Utilization of Leaching Models in the Design of Large Crude Oil Storage Cavities

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ABSTRACT

Utilization of large salt cavities is the most economical way of storing large volumes of crude oil. To develop large cavities in the shortest time, high circulation rates are required. In designing leaching procedures for these cavities, some parameters must receive special consideration. Such design considerations are the subject of this paper.

Operational leaching during the storage life span of a cavity must be predetermined and properly incorporated into the cavity design. The development of a conical roof, which enhances the stability of the cavity, should be considered in the leach/fill type operations. The injection tubing plug-up associated with the accumulation of insolubles at cavity bottom, can be effectively dealt with by maintaining a continuous, high injection rate. Use of a proven numerical model is essential for attaining optimum leaching procedure. Multi-well leaching, which offers better leaching efficiency conceptually, is totally inadequate in practice. The design for the first 3-well cavity group ever drilled had to be completely modified to avoid the formation of hazardous hanging salt spires. Among other considerations for the development of a large cavity is the extended lag time between the termination of circulation and reaching a full saturation state in cavity brine.

INTRODUCTION

LPG and other petroleum products have been stored in salt cavities in the U.S.A. since the 1950's. Underground storage of crude oil, however, was not widespread before the Strategic Petroleum Reserve Act of 1975. And the first industrial underground storage of crude oil, Louisiana Offshore Oil Port storage facilities, did not proceed with offshore and onshore construction before 1977.

The most common technique for cavity development is single well leaching. Injection of water into the well and production of brine out of the well are accomplished through a system of concentric hanging pipes. The dimension of the final cemented casing is used to classify a well. A 30″ or 26″ cemented casing signifies a large well. 20″ or 18″ cemented casing can be termed as a medium large well. 13⅜″ casing is considered the conventional size and any well with a final cemented casing smaller than 10¾″ may be referred to as a small well. The size of the final cemented casing which puts limitations on the dimensions of the hanging strings, in effect, controls the maximum circulation rate. The size selection for the hanging pipe and tubing is partially based on lowering the flow-related frictional losses to a minimum for the designed circulation rate. Velocities higher than 15 ft/sec in the pipe and tubing are generally avoided. High velocities can create undesireable vibrations which could cause tubing break-off.

The development of a large storage cavity with conventional circulation rates would be a lengthy process. The most practical way of accelerating the development process is the use of high circulation rates. For example Figure 1 shows the relation between the development time and the rate of circulation for a one million BBL cavity in a 1000′ section of salt. A similar relation exists for the development of a larger cavity. High circulation rates for accelerated development of cavities require large wells. However, large wells are generally inherent in the design of large cavities in order to meet the fill and withdrawal schedule. Take LOOP's 4 MMB cavities for example, each has four large access wells, aside from the main well. Leaching such cavities with high circulation rates does not introduce additional drilling and well completion costs. The pumping requirements for leaching are also met by the permanent pumps for the storage operation. So the trade-off for the accelerated development can be minimal, especially if seawater is the source of water supply and the resulting brine is returned back to the sea.

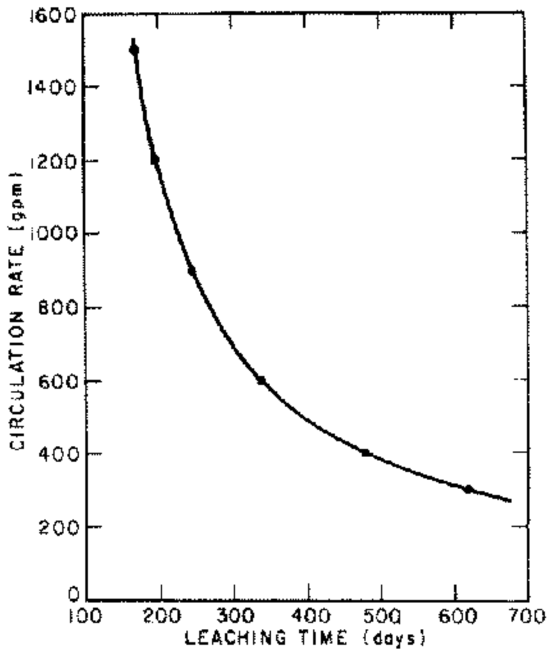


Figure 1. Time vs. Rate for Development of a 1 MMB Cavity in a 1000′ Salt Interval[3].

