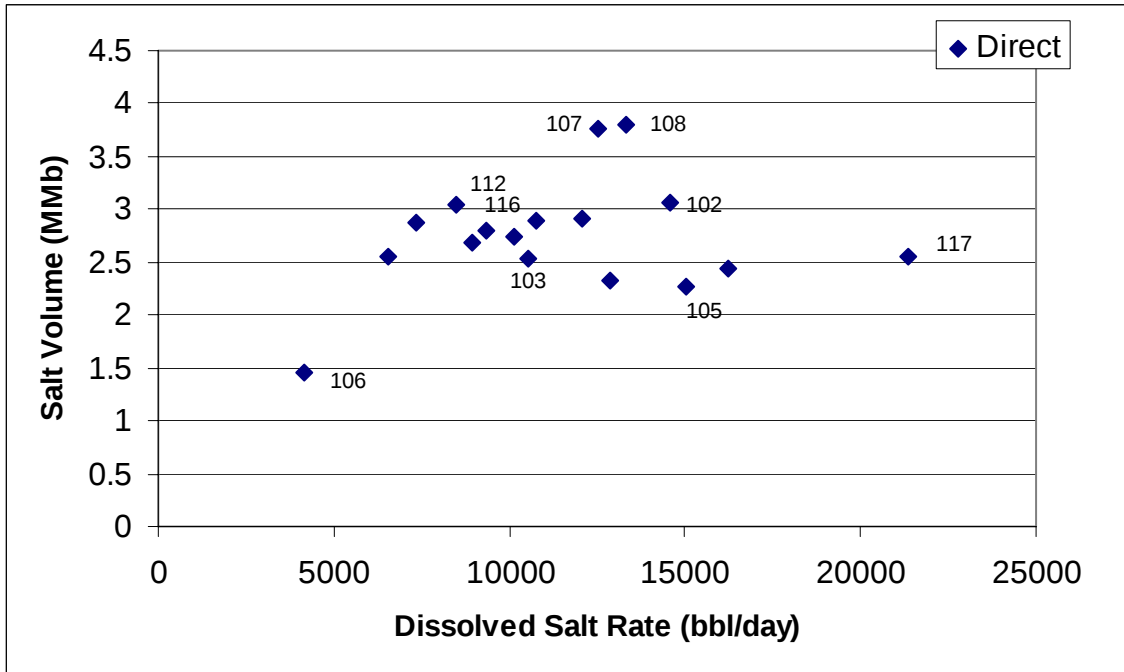


Figure 7. Solutioning Conditions for Direct Sump/Chimney Development Stage.

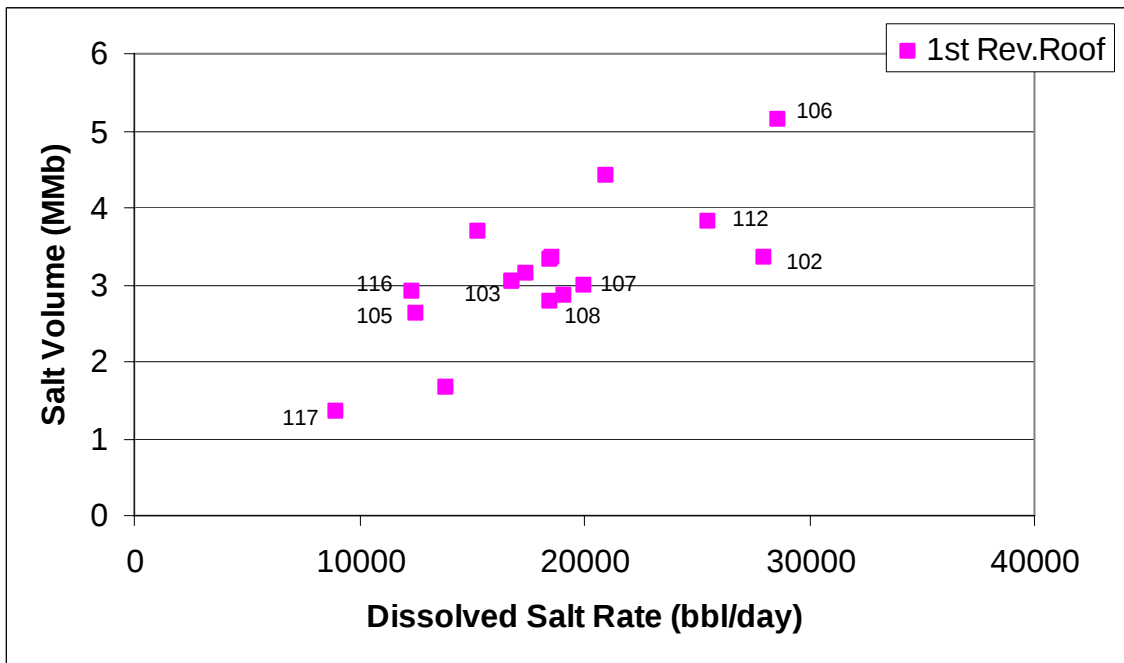


Figure 8. Solutioning Conditions for First Reverse/Roof Construction Stage.

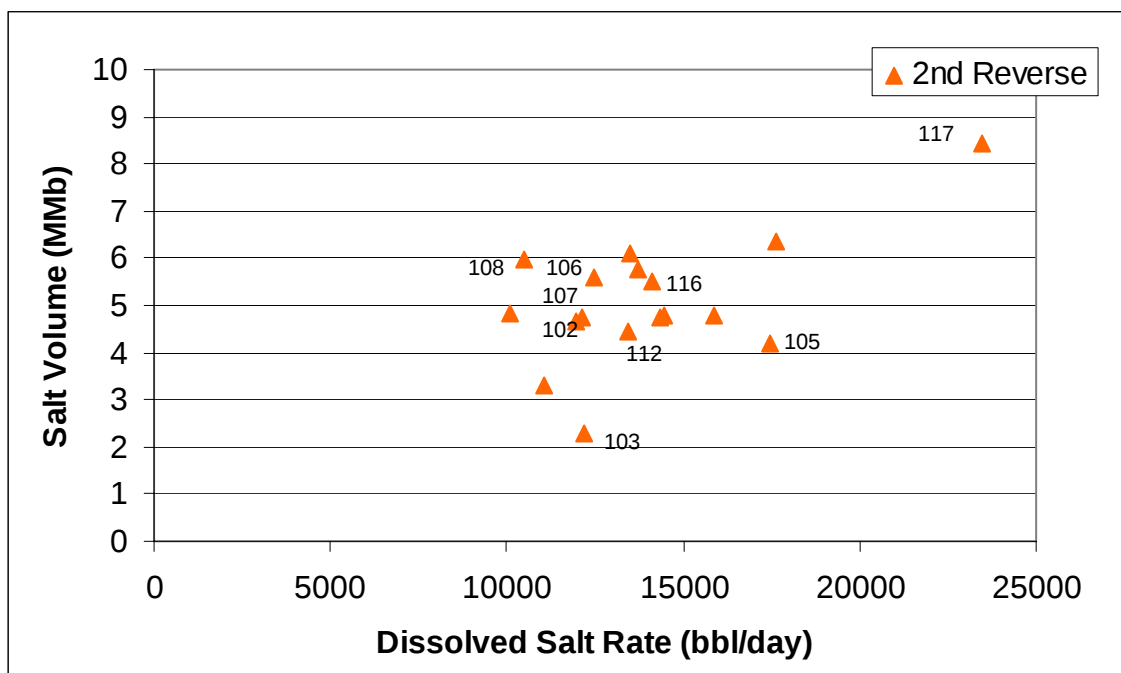


Figure 9. Solutioning Conditions for Second Reverse Construction Stage

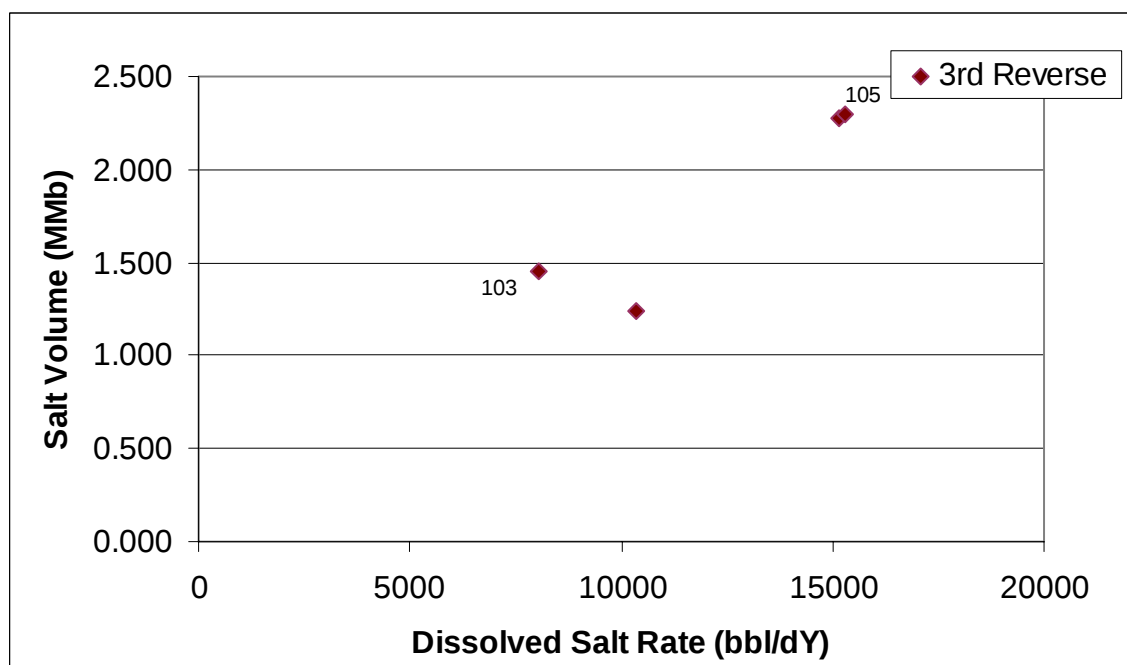


Figure 10. Solutioning Conditions for Third Reverse Construction Stage.

From these figures it is possible to trace the relative flow histories of any given cavern. A few examples are marked which will form the basis for further discussion. Taking WH112 in Figure 7, direct solutioning involved a relatively low fluid flow rate with a relatively large quantity of salt removed. Usually, individual sonar surveys were taken after each stage of

solutioning. In this case, the sonar after the direct stage revealed a well defined chimney with a slightly enlarged sump region [12]. In Figure 8, the 1st Reverse/Roof shows that both the flow rate and the removal quantity are toward the upper extreme for cavern construction. As we will demonstrate, this can produce a bulbous cavern top or other solutioning features. While the sonar survey at the end of this stage shows an enlarged cavern top, it did not develop into a bulbous feature. In Figure 9, the 2nd Reverse stage yielded the final cavern shape as shown in Figure 4. Both the flow rate and the salt removal, while somewhat toward the upper end of conditions, are still within the bulk of the more moderate cavern conditions. Again, the lower $\frac{3}{4}$ of the cavern is relatively smooth, while the top $\frac{1}{4}$ retains some features developed during the 1st Reverse/Roof stage. There was no 3rd Reverse stage.

Even though the above analysis conveys general information, it does not add significantly to an explanation of individual cavern shape differences. To be useful, individual cavern construction histories must be superimposed and compared with rather specific goals in mind.

4.2 Comparison Analysis – Rough vs. Smooth Features

As noted previously, there appears to be two types of cavern surface features, most often occupying different portions of the same cavern. These are distinguished by either a relatively smooth, uniform cylindrical surface or an irregular, rough surface made up of pits and protuberances. Illustrations of these two types of surface conditions were given for WH112 of Figure 4 showing the mixed smooth and rough cavern and with WH108 of Figure 5 showing the completely rough cavern surface. The solution stage history of WH112 has already been described in detail. However, in a comparison description, tracing the construction history for Cavern WH108 shows several aspects differing from those of WH112.

In WH108 the direct solutioning conditions involved flow rates slightly above the average, with exceptionally large amounts of salt removal. At the end of this stage, a sonar survey indicated few of the perturbations in cavern surface found later [13]. Interestingly, the conditions for the 1st Reverse/Roof stage as marked in Figure 8 and the 2nd Reverse stage similarly marked in Figure 9, indicate that the conditions are within the bulk of the cavern conditions, and rather moderate. After the 1st Reverse/Roof stage completion, sonar survey results show the cavern developed an expanded top with surface irregularities [14]. Subsequent sonar surveys during and after the 2nd Reverse state [15], perhaps because of low resolution, did not show the detail revealed in the latest survey obtained in 2003, which formed the basis for Figure 5. The interesting aspect of the comparison between the solutioning rates of WH112 and WH108 is that, if anything, the solutioning rates for WH108 do not appear to be as severe as those of WH112, although the quantities of salt removal for any stage will differ. As a result, one would expect the cavern surfaces to be similar, but they are not. Apparently, the cavern surface of WH108 is produced by something other than just the solutioning practice, with the most likely factor the local inhomogeneity of the salt mass in which this cavern was constructed.

One other comparison seems worthwhile. In Figures 11 and 12, Caverns WH112 and WH116 are compared. As noted previously, WH112 is in the extreme southeastern corner of the SPR facility. WH116, on the other hand, is in the extreme northwestern corner of the facility. Yet, they show similarities in development with large portions of smooth cavern surfaces. Solutioning conditions for WH112 remain as explained above.

Solutioning conditions for WH116 in the direct stage are given in Figure 7 and indicate a relatively low flow rate and a high, but approaching a moderate amount of salt removal.

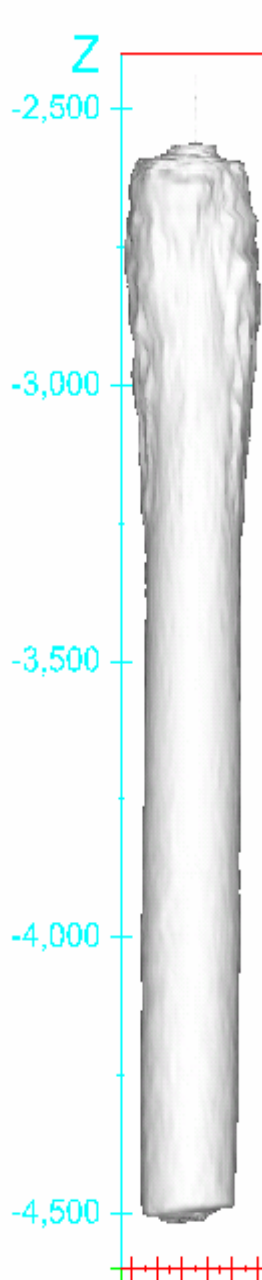


Figure 11. WH112-180°cw, 75% Smooth.

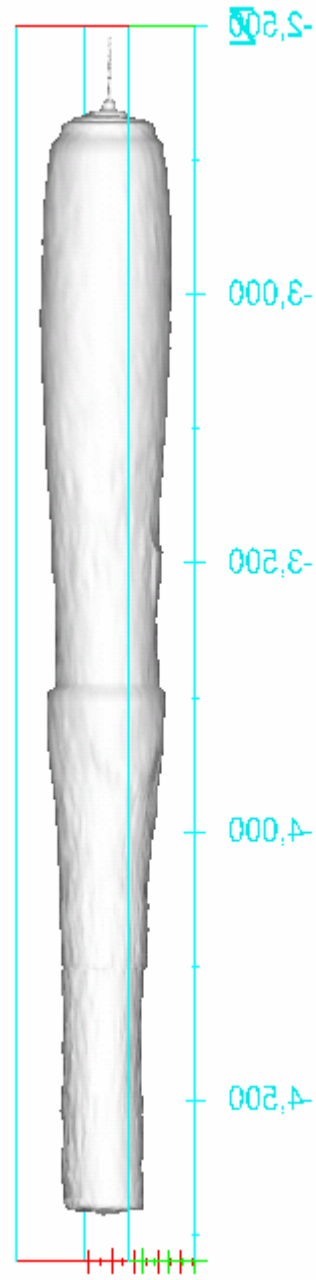


Figure 12. WH116-330°cw-Very Smooth.

The subsequent sonar survey results indicate a typical chimney and sump development. Solutioning rates in the 1st Reverse/Roof stage were among the lowest of the caverns, but with a moderately high salt removal. The sonar survey [16] obtained after this stage showed that the top of the cavern was exceptionally smooth, with little development of the extensive top expansion or bulbous formation more typical of the other caverns. The brief construction records note solutioning was suspended during the 1st Reverse/Roof construction so the cavern could be utilized in a surge capacity mode. After resuming solutioning for a period of time, the inlet/outlet tubes were configured for the 2nd Reverse stage of construction. Solutioning in the 2nd Reverse stage utilized rates toward the higher rates, with removal amounts a little higher than the average, but these were again relatively moderate. Of importance, are the exceptionally smooth cavern surfaces of Cavern WH116, as shown in Figure 12. There is, however, a formidable step developed above the raw water input location at 3953 ft for the 2nd Reverse stage. The cavern diameter is larger below the step than above it. It does not appear the step is associated with the earlier, temporary use as a surge cavern. In any case, the hydrological flow and solutioning for this final stage must have been extremely uniform to develop such a well defined feature.