STORAGE OPERATIONAL LEACHING

The withdrawal of crude oil from a storage cavity requires injection of a ballast fluid, saturated brine being the most adequate ballast fluid. However, surface storage of large volumes of brine needed for operations in a large underground facility may not be practical. For example, at a Strategic Petroleum Reserve site, where upon project completion there could be a 200 MMB oil inventory, it would not be practical to have an equal volume of brine on hand. In the SPR case, in the event of a cut-off in the imported oil and when an emergency is declared, water will be used to displace the stored crude oil. Use of fresh water causes additional leaching in the cavity, increasing the volume by about 15% of the displaced oil volume. Use of water as ballast fluid for the SPR Project is totally justifiable due to the emergency nature of the stockpile. On the other hand, at a continuously operating storage terminal where a cavity may go through a fill/withdrawal cycle every month, use of water as ballast fluid is improper. For such facilities a large source of brine is a necessity. LOOP's storage facility is equiped with a 25 MMB brine pit. The size of the reservoir was predetermined by a study to minimize the operational leaching for the 25–30 year life span of the storage facilities. When brine is stored in an open pit, the operational leaching cannot be eliminated unless there is little or no excess rainfall at the location to dilute the brine.

At some storage sites, where cycling is seasonal and storage capacity expansion is desirable, a well is set aside to provide ballast brine. During product withdrawal season, water is circulated through the brine well and the resulting brine is then injected into storage cavities for product displacement. The cavity that supplies the brine, upon enlarging to a certain size, could be utilized as another storage cavity.

Cavity enlargement resulting from operational leaching can affect the integrity of a cavity. The cavity spacing in storage fields does vary, but generally, a spacing equal to 2½ times the cavity diameter is considered safe. This would leave a salt pillar with a thickness of 1½ the cavity diameter between the adjacent cavities.

Therefore, in designing the initial cavity shape, the growth due to operational leaching must be considered. Predetermination of cavity growth may not be an easy task. For a storage terminal type operation, the withdrawal schedule cannot be pinpointed. So, in predicting the growth pattern a great deal of uncertainty exists. However, it is a certainty that the lower portion of the cavity will be exposed to dissolution much longer than the upper part of the cavity. It is also clear that to reach the maximum capacity within the spacing guidelines, the ultimate cavity configuration must be cylindrical. Combining these two facts, one would conclude that the cavity must initially be developed in a flowerpot type shape (i.e., a cylinder which is wider at the top than at the base).

SPR's 10 MMB cavities with 2000′ storage interval were designed as flowerpot shaped cavities with diameters of 230′ at the top and 150′ at the bottom. Each cavity is to reach a volume of 20 MMB after 5 total displacements of crude oil with fresh water; growing to a true cylindrical shape with a diameter of 270′. Actually, the simulation of withdrawals with the proposed rates showed that the cavities would assume a shape not totally cylindrical, but slightly depressed in the middle.

LOOP's 4 MMB cavities with a 1000′ storage interval were designed to reach diameters of 200′ at the top and 140′ at the bottom. Operational leaching was simulated for the first 10 turnovers using an estimated rate and schedule. The simulation results, where then extrapolated to hundreds of turnovers. The average salinity of ballast brine had been evaluated based on the estimated yearly turnovers, the excess rainfall in the area and the areal extent of the 25 MMB open pit. The simulation of cycling indicated that each cavity after 500 turnovers will assume a cylindrical shape with a diameter of 242′.

CONICAL CAVITY ROOF

Stress analysis would show that a hemispherical or conical cavity roof is more stable than a flat roof. However, except for some of the SPR cavities, almost all the existing cavities have flat or nearly flat roofs. Generally, other stability factors such as roof proximity to the cap rock and the flanks of a dome are of more concern in the design of a cavity. At the same time it should be pointed out that the SPR cavities are the largest storage cavities in the U.S. excluding the brine source cavities.

Creation of a conical roof for cavities with a roof span of 200' or more is highly desireable, though there is not enough convincing physical evidence to show that flat roofs are unstable. One of the converted brine cavities utilized for the SPR's Early Storage Program at West Hackberry, Louisiana, has a 900' roof span. This cavity was certified stable and oil has been stored in it for the past several years.

Development of a conical roof is easily achieved by gradual addition of the blanket material to the cavity during the course of cavity development. This operation is generally performed when reverse circulation is the method of leaching. The gradual lowering of the blanket/brine interface generates a conical roof. There is a wide range of costs for the development of a conical roof. For a leach/fill type operation, conical roof development represents little or no additional cost because the crude oil (blanket) is to be simultaneously injected into the cavity anyway. However, for a leach-then-fill type operation, conical roof development can be very costly. The amount of blanket material needed obviously depends on the dimensions of the conical section. For a large cavity, a blanket volume of 150,000 to 250,000 BBLS may be required. Aside from the cost of the blanket material, large surface facilities will be needed for the temporary storage of the blanket material.

In a leach-then-fill type cavity development, the blanket does not have to be the same as the material for the later storage. In LOOP's case, diesel was used as the blanket material. In the development of a total of 8 cavities when 3 or 4 were leached simultaneously, a total of 25,000 BBLS of diesel was at hand. These cavities, as mentioned before, have flat roofs. For conical roof cavities, 20 or 30 times that amount would have been needed, requiring extensive cost for surface tank facilities and the tying up of many millions of dollars.

There are innovative ways of developing a conical roof with a limited amount of blanket material in the early stages of leaching; but the procedures require laboratory precision. Overall, despite the desireability of conical roofs, except for leach/fill operations, the related cost and effort cannot be justified.

SUMP DEVELOPMENT

Anhydrite accompanies sodium chloride in rock salt both in dispersed and in concentrated forms. Anhydrite, nearly insoluble in water, collects at the bottom of the solution mined cavities; the zone which generally is referred to as the sump. For the cavities developed in the Gulf Coast region salt domes, the sump volume, usually constitutes 5 to 10% of the total leached volume. Therefore, for a large cavity the sump volume can be substantial.

In dealing with insolubles, the main problem is to avoid tubing plug-ups. As leaching goes on and insolubles accumulate at the bottom, the tubing gets buried and conditions for plug-up are created. Interruptions in water injection such as power or pump failure can cause plugging. Check valves on the injection line do prevent the backflow of the insolubles into the tubing. However, even with check valves, sometimes the flow cannot be restarted. When attempts to achieve circulation fail, the tubing has to be repositioned either by lifting it out of the pile or by shooting it off at a level above the insolubles. Premature tubing repositioning could ultimately affect the cavity shape and may require leaching design modifications.

Some designs call for a separate sump development leaching stage. In this approach, the sump is basically a small cavity which is leached below the main cavity. By exposing a limited portion of the borehole to dissolution, the accumulation of insolubles is drastically reduced and therefore the chances for plugging are greatly decreased. However, development of a sump as a separate leaching stage is costly and increases the overall cavity development time significantly.

Simultaneous sump/chimney leaching, where the entire cavity interval is exposed to dissolution, is the most efficient leaching method. And the plugging problem due to insoluble residue can be effectively dealt with. One option is to extend the borehole some distance below the planned cavity bottom. The extended sump section would allow for the occurrence of several plugging incidents and the related tubing repositionings. The drawbacks for this scheme are the cost of additional footage drilled and the required higher injection pressures. There would also be a greater change for plugging due to the extension of the leaching zone.

For sump/chimney leaching, the most effective way to avoid tubing plug-up is maintenance of a continuous high circulation rate. Laboratory tests of water injection into an anhydrite pile, conducted by the author in 1978, showed that the flow through the pile occurs under two mechanisms:

1. A source type streamline flow through the porous medium
2. Through a conical floatation zone around the injection pipe.