Although the evidence is sparse, it appears irregularity at the top of the caverns is aided by aggressive flow condition during the 1st Reverse/Roof stage of cavern development. While moderate flow conditions in the 2nd Reverse stage yield smooth cylindrical cavern shapes in the lower portions of most caverns, they appear to be insufficient to remove the remnants of the aggressive solutioning in the top of the caverns developed during an earlier solutioning stage.

However, it also appears the irregular surface over all of WH108 occurred, even though the solutioning conditions were moderate and should have resulted in a smooth lower portion of the cavern. This supports the postulate that inhomogeneities may be the controlling factor, under certain solutioning conditions, responsible for the irregularities in the rough caverns.

In a very crude sense, it is possible to categorize the West Hackberry cavern according to the dominant features. Only WH108 is distinguished by general preferential dissolution features over the entire cavern, features exhibited to a lesser extent in WH101, WH106, and WH117. Marked irregular features appear in the top portions of WH103, WH104, WH105, WH109, WH110, WH114, and WH117. Solutioning steps appear in WH101, WH109, WH113, and WH114, in addition to the previously noted WH116. Although the only completely smooth cavern is WH116, Cavern WH111 would also be characterized as a completely smooth cavern, except for a very unusual feature. In this cavern (which is not shown in the text, appears in Appendix A), a very distinct step at what should have been the top of the cavern separates a very unusual false top of some 12 % in height where the shape becomes a very directional, elongated lozenge shaped "sail." While the exact cause of the unusual top is not known, Cavern WH111 construction was abnormal in that difficulties were experienced in maintaining an oil blanket, with apparent loss of oil. In addition, pressure irregularities and loss of nitrogen occurred during a subsequent well integrity test. The only sonar survey records for WH102 and WH115 are from 1983 and 1985, respectively, both taken just after completion of the 1st Reverse/Roof stage. While sonar survey results for all caverns exist to show progressive cavern development, only these two results have been treated using the MVS software. These show very marked irregularities in the top portion of

the cavern, and smooth cavern walls in the bottom portion of the cavern, as seen in the figures of these caverns in Appendix A. It appears that some of these features can persist through subsequent solutioning stages. This means that any stage of solutioning is potentially as important as any other stage in determining the cavern wall conditions.

4.3 Comparison Analysis - Alternative Graphical Representations

Although the graphics of Figures 4 and 5 where the vertical cavern is observed straight on are outstanding, a slight alteration of the angle of viewing and additional special modes of MVS software can provide even more definition. Thus, Figure 13, again of WH108, provides both an enhanced illustration of cavern features and cavern surface insights through selected geometric cross-sections. In Figure 13a, a gray-scale (opacity 100%) graphical representation is shown of the most recent sonar survey of Cavern WH108. Rotations from North about the vertical axis, always in degrees clock wise, are indicated. These rotations position the cavern so that the most salient features of the cavern surface are facing the viewer. Further, in order to better define these features, the cavern is also rotated 45° about a horizontal axis roughly at cavern midheight, with the top of the cavern displaced toward the viewer. This tends to add depth to the protuberances and to better accentuate the features.

In Figure 13b, the same WH108 cavern orientation as above is maintained, but the MVS software is used to make the cavern essentially transparent (opacity 30%). In addition, three geometric cross-sections are imposed on the cavern geometry. Compared to Figure 5, the rendition of Figure 13b brings considerably better definition to the cavern geometry. As previously noted, these cross-sections illustrate clearly that the cavern is indeed very irregular. Even greater deviations from a cylindrical cross-section are found in the top quarter of the caverns. Upon examination, WH108 illustrates marked features, which can be found to a degree in other West Hackberry caverns, but actually are somewhat unique. Most caverns tend to show effects of aggressive solutioning in the top portion and smooth features in the bottom portions of the caverns.

Again in a direct comparison to Cavern WH108, Cavern WH116 (number 11 in order of construction) is shown with the same enhanced perspectives in Figure 14. In this perspective, the close cylindrical symmetry is apparent in the cross-sections in Figure 14b. Solution steps are extremely clear where the conditions of solutioning changed. As noted previously, apparently the homogeneity of the salt and the steadiness of the solutioning flow were so uniform that the steps of this magnitude could form. Other caverns display similar but less perfect solutioning steps. Representations with enhanced perspective of the type illustrated here are given for the SPR constructed West Hackberry caverns in Appendix A, Figures 1-A through 17-A, and for the commercial caverns purchased by the SPR in Appendix A, Figures 06-A through 011-A.

4.4 Comparison Analysis – Aggressive Solutioning

Sonar surveys of the West Hackberry caverns were scheduled to take place periodically, perhaps optimally every ten years. In practice this did not occur and, in fact, while most of the caverns had been surveyed by approximately the year 2000, some of the caverns remained without available final surveys, until just recently. Thus the data prepared by Rautman et al.

[6] in two cases was, at that time, based on sonar surveys taken just after completion of the 1st Reverse/Roof stage. While recent surveys have become available since the MVS database was prepared, they have not yet been incorporated into the database, fortunately these cases permit examination of cavern shapes at an intermediate state. The involved caverns are WH102 (number 7 in order of construction) and WH115 (number 15 in order of construction).

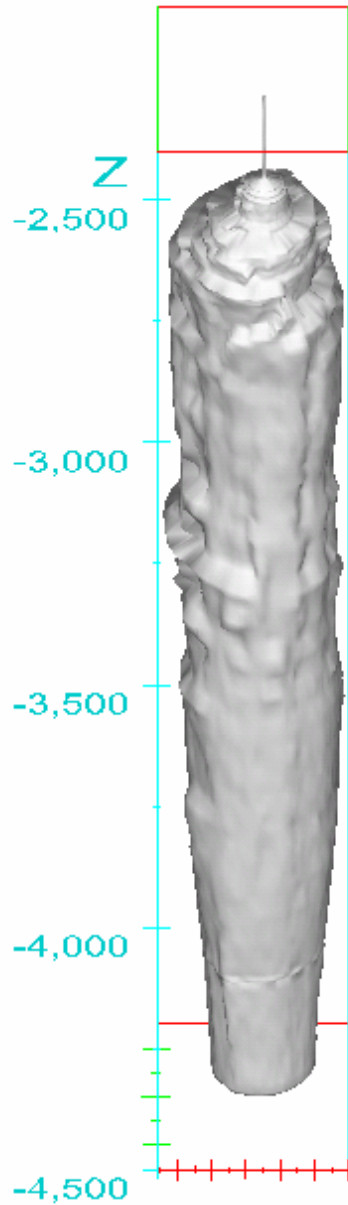


Figure 13a. WH108-180°cw-45°, Solid.

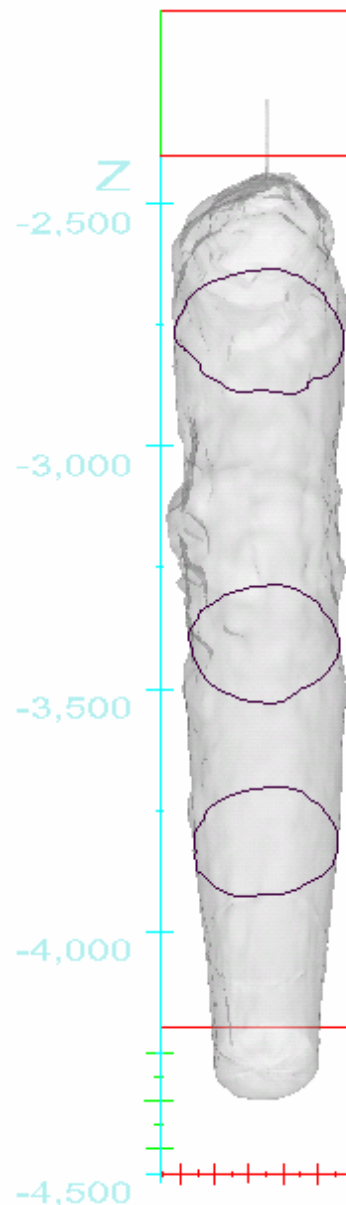


Figure 13b. WH108-180°cw-45°, Sections.

Perspective views of the sonar of WH102 after the 1st Reverse/Roof stage are shown in Figure 15. This illustrates the bulbous top ¼ of the cavern with both irregular and horizontal solution features. The location of the raw water inlet was just at the base of the bulbous top. From Figure 7 it is apparent the solutioning rate for this stage was extremely aggressive at some 27,970 bbl/day of salt. Note, however, the quantity of salt removed was commensurate with most of the caverns. Interestingly, the bottom ¾ of the cavern at this point is relatively uniform, cylindrical, and smooth.

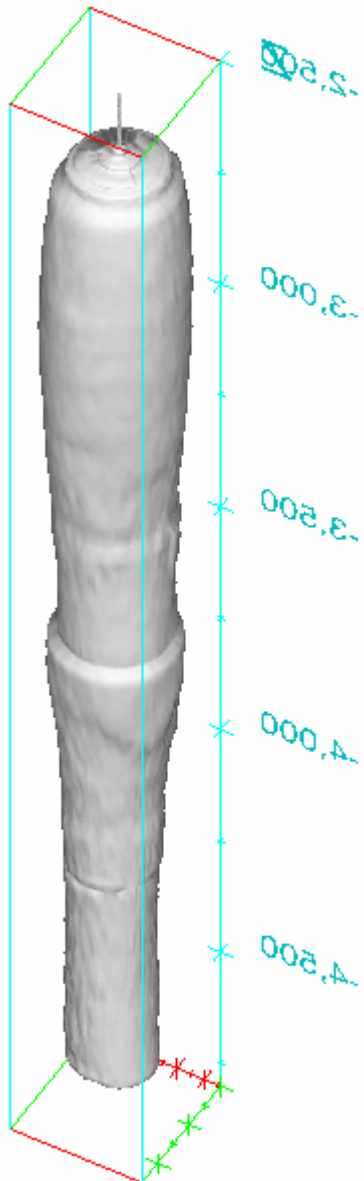


Figure 14a. WH116-330°cw-45°, Solid.

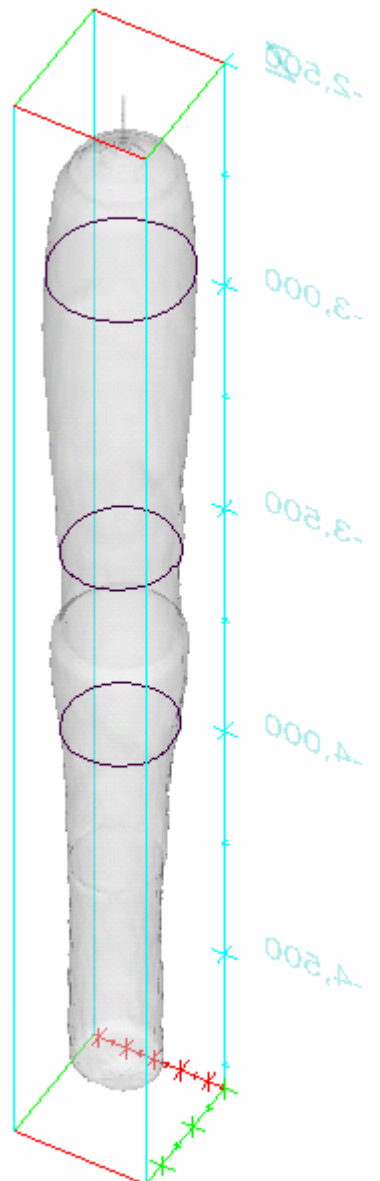


Figure 14b. WH116-330°cw-45°, Sections.

WH115, as shown in the perspectives of Figure 16, was solutioned somewhat less aggressively than WH102, but had one of the highest quantities of salt removal. As the figure illustrates, the top ¼ of the cavern at the completion of the 1st Reverse/Roof stage had a significant directional solutioning on one side, but was not bulbous. The bottom ¾ of the cavern is smooth and cylindrical.

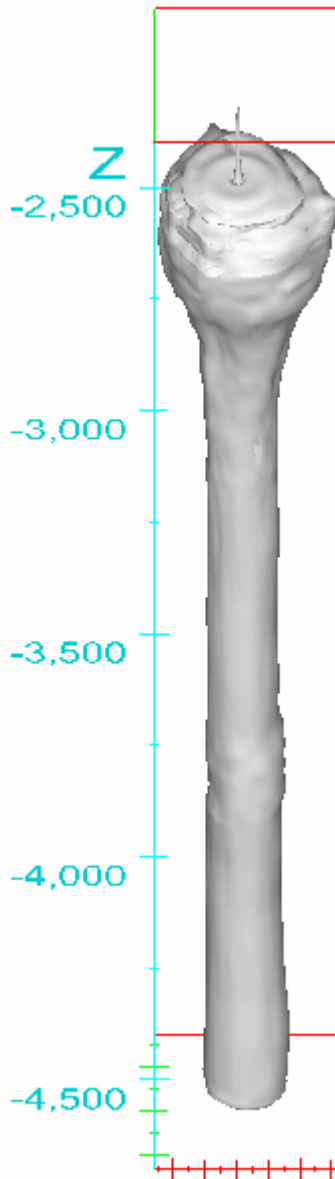


Figure 15a. WH102-180cw-45°, Solid.

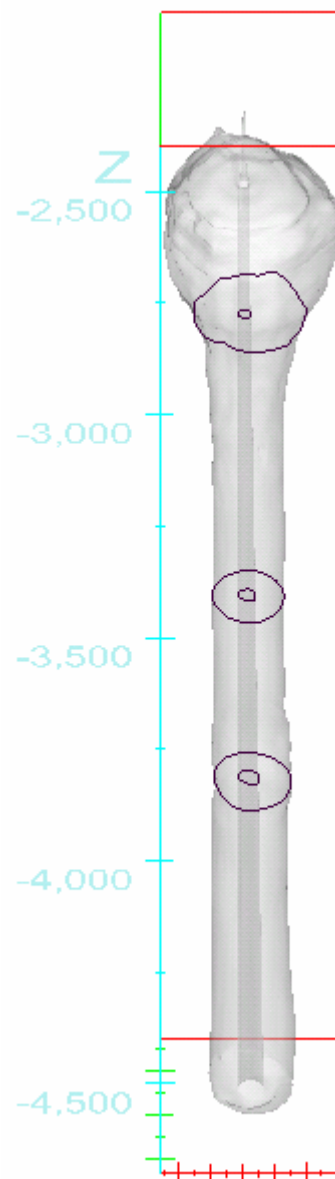


Figure15b. WH102-180cw-45°, Sections.

While the effects of aggressive solutioning are difficult to quantify because of the variations in practice from one cavern to another, it does appear that the effects of the aggressive solutioning in the 1st Reverse/Roof stage affects the roughness of the tops of many caverns. The most aggressive solutioning in this stage occurred in Cavern WH106, followed closely by

WH102, and to a lesser extent in WH112 and then WH115. Cavern WH106 is not shown in the text, but can be found in Appendix A. How the subsequent solutioning stages blend into the cavern shape produced by the 1st Reverse/Roof stage can be visualized from these four caverns. In WH106, with a large amount of salt removal in the 1st Reverse/Roof stage, the cavern exhibits a “waist” where it blends with the less aggressive subsequent solutioning stage. In comparison, WH112 shows a smooth lower portion from the subsequent stage, but retains some of the irregularity and a slight bulbous top from the aggressive 1st Reverse/Roof stage. It must be pointed out that in most of the caverns with smooth lower parts and rough top portions the irregularities obviously arise from aggressive solutioning practice and probably not from material inhomogeneities.

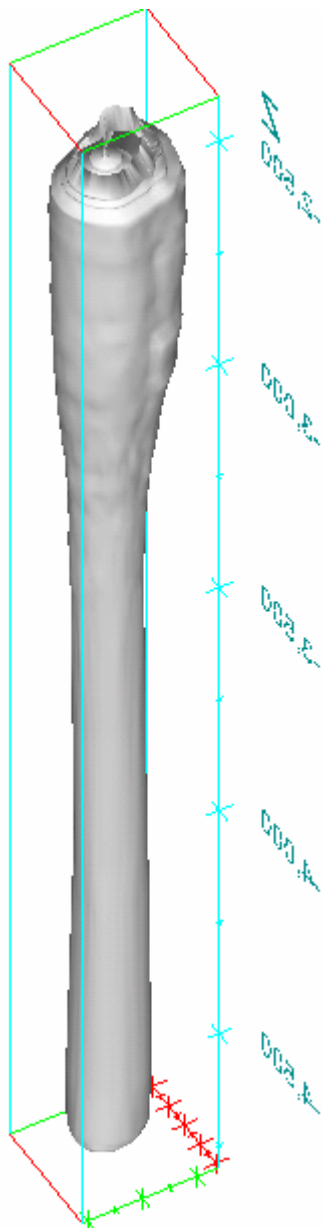


Figure 16a. WH115-300°cw-45°, Solid.