So long as the flotation zone exists, a portion of flow is short-circuited out of the pile and no interruption in the circulation is likely to happen. However, in the absence of the flotation zone, total flow must occur through the pile's porous medium and conditions for circulation interruption ripen. For a constant injection pressure, the additional pressure losses due to total porous medium flow cause a reduction in the circulation rate. A lower rate results in the salinity buildup in cavity brine which in turn causes higher differential head between water and brine columns. This further reduces the flow rate and the continued effect ends in a no-flow condition.

For LOOP cavities, during sump/chimney development, continuous high circulation rates averaging around 3000 GPM were maintained and not a single case of plugging was experienced in developing the eight cavities. At the end of the sump/chimney stage, each cavity had reached a total leached volume of 1.2 MMB and the injection tubing was buried under some 60′ of anhydrites (Figure 2). By maintaining the high circulation rate, the insolubles around the injection tubing had been kept in flotation and the leaching stage was completed without any interruptions.

The above procedure was not followed for some of the SPR cavities at Bryan Mound, Texas, and severe plugging problems were encountered. A 24 hour test period, for which circulation was halted, may have contributed to the problems. The 2500′ height of the cavities was certainly a factor in the excessive accumulation of insolubles.

DEVELOPMENT OF THE STORAGE SECTION

Upon completion of the sump/chimney stage, the hanging pipe and tubing are repositioned for the development of the storage section. Resetting the pipe requires removal of the tubing. Generally, at this stage a sonar survey of the cavity is conducted. The results could provide additional information about the salt formation based on the dissolution pattern.

To develop a cavity in the desired flowerpot shape, several pipe resettings may be required. Numerical simulation is used to determine the optimum injection levels for achieving the target cavity configuration. The SPR cavity design for leach/fill operation called for three pipe/tubing repositionings. For LOOP cavities two resettings had been anticipated. Later leaching simulation indicated that the flowerpot shape can be achieved with one pipe/tubing repositioning. After completion of the sump/chimney stage in one step, the tubing was removed and a survey conducted. The hanging casing was then lowered some 400′ and the tubing was placed about 150′ above the insolubles pile. Leaching was commenced and 4 MMB storage section was developed in one step by reverse circulation method (Figures 3, 4A and 4B).

The time and expense associated with each pipe/tubing repositioning are considerable. Reducing the resettings to a minimum, as was achieved for LOOP's cavities, has to be a major objective in cavity design.

MULTI-WELL CAVITY LEACHING

As mentioned earlier, the large crude oil storage cavities are designed to handle large fill and withdrawal