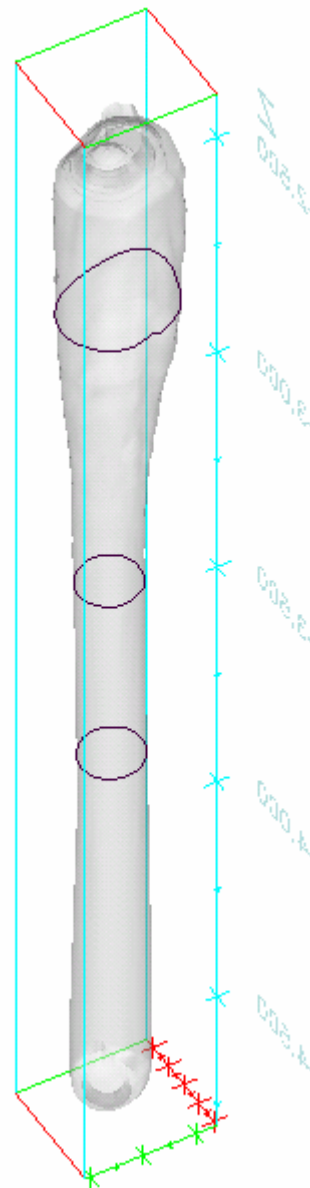


Figure 16b. WH115-300°cw-45°, Sections.

While it is tempting to try to make generalizations linking the solutioning rate and salt removal amounts to the differences in the cavern shapes, unfortunately, it is also easy to overreach to the point of useless speculation. Nevertheless, it can be pointed out that Cavern WH116, a creditable example, where the solution rate was very modest, the roof and top ¼ of the cavern resulted in a well behaved cavern shape. Subsequent solutioning stages were also modest in rates and amounts.

Even though the analysis of any relationship between solutioning practice and the eventual shape of a cavern remains relatively cloudy and uncertain, there appear to be certain obvious consequences of practice on shape. Perhaps this understanding could be instructive during the design of future solutioning procedures. In fact, it may be possible to design smooth cavern surfaces by controlling, where necessary, overly aggressive solutioning to reduce surface irregularities, and hence, future mechanical instabilities.

4.5 Comparison Analysis – Big Hill

Based on the new MVS capabilities, it is possible to expand the analysis of the internal structure of salt domes based on cavern shapes. Two of the SPR facilities have now been examined using the MVS representation: Big Hill and West Hackberry. In fact, one might expect considerable similarity between these two domes because they are diapirs arising from the same Louann bedded salt source. In fact, both of the general types of characteristic features, either of the smooth or irregular cavern surface type, that dominate in the West Hackberry caverns are also found in the surface features of the previously studied Big Hill caverns [3]. However, in distinct contrast, none of the West Hackberry caverns display the often dominant lineament features found in the Big Hill caverns. For comparison, MVS representations are shown in Figure 17 of Big Hill Cavern 103, which is an exceptional example of these lineament features. Sonar surveys taken at two different times (years 2000 and 2002) clearly illustrate the development of a lineament. Eventually, the lineament feature in Cavern BH103 developed into a spall and resulted in a massive salt fall [3].

As postulated by Munson et al. [3], the lineaments in Big Hill caverns are thought to be the distinct remains of the initial interbeds of the bedded Louann salt. As these interbeds, composed of anhydrite, polyhalite, and clay components, are extruded along with the salt layers into the diapir or salt dome, they retain their identity during the deformation, but elongate markedly while becoming vertical, and taking up a shell-like cylindrical form within the dome. This retention of identity is common for the self-mandrel extrusion process. During solutioning, these concentrations of impurities will increase the local dissolution rate of the surrounding salt to enhance the lineament features. The reason similar lineaments are not found in the West Hackberry dome, as previously noted, is based on a postulate given by Magorian et al. [5]. Normally, the sequence of rock formations immediately overlying the Louann salt are the same everywhere in the Gulf Coast where salt diapirs form. Instabilities in these overlying rocks and the density contrast with the salt leads to a single extrusion process of the Louann salt. However, the overlying rock formations immediately above the Louann salt at the location of the West Hackberry dome differ from the normal sequence, with the expected formations missing entirely. According to the postulate, the Hackberry sequence of domes may be beyond the initial margins of the Louann evaporite formation.

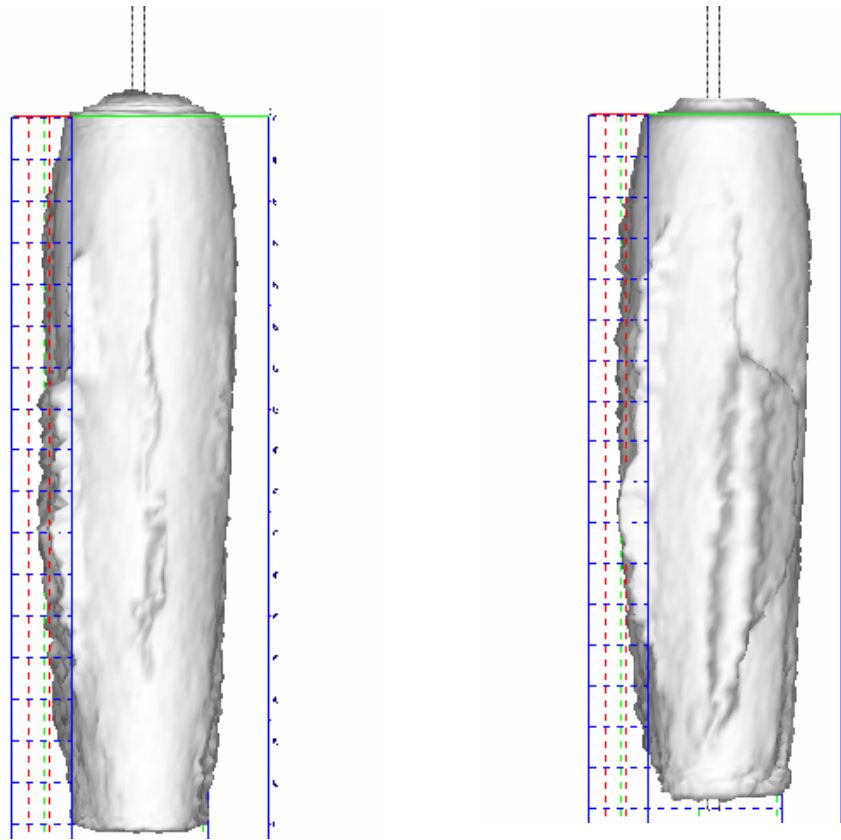


Figure 17a. Big Hill 103-285°cw, 2000. Figure 17b. Big Hill 130-285°cw, 2002.

In fact, it is believed to be a lateral extrusion from the initial bedded salt to form a tongue or sill into an existing rock formation. Later, an instability in these rock formations led to vertical uprising of the West Hackberry dome. In the lateral extrusion process, additional deformation of the Louann bedded salt would occur which served to spread and disrupt the interbeds. As a consequence, the salt body became better mixed and therefore more homogeneous. Thus, West Hackberry caverns are less likely to contain the prerequisite defined interbeds for lineament formation. The more homogeneous salt material would be more likely to yield smooth cavern walls, or at the worst, dissolution irregularities. To a large extent, these types of differences in cavern surfaces, while relatively simple, are the only method to determine the large scale stratigraphy of the salt dome.

4.6 Comparative Analysis – Mechanical Behavior, Salt Falls

One aspect of cavern surface features is the possibility that some features can become the precursors to salt failure with subsequent spalls and salt falls. In fact, the high resolution sonar surveys clearly point to such features. Typically, a source of salt failures is a salt protrusion into the cavern. These protrusions can be in combination with a pit into the wall of the cavern, or in some instances the occurrence of lineaments. Regardless of their exact details, the protuberance produces a reconfiguration of the stresses such that the stresses concentrate in the root of the protuberance, i.e., within the salt interior behind the protuberance. The stress causes a continued accumulation of strain, eventually in some cases becoming of sufficient magnitude to cause initial fracture. Further accumulation of strain causes the fracture to propagate, which results in a spall and a salt fall [17]. In some

instances, but not always because the hanging string presents a “small” target, the salt fall can impact the hanging brine string in the cavern and produce damage with potential loss of casing (tubing). Impact can take place anywhere below the elevation of origin of the salt fall. Typically, the damage causes loss of casing function by allowing crude into the brine string, requiring a workover to replace the hanging brine string [18].

If the hanging string is damaged or lost, it is clear evidence that a salt fall has occurred, however, since many salt falls do not impact the hanging string, the evidence of their existence is found only in a progressive rise in cavern bottom elevation. Although these data on cavern bottom elevation history are available for West Hackberry, they have not been compiled.

There has been a number of hanging string damage events in West Hackberry caverns, and details of all West Hackberry events causing tubing loss or damage are given in Appendix Table I-C. Specifically, as summarized in 2004 [18, 19], the caverns have had the following hanging string losses and damage event totals: WH103, with an extremely rough cavern top had four events; WH108, with marked roughness over the entire cavern had two events; WH109, with a rough cavern top half had two events; WH110, with generally rough entire cavern had two events; WH113, with some roughness toward the cavern bottom had two events; WH114, with a rough top half of the cavern had two events; WH102, with a very rough cavern top had one event; and WH107, with a somewhat rough cavern top half had one event.

Although it is impossible to generalize with such a small database, four of those caverns exhibiting salt falls tend to be in the central portion of the facility, with two caverns on the periphery of the facility showing salt falls. While some of these caverns showing salt fall events are within or close to the possible shear zones described by Magorian et al. [5], correlation remains rather indistinct.

In all likelihood, the dominant factor in determining whether a cavern is susceptible to salt falls remains the interior surface geometries. Protuberances offer such geometries because of the alteration of the stress fields and the potential to concentrate strain and fracture at the root of the protuberance. Thus, WH103, which had four salt fall events, is probably more susceptible because of the very irregular top portion of the cavern. The fact that the most events occurred in WH103 certainly correlates to the cavern exhibiting features possibly more conducive to salt fall generation. Cavern geometries clearly have developed as a consequence of solutioning practice or flow condition, with possible, but unproven, contributions from local impurity distributions.

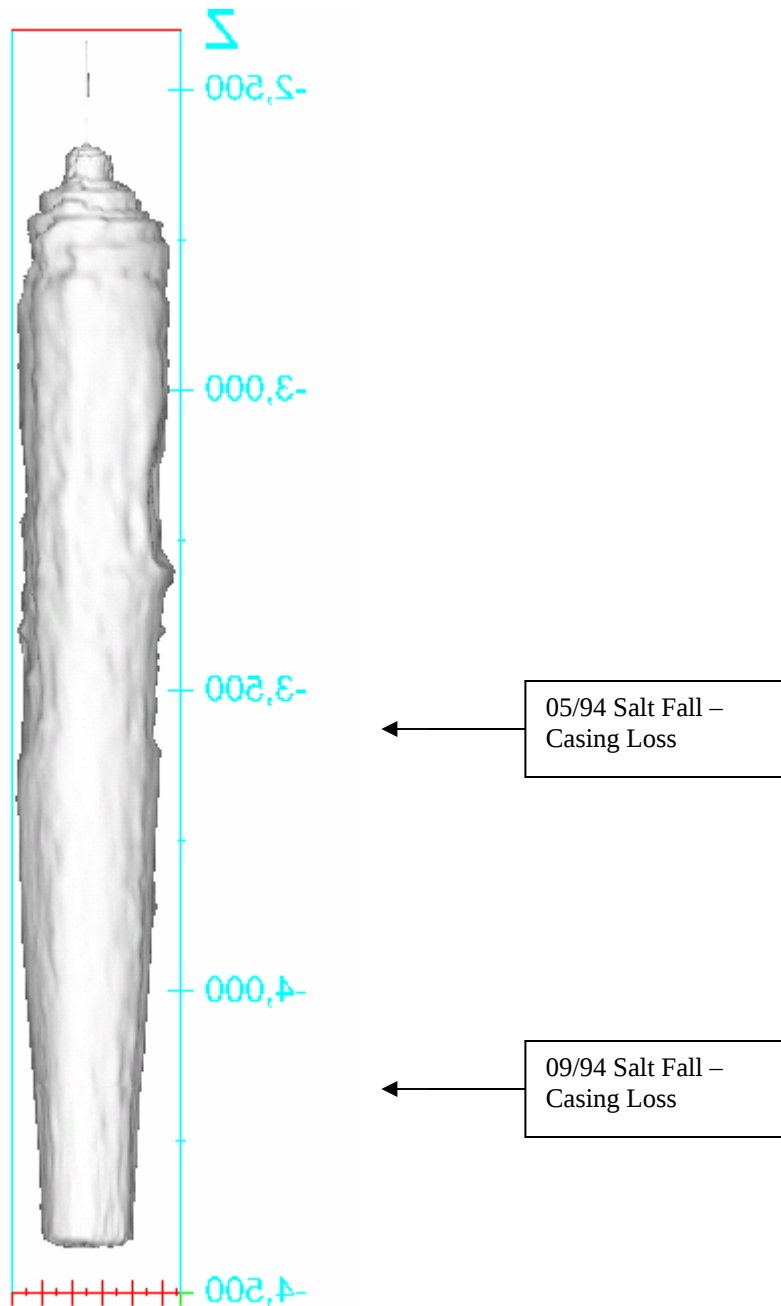


Figure 18. WH108-0°North, Solid, with Locations of Casing Loss Events.

In Figure 18, Cavern WH108 is shown together with the depth location of the point of loss of hanging string tubing. This cavern illustrates a type of feature thought to be associated with creation of salt falls. Specifically, the rough cavern surface above the casing loss location certainly could be the source of salt falls. While in some SPR caverns at other sites the suspected source of a salt fall appears to have a mechanically fractured surface, WH108 does not indicate such distinct mechanical evidence. However, cavern appearance does not necessarily guarantee that salt falls will occur, at least within the current time-frame of the West Hackberry caverns. For example, WH106 has surface roughness nearly equivalent to

WH108 but has not experienced any casing losses. WH104 has a very rough top 25% similar to WH103, but again has no instances of casing loss. Thus, it seems the nature of the cavern surface may suggest the potential for creation of salt falls, but this does not necessarily mean that salt falls will actually occur in any given cavern.

4.7 Comparative Analysis – Material Creep Response

The available laboratory creep data for West Hackberry is very limited, coming from only four tests on Cavern WH6 salt and two tests on Cavern WH108 salt [20, 21]. The results of analysis in terms of the Multimechanism-Deformation creep model are contained in Table II-C, Appendix C. They indicate the creep resistance is low, i.e., the salt is relatively soft.

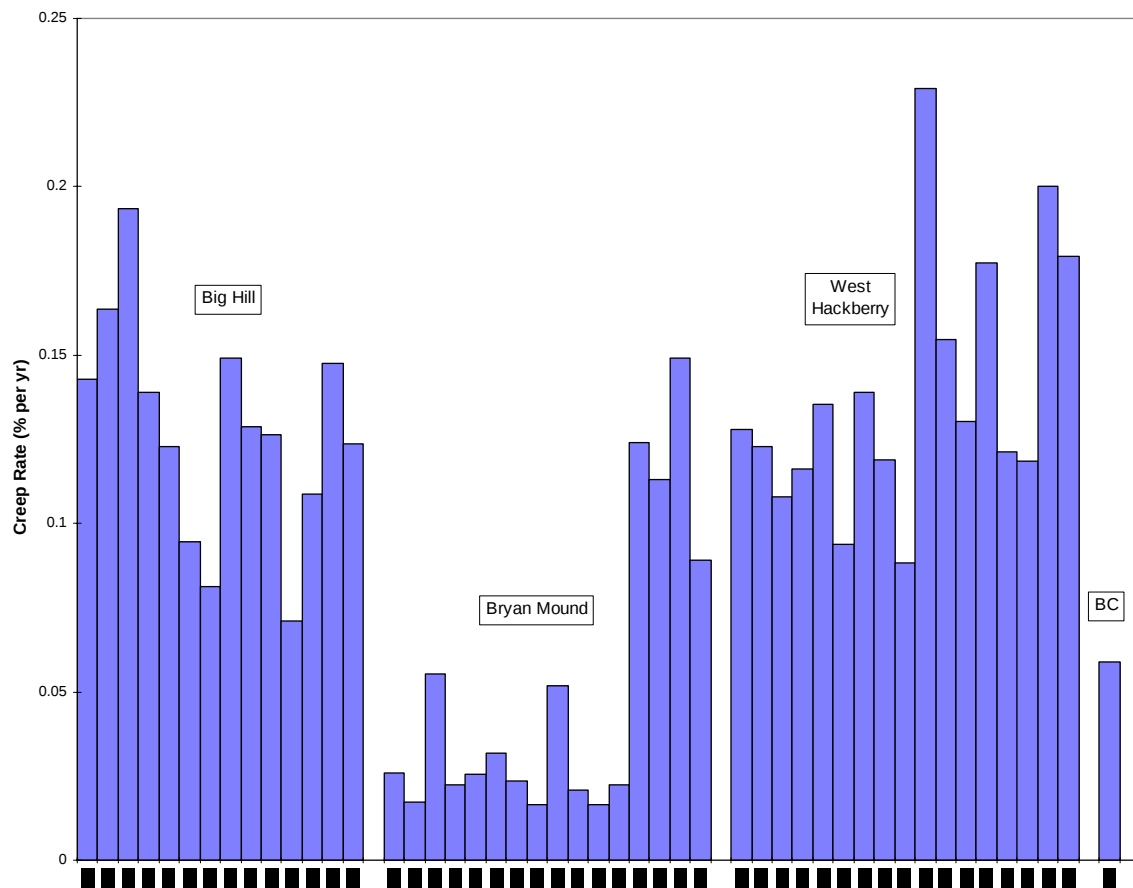


Figure 19. CAVEMAN Volume Creep Closure Rates for SPR Caverns [from 9].

Indirect information about the creep response is obtained from the analysis by Ehgartner [9] where the volume creep closure of the West Hackberry caverns was determined using time-dependant pressure increases of shut-in caverns. Although not currently understood, four caverns, WH116, WH113, WH111, and WH110, on the northwestern periphery of the site all have very high creep closure rates, greater than 0.15% per year, as does the single cavern, WH117, in the midst of other caverns toward the south central portion of the site. These caverns are shown shaded in Figure 1. It should be noted, however, that the range of closure

rates is more-or-less continuous, without discrete separation between the different cavern rates. Indeed, the bulk of the West Hackberry caverns have relatively high closure rates, as shown in Figure 19.

The caverns with the very high closure rates occur mainly on the northern area of the facility. These locations correspond to the region of the nearly vertical, or perhaps a rather modest dome overhang, northern dome flank. The highest closure rate is in Cavern WH110, which has a north central location but not at the extreme edge of the dome. WH110 also is somewhat rough, and exhibits one salt fall. Although the relative creep behavior of the salt surrounding a given cavern may be in theory something of a factor, little significant correlation is apparent at this point.

In terms of gross cavern characterization, it is possible to determine roughly the volume content of impurities in the salt removed by solutioning [11]. These results are tabulated for the West Hackberry caverns in Table II-B, Appendix B. Both the apparent insoluble percentages, which are based on the uncompacted volume of insolubles, and the calculated solid insolubles percentages based on an assumed 0.55 compaction are given. The range of the solid insolubles content is from 5.68 % to 2.34 %. There is little observable trend in the distribution of these results, rather, the distribution appears random in relation to the position of the cavern in the dome

5.0 SUMMARY

Unfortunately, at this time, based on the information available on the West Hackberry caverns, there are few cavern geometry or solutioning history comparisons that lead to unequivocal conclusions or to the ability to arrive at predictive mechanisms for variation of geometric configurations, propensity for salt falls, or material response. Undoubtedly, there are many factors that could influence the cavern behavior, but none are sufficiently dominant to stand out in West Hackberry. Perhaps, the collective observations of the three caverns initially compared at the beginning of this report might be instructive. In order from worst to best visual appearance of the cavern geometry and surface, the caverns are:

- WH108 --- Location at the southeastern periphery of the SPR facility.
Direct solutioning, aggressive flow rate, large quantity of salt removed.
1st Rev.Roof solutioning, average flow rate and quantity of salt removed.
2nd Reverse solutioning, below average flow rate, large salt removal amount.
Extremely tough cavern surface, especially in top $\frac{3}{4}$ of cavern.
Many potential sites for salt spall formation, and potential salt falls.
Two salt falls that caused casing loss of 860 and 143 ft.
Cavern creep volume loss of 0.12 % per year, roughly average of caverns.
Calculated solid insolubles 4.11 %, roughly average of caverns.
- WH112 --- Located at the southeastern periphery of the SPR facility.
Direct solutioning, below average flow rate and salt removal quantity.
1st Rev.Roof solutioning, very high flow rate, below average salt removal.
2nd Reverse solutioning, average flow rate, below average salt removal.
Smooth lower $\frac{3}{4}$ of cavern, top $\frac{1}{4}$ very rough.
Potential sites for salt spall formation, and for potential salt falls.
No salt falls.
Cavern creep volume loss of 0.13 % per year, roughly average of caverns.
Calculated solid insolubles 4.18 %, roughly average of caverns
- WH116 --- Located at the farthest northwestern periphery of the SPR facility.
Direct solutioning, below average flow rate, average salt removal.
1st Rev.Roof solutioning, low flow rate, average removal amount.
2nd Reverse solutioning, average flow rate and salt removal quantity.
Entire cavern smooth.
No potential sites for spall formation and for potential salt falls.
No salt falls.
Cavern creep volume loss of 0.2 % per year, relatively high rate.
Calculated solid insolubles 2.34 %, well below average of caverns.

It may be of interest to include in this list Cavern WH103, the cavern with the most recorded casing damage events. This cavern has a bulbous top, rather narrowly confined to the top $\frac{1}{8}$, with many solution features contained in this region. Appendix A contains the graphical representation of WH103.

- WH103 --- Located near the center of the SPR facility.
Direct solutioning, slightly below average flow rate and salt removal.

1st Rev. Roof solutioning, below average flow rate, average salt removal.
2nd Reverse solutioning, below average flow rate, very low removal amount.
3rd Reverse solutioning, very low flow rate, moderate removal amount.
Top ¼ of cavern bulbous and rough, lower ¾ of cavern smooth.
Many potential sites for spall formation at top of cavern.
Four salt falls, casing damage at 4433 ft., casing loss of 188, 476, and 161 ft.
Cavern creep volume loss of 0.11 % per year, average rate.
Calculated solid insolubles 5.38 %, higher end of insolubles range.

While one may argue that the aggressive solutioning tends to produce the rough cavern surfaces that favor the formation of salt spalls and hence salt falls, the construction history of WH103, with the greatest number of events, counters this argument. WH103 solutioning practice was moderate in every respect. Even with such moderate solutioning practice the final cavern geometry included marked preferential solutioning features. Thus, it appears any solutioning rate can produce irregular features in a portion of the cavern as governed by the positioning of the intake/outlet tubing. Subsequent solutioning using either reverse flow or repositioning of the intake/outlet tubing locations can ameliorate the irregular features, or leave them intact, depending upon the extent of the subsequent solutioning. In some instances, it seems the subsequent solutioning produced smooth cavern surfaces over the lower portion of the cavern while leaving the top of the cavern irregular. Overall, there appeared to be no boundary set of flow rate or salt removal conditions that undoubtedly produced irregular cavern features. Rather, any set of construction conditions seemed capable of producing these features. Perhaps such irregular features could be blended away by subsequent solutioning, perhaps not.

While the flow rate and salt removal quantity seem important to the potential for development of sites for spall formation, these factors seem actually rather insignificant. The principal factor appears to be the marked homogeneity of the salt dome. Even though some cavern surfaces are undoubtedly subject to solution pits and protuberances, the West Hackberry caverns retain a general cylindrical character. For example, there are no marked directional dissolution features, such as wings, which were frequent in the Big Hill caverns. Furthermore, there were no pronounced lineaments found in the West Hackberry caverns, such as were found in the Big Hill caverns.

The mechanical or creep response, even though some variation of the material behavior over the dome is apparent, does not appear to be a factor in the geometry or features of the West Hackberry caverns.

Another interesting aspect is that the cavern geometry is not greatly affected by the location of the caverns within the facility area, even though the extent of the facility is considerable.

One aspect of the West Hackberry caverns seems clear. The generally well defined cavern cylindrical geometry, while certainly a product of the homogeneous salt matrix, is greatly aided by the well defined solutioning procedures utilized in cavern construction. This is undoubtedly even further improved by the single well design of the caverns, which in itself is inherently cylindrically symmetrical.

In general summary, the West Hackberry caverns are remarkably similar. These caverns are remarkable in that they retain a marked degree of cylindrical symmetry, even when the surface features are rough. The rather uniform behavior during construction occurs regardless of the number of potential factors, either inherent to the salt dome or to the construction practices, that one would suppose should influencing their development.

If any recommendation with respect to cavern shape could be inferred, it would be that the design of caverns should be of the single well type, with perhaps leaching plans based on West Hackberry construction conditions.

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APPENDIX A

THREE DIMENSIONAL REPRESENTATIONS OF WEST HACKBERRY 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 sonar surveys available at the time of the preparation of the West Hackberry database [6]. The graphics program used to create these representations was the Mining Visualization System (MVS) software. 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. Consequently, some of the cross-sections will not appear for caverns of limited height.

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

- (1) The cavern number is actually the well number, which except for the two well Cavern 117, is identical to the cavern number. For Cavern 117, a large letter designation indicates the well through which the sonar surveys were obtained. For Cavern 116, the small letter designation is for the second of two closely timed sonar surveys.
- (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 “solid” 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.

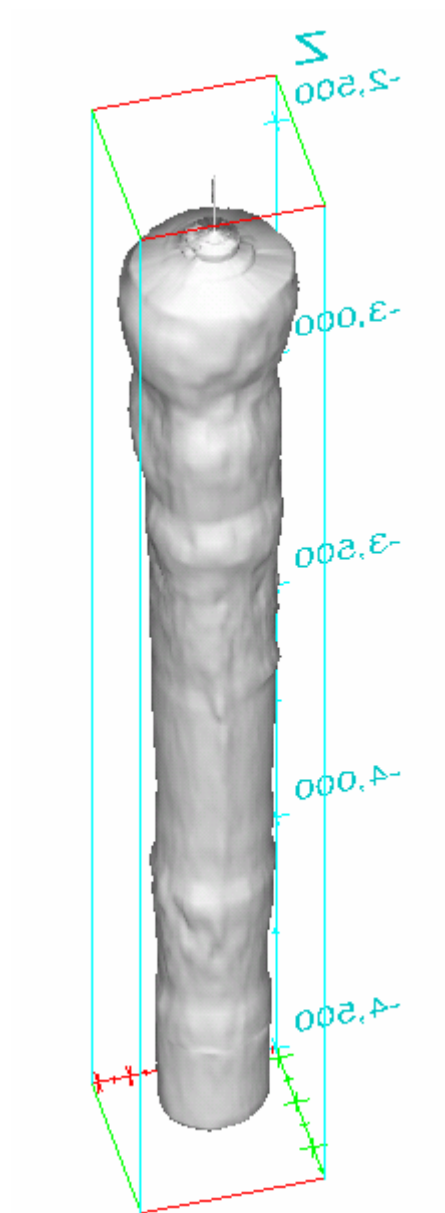


Fig. 1a-A. WH101-15°cw-45°, Solid.

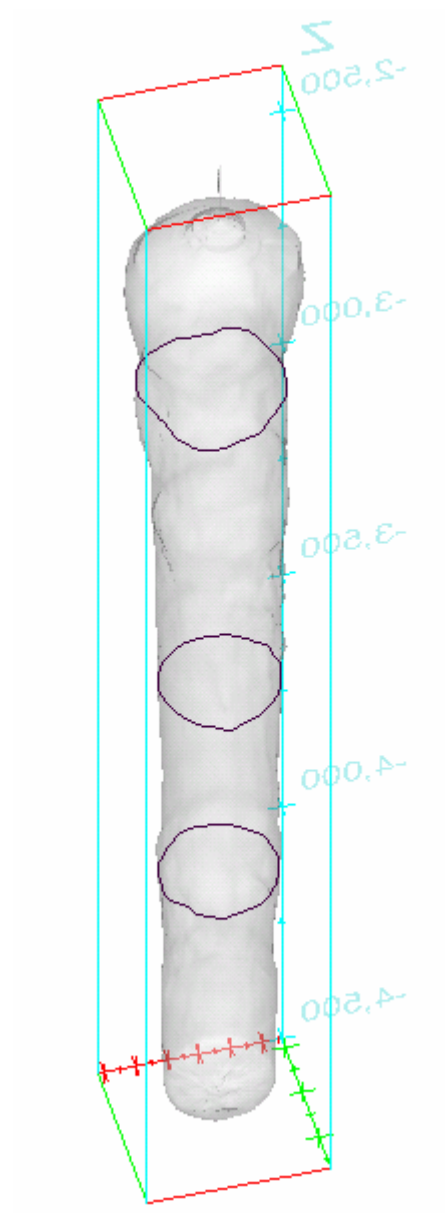


Fig. 1b-A. WH101-15°cw-45°, Sections.

Construction completed December 28, 1983, after 2nd Reverse leaching stage.
Sonar of January 16, 2000.

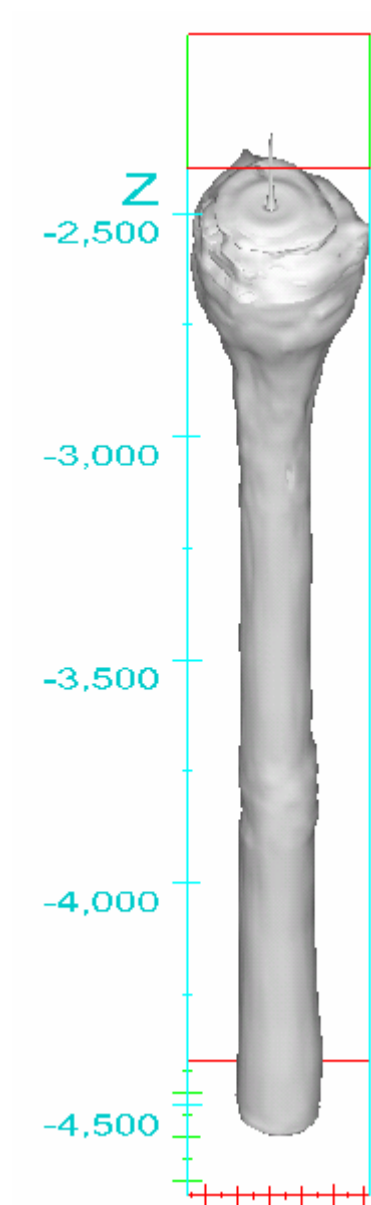


Fig. 2a-A. WH102-180cw-45°, Solid.

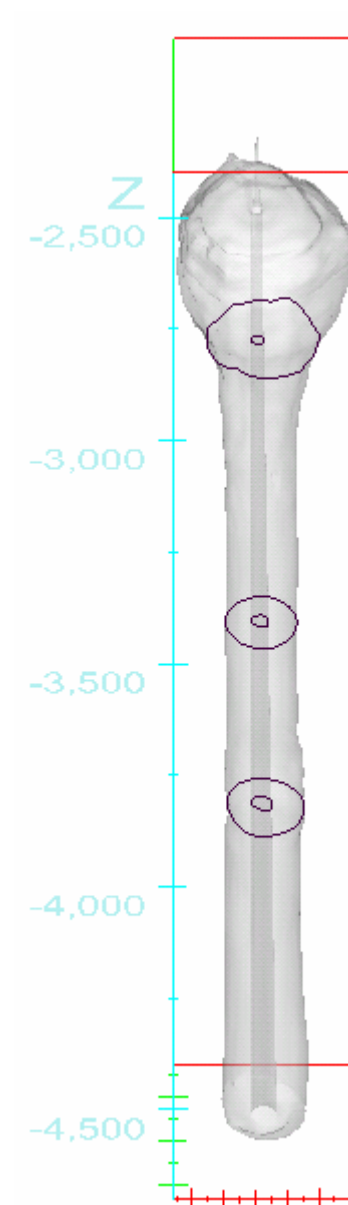


Fig. 2b-A. WH102-180cw-45°, Sections.

Construction completed November 8, 1984, after 2nd Reverse leaching stage.
 Sonar of August 22, 1983, after the 1st Reverse roof development leaching stage.
 No completed cavern or more recent sonar surveys were available.

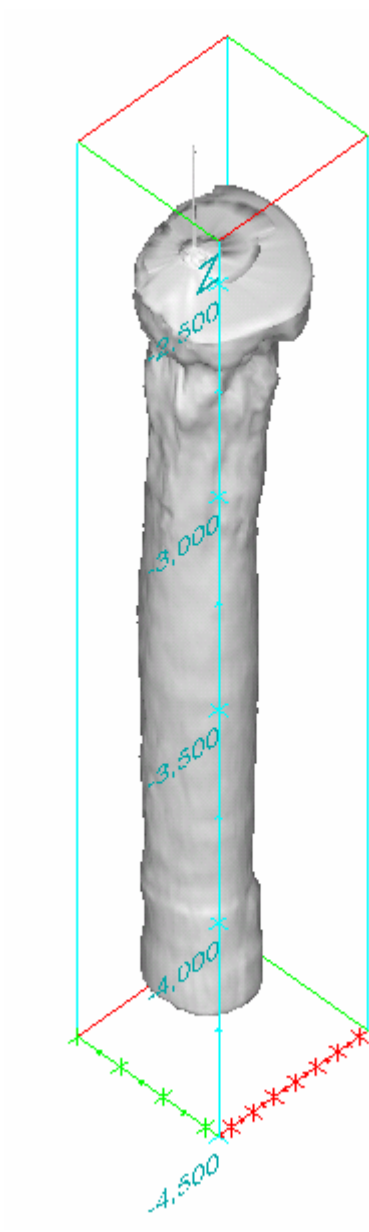


Fig. 3a-A. WH103-225°cw-45°, Solid.

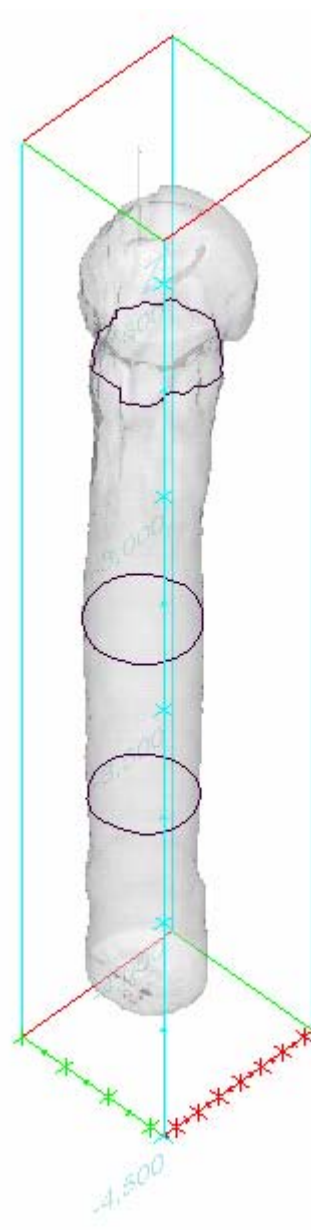


Fig. 3b-A. WH103-225°cw-45°, Sections.

Construction completed January 14, 1984, after 3rd Reverse leaching stage.
 Sonar of August 27, 2000.

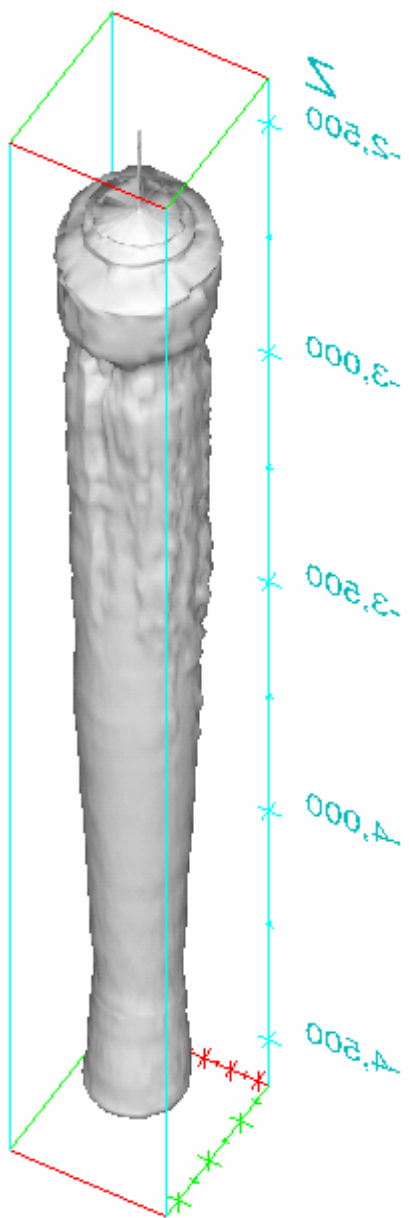


Fig. 4a-A. WH104-330°cw-45°, Solid.

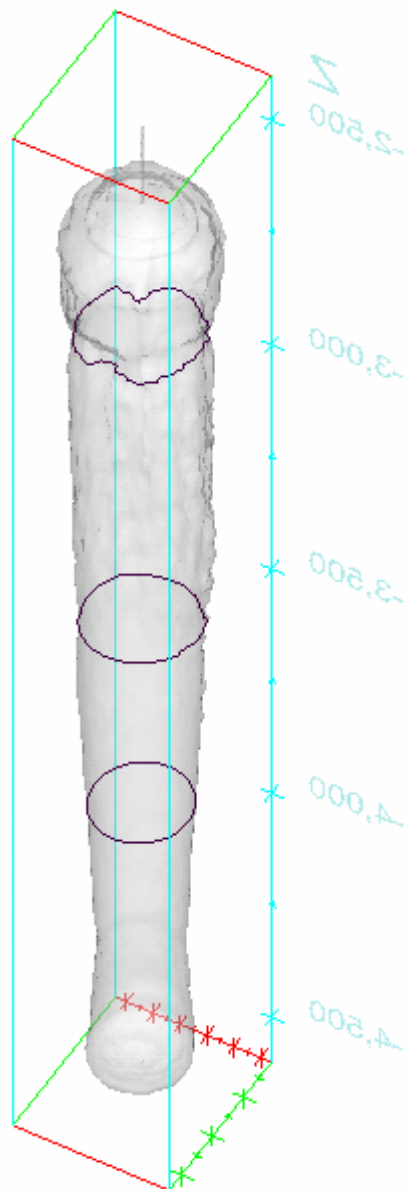


Fig. 4b-A. WH104-330°cw-45°, Sections.

Construction completed February 27, 1984, after 3rd Reverse leaching stage.
Sonar of July 11, 2000.

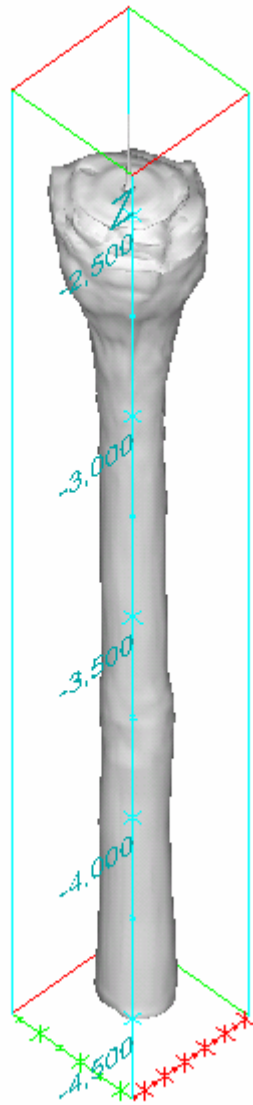


Fig. 5a-A. WH105-225°cw-45°, Solid.

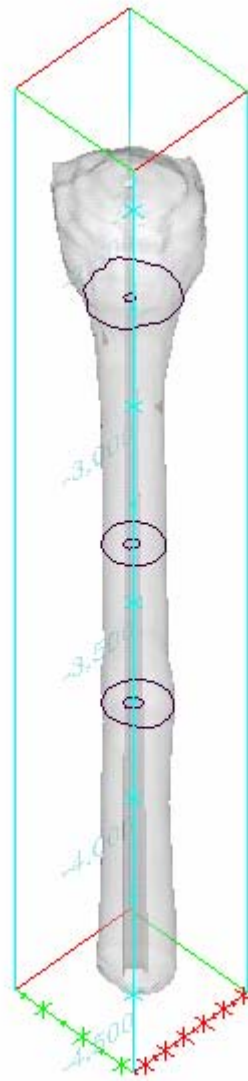


Fig. 5b-A. WH105-225°cw-45°, Sections.

Construction completed January 15, 1984, after 3rd Reverse leaching stage.
 Sonar of August 2, 2000.

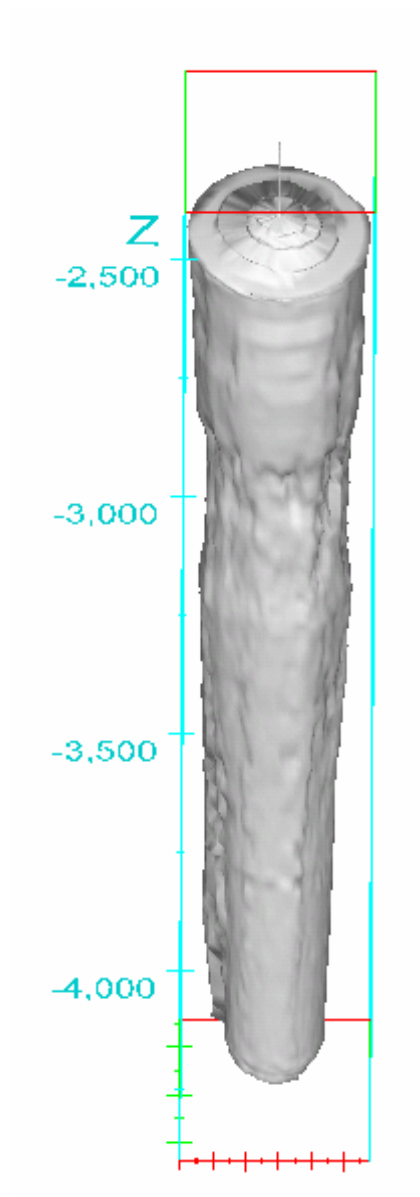


Fig. 6a-A. WH106-180°cw-45°, Solid.

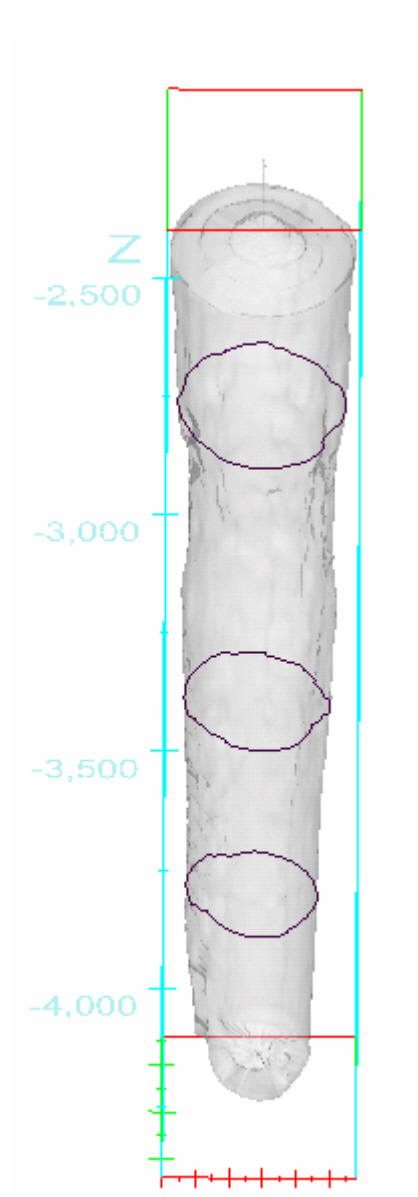


Fig. 6b-A.WH106-180°cw-45°, Sections.

Construction completed November 2, 1987, after 2nd Reverse leaching stage.
 Sonar of June 28, 2000.

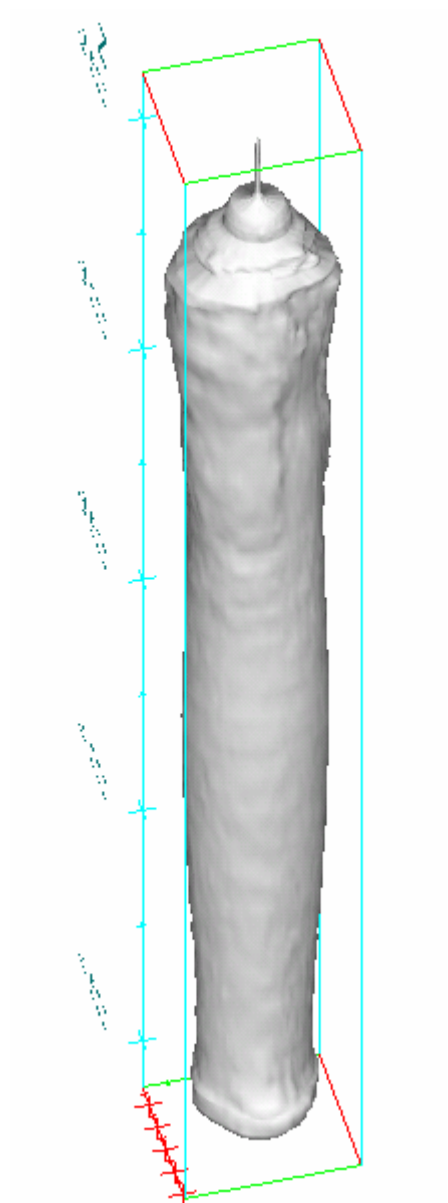


Fig. 7a-A. WH107-105°cw-45°, Solid.

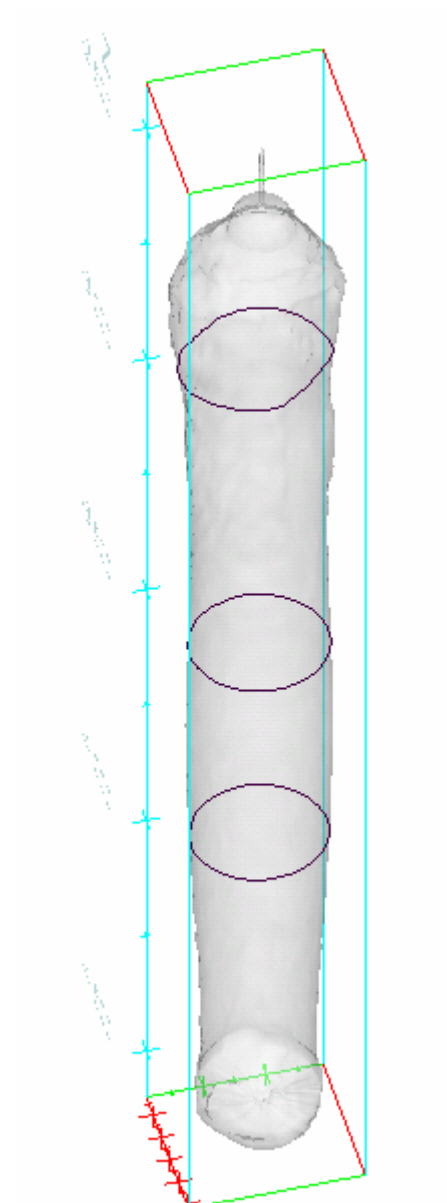


Fig. 7b-A. WH107-105°cw-45°, Sections.

Construction completed July 6, 1984, after 2nd Reverse leaching stage.
Sonar of November 26, 1999.

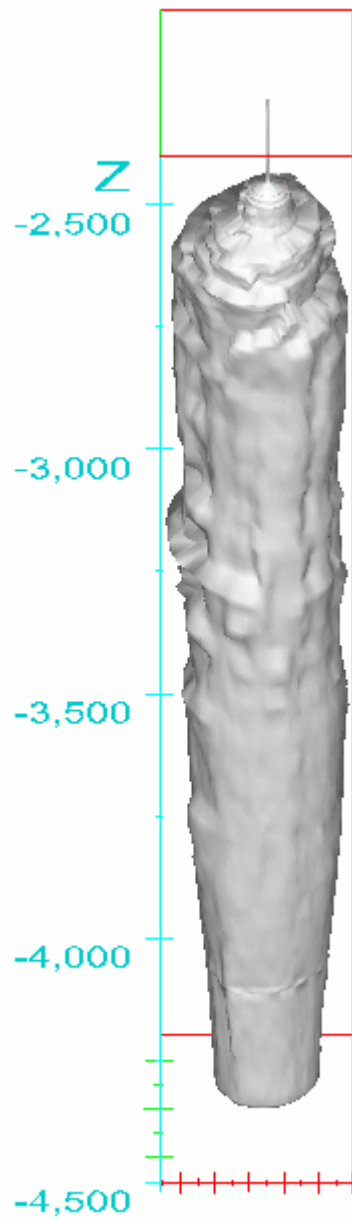


Fig. 8a-A. WH108-180°cw-45°, Solid.

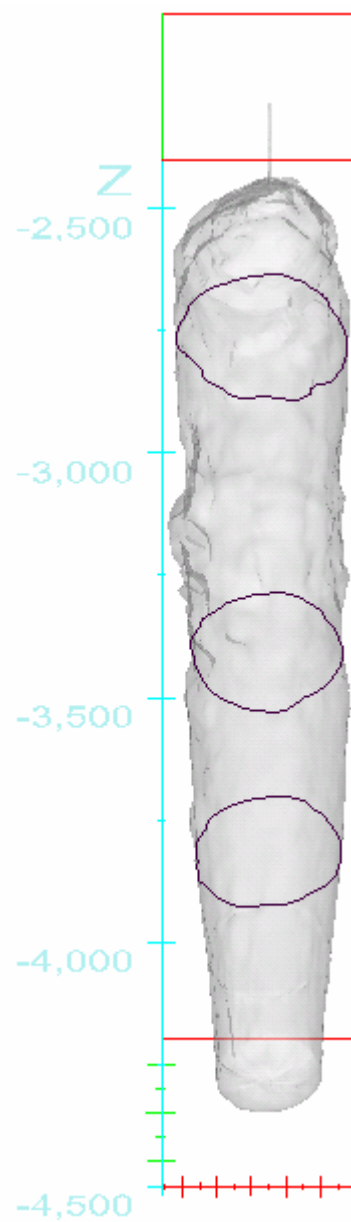


Fig. 8b-A. WH108-180°cw-45°, Sections.

Construction completed November 22, 1983, after 2nd Reverse leaching stage.
 Sonar of April 22, 2003.

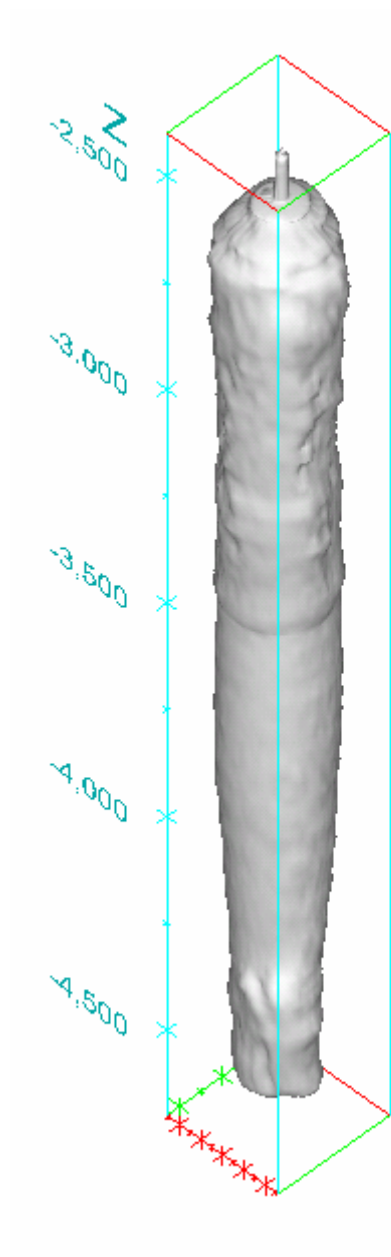


Fig. 9a-A. WH109-135°cw-45°, Solid.

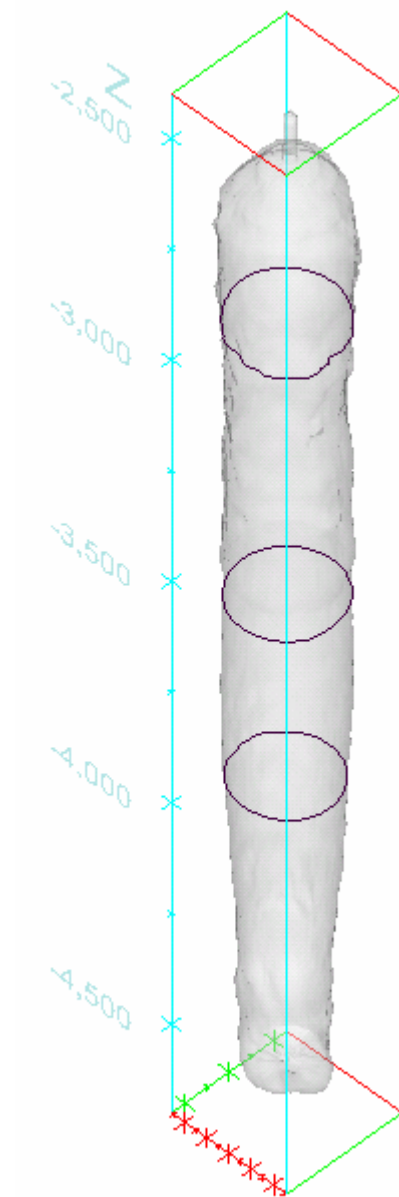


Fig. 9b-A. WH109-135°cw-45°, Sections.

Construction completed September 9, 1987, after 2nd Reverse leaching stage.
 Sonar of March 14, 1997.

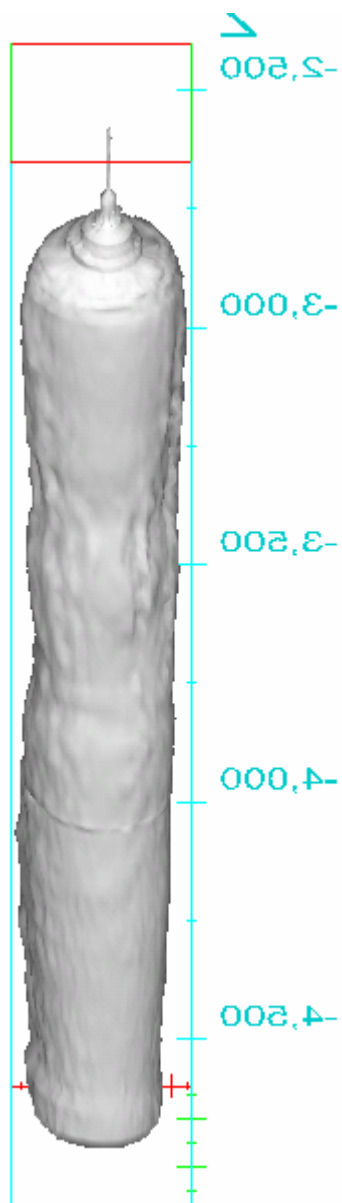


Fig. 10a-A. WH110-0°North-45°, Solid.

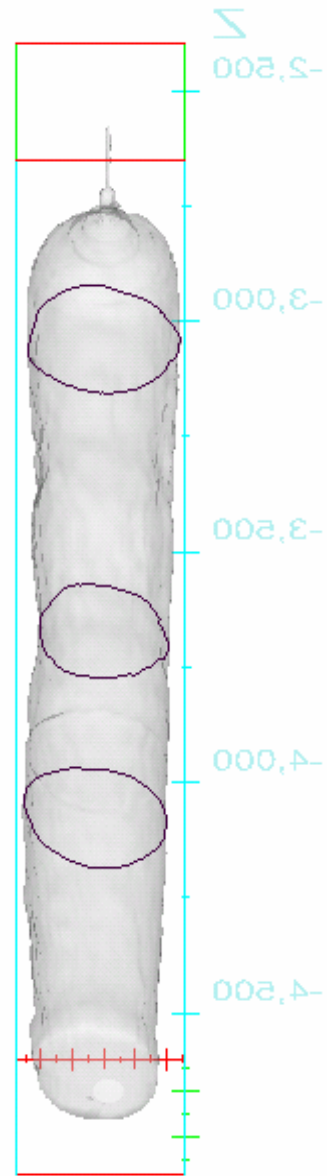


Fig. 10b-A. WH110-0°North-45°, Sections.

Construction completed March 15, 1985, after 2nd Reverse leaching stage.
 Sonar of May 19, 2003.

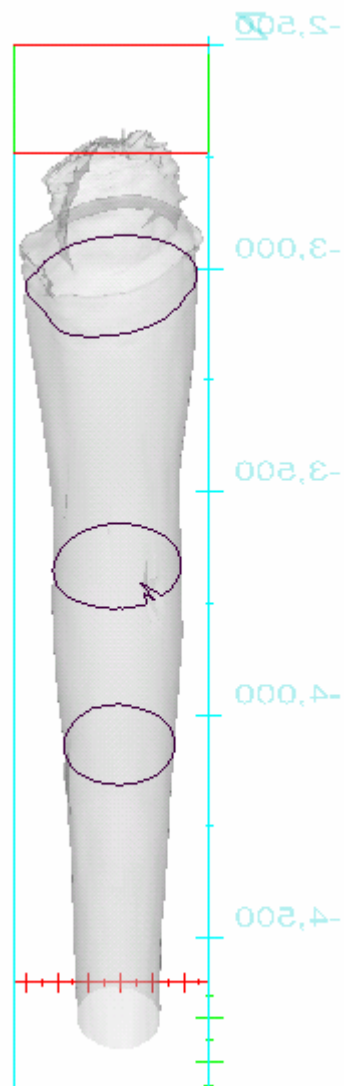
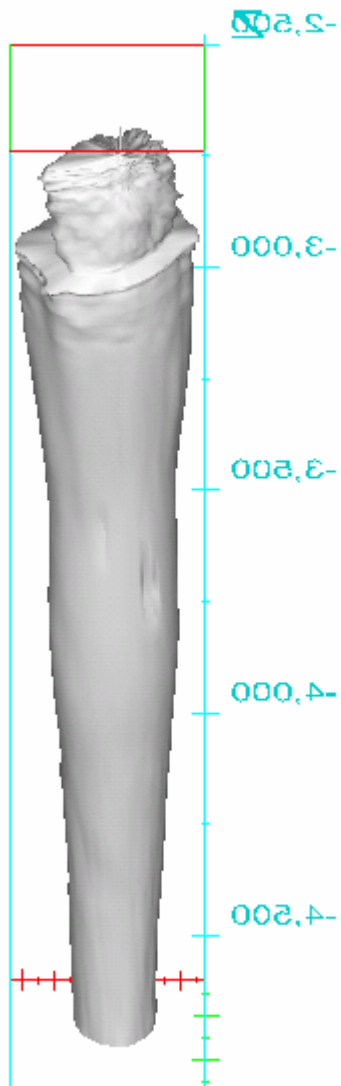


Fig. 11a-A. WH111-0°North-45°, Solid.

Fig. 11b-A. WH111-0°North-45°, Sections.

Construction completed April 1, 1988, after 2nd Reverse leaching stage.
 Sonar of October 4, 1988.
 No recent sonar surveys were available.

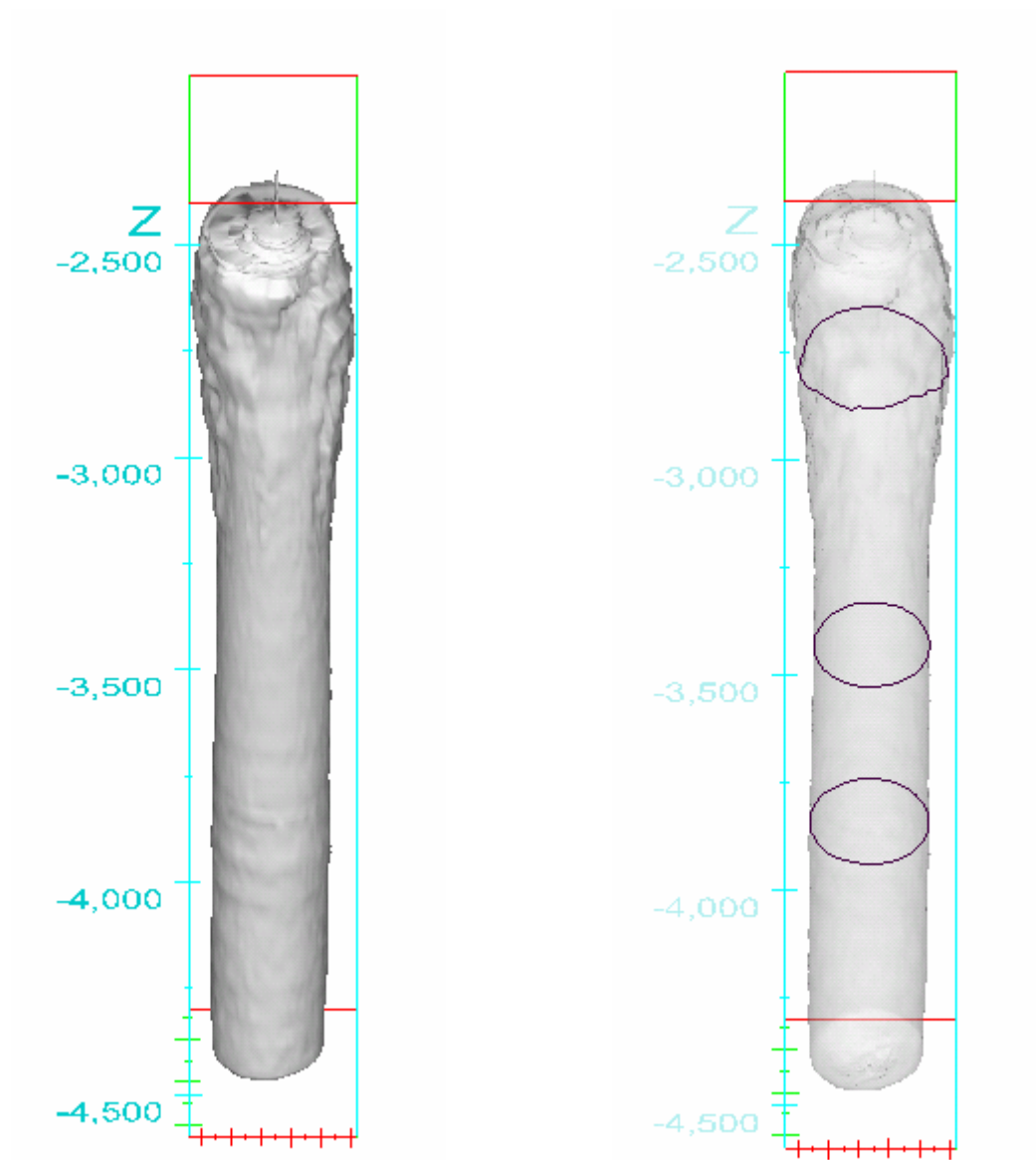


Fig. 12a-A. WH112-180°cw-45°, Solid.

Fig. 12b-A. WH112-180°cw-45°, Sections.

Construction completed January 3, 1987, after 2nd Reverse leaching stage.
Sonar of August 15, 2000.

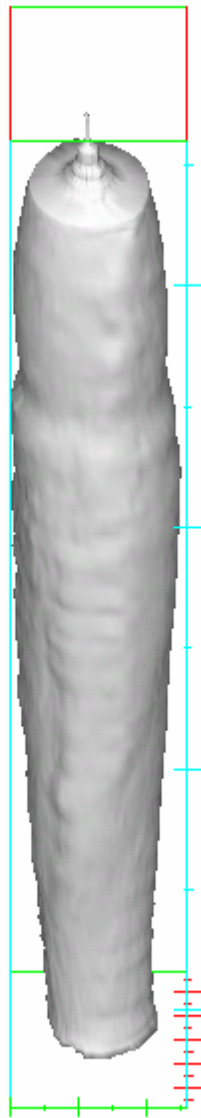


Fig. 13a-A. WH113-270°cw-45°, Solid.

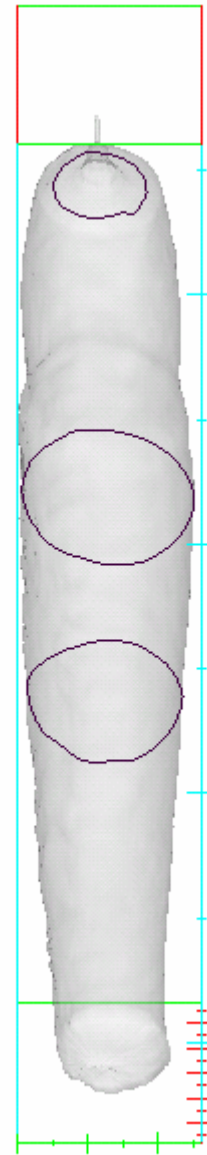


Fig. 13b-A. WH113-270°cw-45°, Sections.

Construction completed June 10, 1985, after 2nd Reverse leaching stage.
Sonar of November 4, 2000.

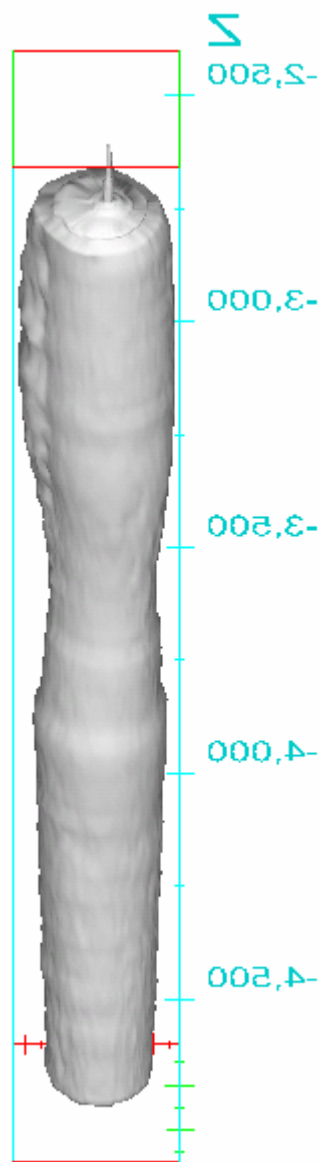


Fig. 14a-A. WH114-0°North-45°, Solid.

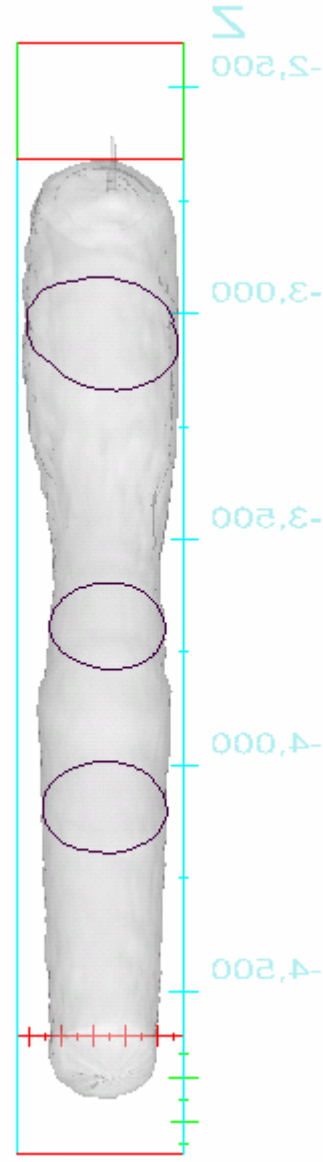


Fig. 14b-A. WH114-0°North-45°, Sections.

Construction completed September 5, 1985, after 2nd Reverse leaching stage.
 Sonar of November 14, 2000.

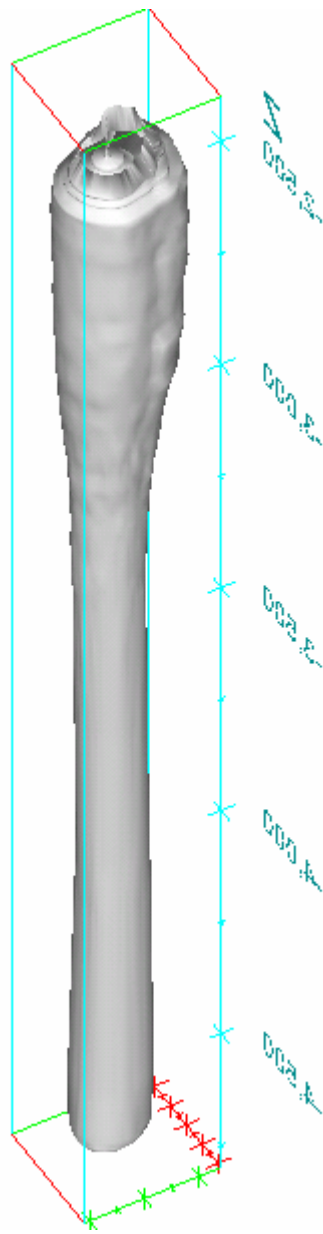


Fig. 15a-A. WH115-300°cw-45°, Solid.

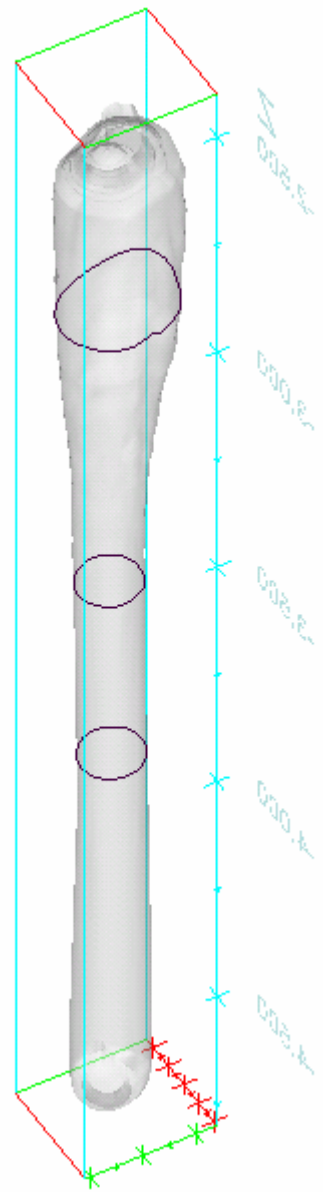


Fig. 15b-A. WH115-300°cw-45°, Sections.

Construction completed May 30, 1987, after 2nd Reverse leaching stage.
 Sonar of October 24, 1985, after the 1st Reverse roof development leaching stage.
 No completed cavern or more recent sonar surveys were available.

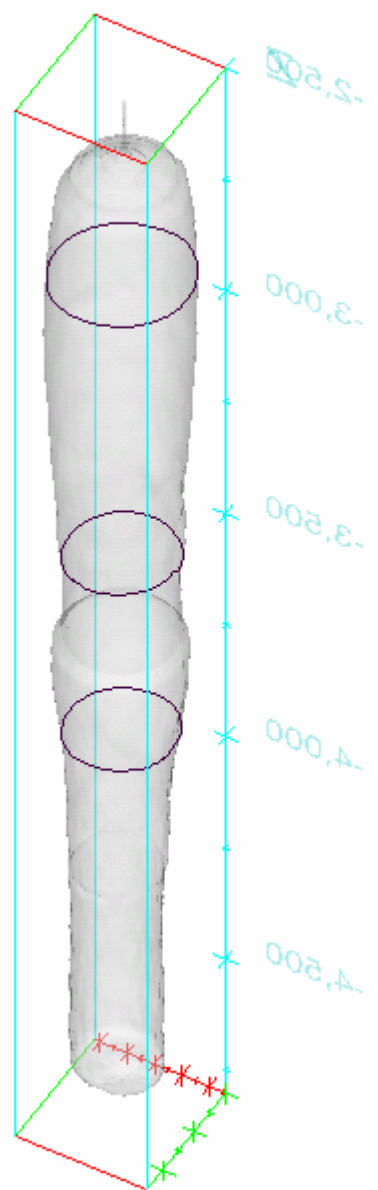
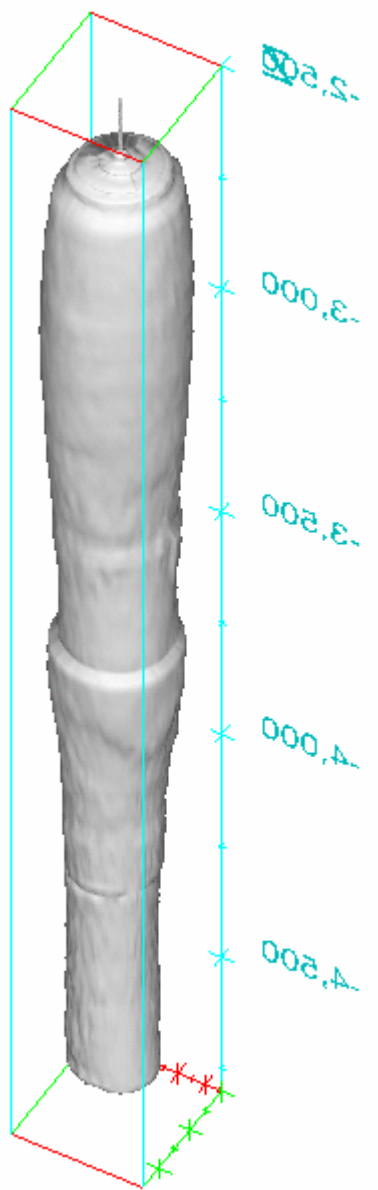


Fig. 16a-A. WH116b-330°cw-45°, Solid. Fig. 16b-A. WH116b-330°cw-45°, Sections.

Construction completed September 4, 1985, after 2nd Reverse leaching stage.
 Sonar of April 22, 2000, labeled "b" the second of two closely timed surveys.

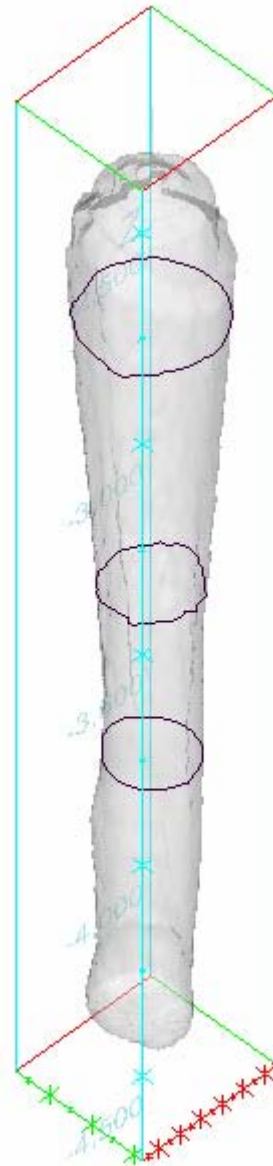
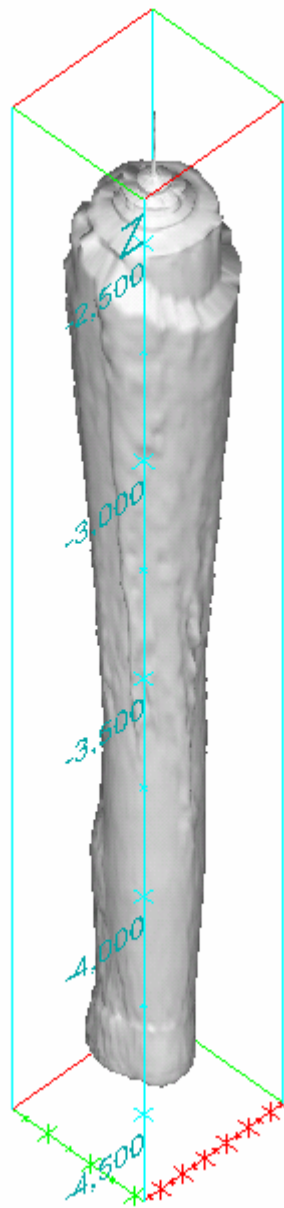


Fig. 17a-A. WH117A-225°cw-45°, Solid. Fig. 17b-A. WH117A-225°cw-45°, Sections.

Construction completed October 30, 1988, after 2nd Reverse leaching stage.
 Sonar of March 29, 2004, obtained through Well B.

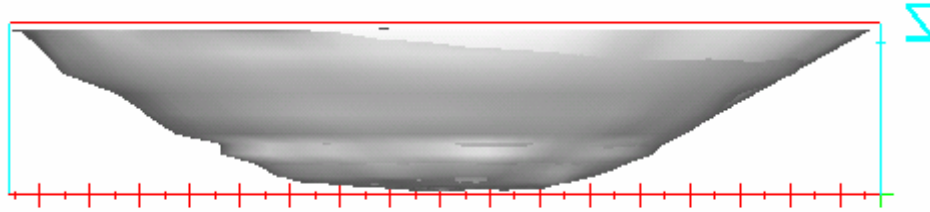


Fig. 06-A. WH6-0°North, Solid.

Purchased commercial cavern, construction completion date unknown.
Sonar of August 12, 1982.

Cavern WH6, which resembles a bowl, is at a depth of about 3249 ft. below ground surface, is only about 141 ft. in height, but has a roof diameter, which is difficult to measure, of perhaps as much as 700 ft. This large roof span is of concern because of the potential for failure and collapse.

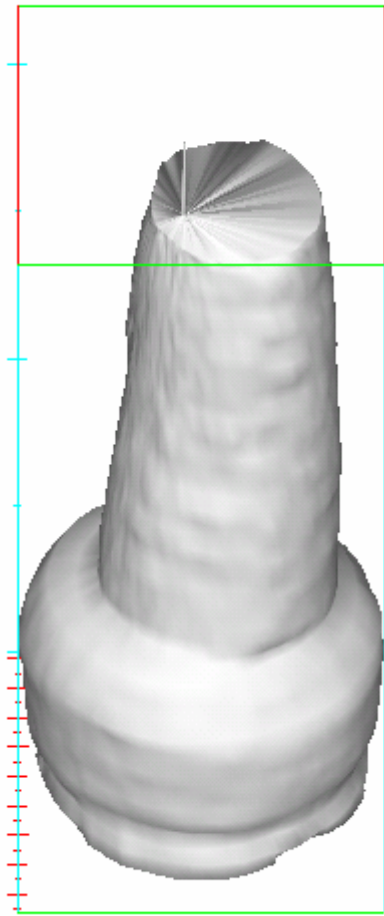


Fig. 07a-A. WH7B-90°cw-45°, Solid.

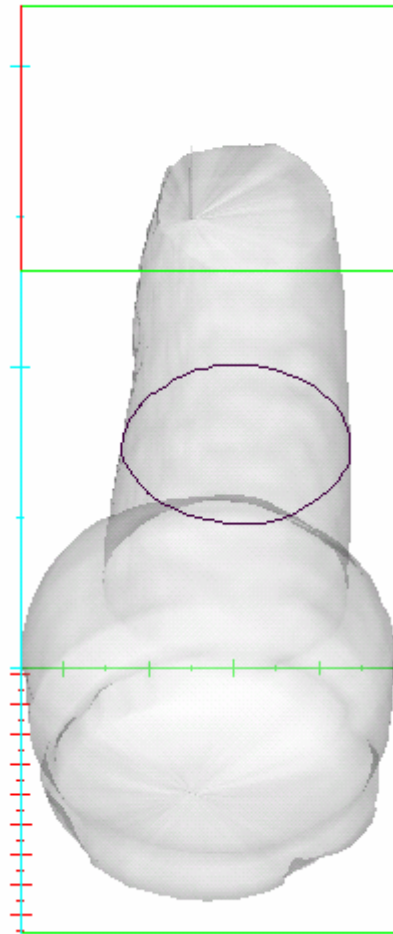


Fig. 07b-A. WH7B-90°cw-45°, Section.

Purchased commercial cavern, construction completion date unknown.
Sonar of May 7, 1999.

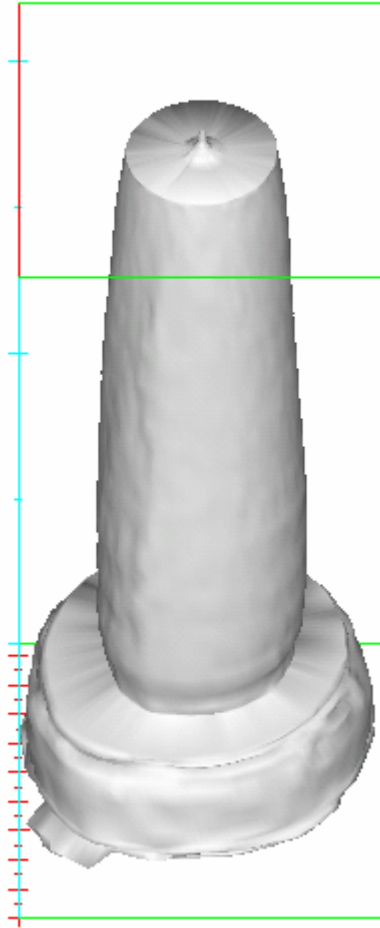


Fig. 08a-A. WH8-90°cw-45°, Solid.

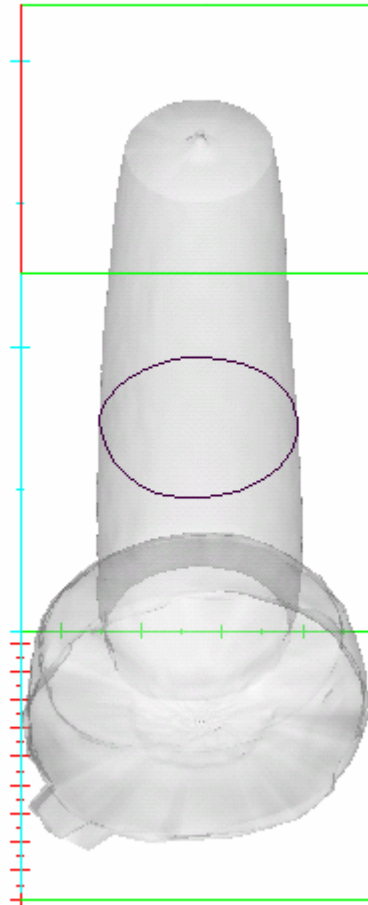


Fig. 08b-A. WH8-90°cw-45°, Section.

Purchased commercial cavern, construction completion date unknown.
Sonar of September 11, 2003.

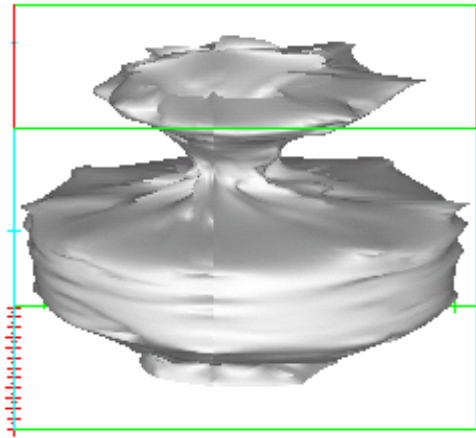


Fig. 09a-A. WH9-90°cw-15°, Solid.

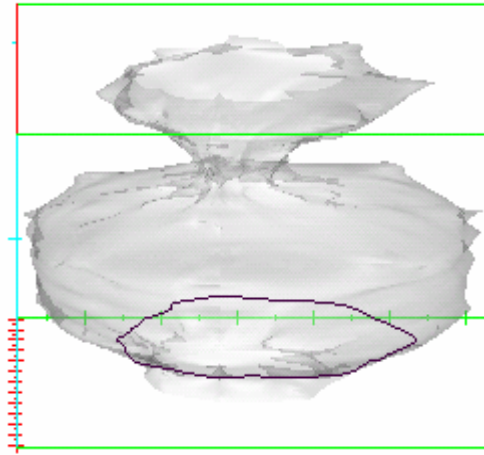


Fig. 09b-A. WH9-90°cw-15°, Section.

Purchased commercial cavern, construction completion date unknown.
Sonar of May 26, 1977.

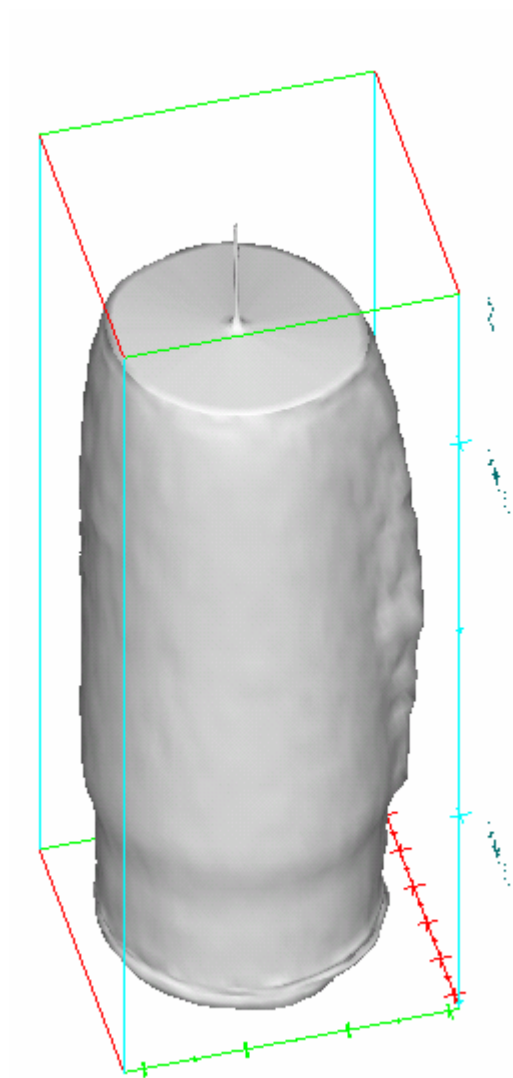


Fig. 011a-A. WH11-285°cw-45°, Solid.

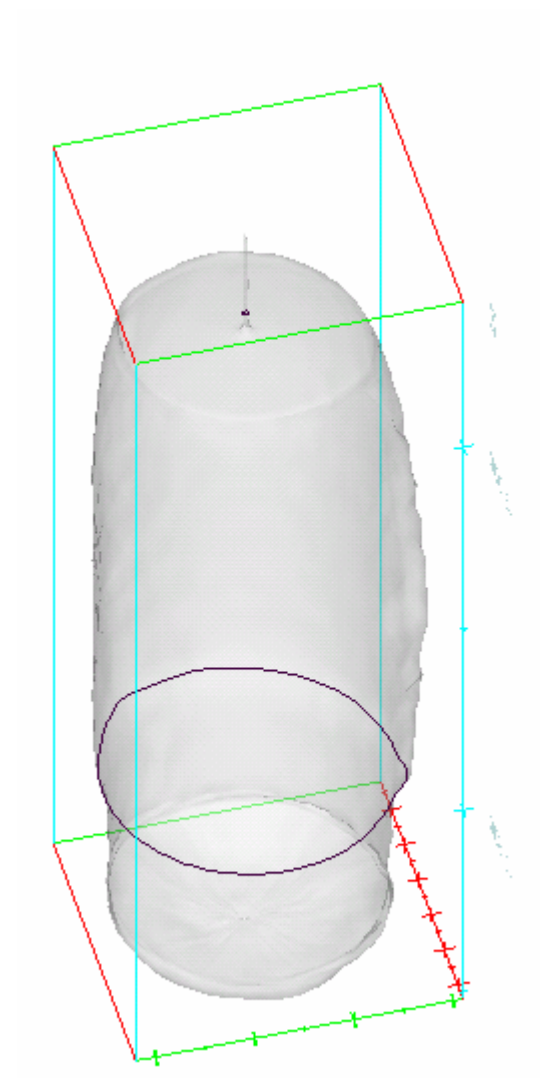


Fig. 011b-A. WH11-285°cw-45°, Section.

Purchased commercial cavern, construction completion date unknown.
Sonar of May 28, 2003.

APPENDIX B

WEST HACKBERRY SOLUTIONING TABLE

Table I-B. West Hackberry Leaching Sequence and Salt Solution Rates.

Cavern No. Start Date	Stage	Depth input ft	Depth output ft	Duration days	Salt Amt. MMb	Salt Sol. Rate bbl/day	Remarks
WH103							
04/81	DirectSp/Ch.	4942	2784	240	2.536	10560	
01/82	1 st Rev.Roof	2784	4652	180	3.027	16820	
09/82	2 nd Reverse	3745	4546	270	2.291	12190	Smooth
07/83- 01/84	3 rd Reverse Completed	4136	4371	180	1.453	8070	Smooth
WH101							
05/81	DirectSp/Ch	4960	2796	180	2.317	12870	
01/82	1 st Rev.Roof	2796	4773	150	2.866	19100	Rough
07/82	2 nd Reverse	4150	4412	300	4.767	15890	Smooth
08/83- 12/81	3 rd Reverse Completed	4150	4412	120	1.240	10330	Smooth
WH104							
05/81	DirectSp/Ch.	4989	2848	150	2.431	16230	
12/81	1 st Rev.Roof	2807	4785	180	3.346	18590	Bulbous
10/82	2 nd Reverse	3735	4621	300	3.313	11040	Smooth
09/83- 02/84	3 rd Reverse Completed	4147	4527	150	2.271	15140	(Foot)
WH105							
06/81	DirectSp/Ch.	4955	2824	150	2.260	15060	
03/82	1 st Rev.Roof	2824	4744	210	2.630	12520	Bulbous
11/82	2 nd Reverse	3749	4630	240	4.196	17480	Smooth
08/83- 01/84	3 rd Reverse Completed	4117	4528	150	2.292	15280	Smooth
WH107							
07/81	DirectSp/Ch.	4920	2840	300	3.764	12540	
10/82	1 st Rev.Roof	2997	4657	150	2.997	19980	Rough
06/83- 07/84	2 nd Reverse Completed	3947	4540	390	4.739	12150	Smooth
WH111							
01/82	DirectSp/Ch.	4949	2890	390	2.560	6560	
08/84	1 st Rev.Roof	3009	4664	120?	1.669	13910	Rough
04/87- 04/88	2 nd Reverse Completed	3950	4611	360?	6.357	17650	Smooth

Table 1-B (Continued). West Hackberry Leaching Sequence and Salt Solution Rates.

Cavern No. Start Date	Stage	Depth		Duration days	Salt Amt. MMb	Salt Sol. Rate bbl/day	Remarks
		input ft	output ft				
WH102							
02/82	DirectSp/Ch.	4981	2808	210	3.066	14600	
12/82	1 st Rev.Roof	2810	4655	120	3.357	27970	Rough
08/83- 11/84	2 nd Reverse Completed	3950	4555	390	4.671	11980	Smooth
WH108*							
02/82	DirectSp/Ch.	4817	2777	210	3.795	13310	
11/82	1 st Rev.Roof	3001	4701	150	2.774	18490	Rough
05/83- 12/84	2 nd Reverse Completed	3892	4573	570	5.970	10470	Rough
WH110							
02/82	DirectSp/Ch.	4954	2790	270	2.901	10740	
04/83	1 st Rev.Roof	3003	4726	180	3.138	17430	Rough
11/83- 03/85	2 nd Reverse Completed	3956	4575	480	4.830	10070	Rough
WH113							
07/82	DirectSp/Ch.	5002	3139	270	2.734	10120	
05/83	1 st Rev.Roof	3333	4810	180	3.029	16830	Smooth
03/84- 06/85	2 nd Reverse Completed	4105	4733	450	6.082	13520	Smooth
WH116							
07/82	DirectSp/Ch.	4972	2970	300	2.802	9340	
06/83	1 st Rev.Roof	3094	4790	240	2.907	12360	Smooth
08/84- 09/85	2 nd Reverse Completed	3953	4730	390	5.507	14120	Smooth
WH114							
10/82	DirectSp/Ch.	4958	2799	390	2.873	7360	
01/84	1 st Rev.Roof	3004	4675	240	3.677	15320	Rough
10/84- 09/85	2 nd Reverse Completed	3950	4542	330	4.774	14460	Smooth
WH112							
11/83	DirectSp/Ch.	4942	2865	360	3.053	8480	
12/84	1 st Rev.Roof	2903	4659	150?	3.830	25530	Rough
06/85- 01/87	2 nd Reverse Completed	3950	4459	330	4.435	13440	Smooth
WH106							
01/84	DirectSp/Ch.	4887	2624	330	1.455	4140	
02/85	1 st Rev.Roof	2904	4562	180	5.155	28630	Rough
10/85- 11/87	2 nd Reverse Completed	3956	4395	450	5.610	12460	Rough

Table 1-B (Continued). West Hackberry Leaching Sequence and Salt Solution Rates.

Cavern No.	Stage	Depth		Duration	Salt	Salt Sol.	Remarks
Start Date		input	output	days	Amt.	Rate	
		ft	ft		MMb	bbl/day	
WH115							
02/84	DirectSp/Ch.	4938	2590	300	2.688	8960	
02/85	1 st Rev.Roof	2999	4735	210	4.410	21000	Rough
11/85-	2 nd Reverse	3951	4625	330	4.745	14370	Smooth
05/87	Completed						
WH109							
03/84	DirectSp/Ch.	4847	2625	240	2.905	12100	
05/85	1 st Rev.Roof	2998	4659	180	3.324	18460	Rough
12/85-	2 nd Reverse	3954	4613	420	5.758	13710	Smooth
09/87	Completed						
WH117A [#]							
06/85	DirectSump	4957B ⁷	4679B	90	0.320	3550	(Foot)
11/85	DirectChmy	4845B	2990A	120	2.560	21330	Rough
11/86	1 st Rev.Roof	4158B	2990A	150	1.344	8960	Rough
08/87-	2 nd Reverse	4617B	3305A	360	8.444	23450	Rough
10/88	Completed						

Note: The caverns are in order of their start dates. WH105, the 4th in order of start date is the last single well cavern to have four solution stages. WH117 is the only two well cavern constructed at West Hackberry and the 4957B⁷ notation indicates the direct sump stage used the B well as input through the 7 inch inner tubing with the output through the 10 ¾ inch outer tubing of the same well. Subsequent stages in WH117 used the 10 ¾ inch tubing in the B well as input and the 10 ¾ inch tubing in the A well as the output.

APPENDIX C

WEST HACKBERRY MISCELLANEOUS DATA

Table I-C. West Hackberry Site Hanging String Events (Modified [18, 19]).

No. (Wells)	Typ.	Start-End (years)	Depth to		Cavern		Casing Failure				Notes
			Salt (ft.)	Roof (ft.)	Height (ft.)	Diam. (ft.)	No.	Date	Loss (ft.)	Depth (ft.)	
WH 6	(3)	Sour46(78)	1300	3249	141	662					
WH 7	(3)	Swt46(78)	560	2552	942	315					
WH 8	(1)	Sour46(78)	415	2450	999	272					
WH 9	(3)	Sour47(78)	1113	3213	342	454					
WH 11	(3)	Sour62(78)	866	2951	804	276					
WH 101	(1)	Swt81-83	505	2555	1885	206					
WH 102	(1)	Swt82-83	565	2628	1870	206	102*	09/95	Damg.	4433	D UC
WH 103	(1)	Swt81-84	629	2667	1756	205	103*'	07/82	188	4215	BL UC
							103*	05/95	476	3927	PL UC
							103*+	05/97	161	4242	L UC
							103	09/00	Damg.	3481	
WH 104	(1)	Swt81-84	549	2625	1921	206					
WH 105	(1)	Swt81-84	582	2640	1969	204					
WH 106	(1)	Sour84-87	491	2556	1790	212					
WH 107	(1)	Swt81-84	527	2585	1971	204	107*'	11/82	300	4234	BL PC
WH 108	(1)	Swt82-84	543	2596	1844	212	108*	05/94	860	3573	PL UC
							108*	09/94	143	4290	L UC
<u>WH 109</u>	(1)	Sour84-87	526	2583	2061	204	109*	10/93	40	4573	D UC
							109**	12/96	217	4396	D L R
WH 110	(1)	Swt82-85	495	2567	2001	200	110*+	03/96	Damg.	4425	PWUC
							110	05/03	Damg.		
WH 111	(1)	Sour82-88	937	2622	1974	196					
<u>WH 112</u>	(1)	Sour83-87	512	2562	1970	203					
WH 113	(1)	Swt82-85	714	2827	1865	216	113	11/92	40	4630	D UC
							113	11/00	Damg.		
<u>WH 114</u>	(1)	Sour82-85	447	2520	2029	200	114	12/96	Damg.	4396	
							114	07/00	740	3655	
<u>WH 115</u>	(1)	Sour84-87	467	2540	2094	201					
WH 116	(1)	Swt 82-85	552	2640	2078	199					
WH 117	(2)	Sour85-88	509	2560	2049	211					

Underlined = Caverns that participated in the recent 1996 oil sale, partial oil removal using raw water insertion. Order of draw down is 109, 115, 114, and 112.

+ Taken from West Hackberry Weekly Report, December 26, 1996, P. Hetznecker to L. Johnson.

' Boeing Petroleum Services, Inc., DOE SPR Constructed Cavern History, Rev. 2, January 1991.

* New events reported by individual cavern reports, private communication Harry Lombard.

** New events from individual cavern engineers.

B = Brine solutioning

S = Static operation

W = Workover operation

R = Raw water partial fill

P = Depressurization

L = Loss of pipe

D = Damaged pipe

SF = Salt fall

PC = Pipe collapse

UC = Unknown causes

Table II-C. Transient Analysis M-D Model Parameters [from 20].

Specimen	A ₂ (x10 ¹² /s) #		K ₀ (x10 ⁵ /s)		α(T(°C))		Closure (%/yr.)
	-----Factor		-----Factor		-----Factor		
BASELINE	9.672	1.00	6.275	1.00	-17.35(25)	1.00	WIPP Clean Salt
WEST HACKBERRY DOME							
Cavern 6C							
WH1 6C-2243	11.32	1.17	9.777	1.56	-17.37(22)	1.00	(Very Soft)
WH3 6C-2225	11.32	1.17	9.777	1.56	-17.37(22)	1.00	(Very Soft)
WH2 6C-2201	11.32	1.17	9.777	1.56	-17.37(80?)*	1.00	(Very Soft)
WH4 6C-2196	11.32	1.17	9.777	1.56	-17.37(80?)*	1.00	(Very Soft)
Cavern 108							
WH5 108-2267	11.32	1.17	8.512	1.36	-13.37(60)	0.77	0.145 (V. Soft)
			6.275**	1.00	-9.37(80)	0.54	
WH6 108-3652	11.32	1.17	8.512	1.36	-13.37(60)	0.77	0.145 (V. Soft)
			6.275**	1.00	-9.37(80)	0.54	

Table III-C. West Hackberry Insoluble Contents from Leaching Stages [Modified 11].

Cav. No.	Stage	Apparent Insoluble Content*			Calc. Solid %	Remarks
		Stage %	Vol. (MMb)	Tot. %	Tot. % x 0.55	
WH101	1	08.50	4.8	08.50	04.68	
WH102	1	10.33	2.9	10.33	05.68	
WH103	1	10.78	1.9			
	2	09.35	4.5	09.77	05.38	
WH104	1	08.99	1.6			
	2	06.19	4.1	06.98	03.84	
WH105	1	03.24	2.3			
	2	05.73	4.2	04.85	02.67	
WH106						No Data
WH107	1	09.74	3.0	09.74	05.36	
WH108	1	08.53	2.5			
	2	06.59	3.0	07.47	04.11	
WH109						No Data
WH110						No Data
WH111	1	05.39	6.5			
	2	06.88	1.3	05.64	03.10	
WH112	1	06.46	3.8			
	2	09.35	2.5	07.61	04.18	
WH113	1	07.70	6.1	07.70	04.24	
WH114	1	06.39	4.7	06.39	03.51	
WH115	1	06.34	4.4	06.34	03.49	
WH116	1	04.61	0.9			
	2	04.14	3.0	04.25	02.34	
WH117	1	07.71	6.0			
	2	05.00	2.2	06.98	03.84	
Facility Insoluble Content Ave. Vol. %					03.94	

* Stage % in volume percent is for the partial Vol. (MMb) involved in that stage, and Tot.% is the cavern insoluble content calculated using the Stage % weighted by stage/cavern volumes.

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