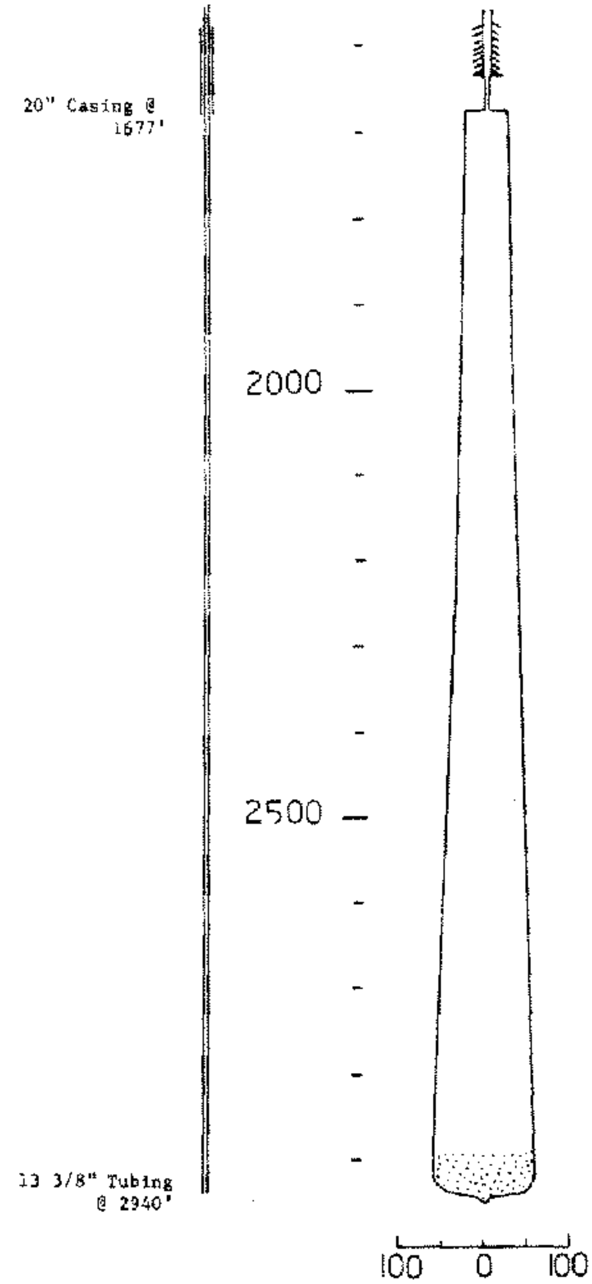


Figure 2. Simulated Shape for a Typical LOOP Cavity at Completion of Sump/Chimney Leaching Stage.

rates. For instance, each of the LOOP's cavities is designed to accept oil at 100,000 BPH through the main well and the (30″-22″) annular spaces of the four access wells. The withdrawal will be at 50,000 BPH by injection of ballast brine through the 22″ hanging pipes in the four access wells.

SPR cavities must also meet high withdrawal rates during an emergency. In the original conceptual design of the SPR cavities, to speed up the leaching process, a scheme had been introduced to utilize the access wells in

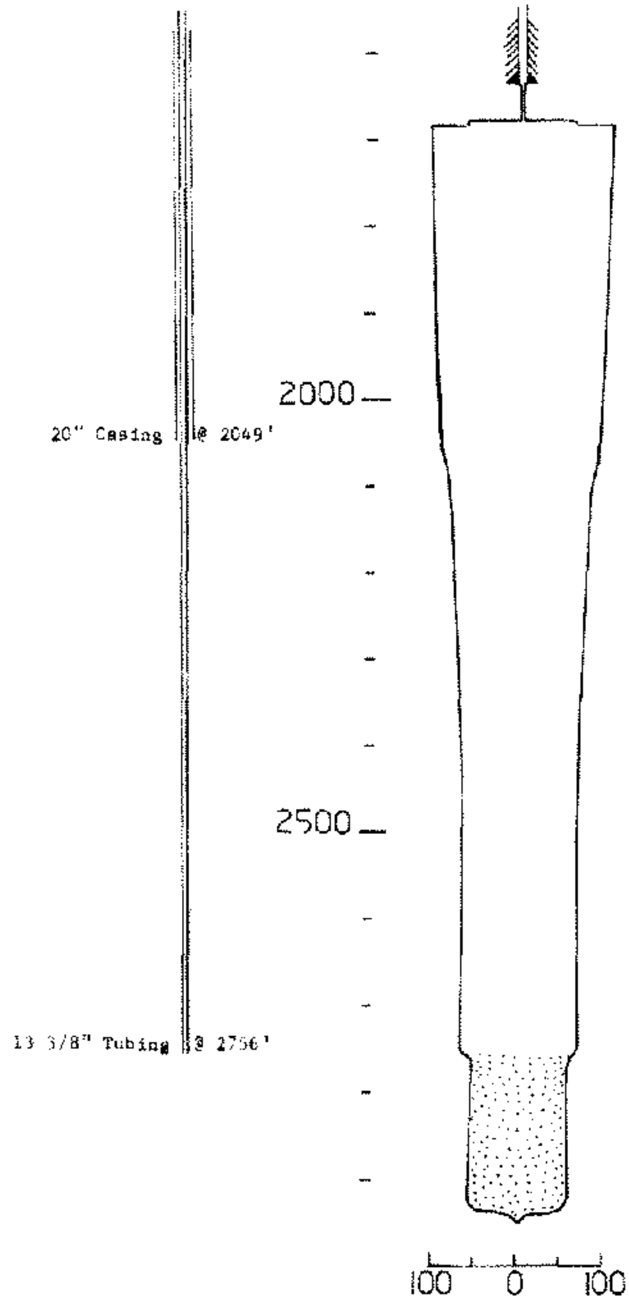


Figure 3. Simulated Shape for a Typical LOOP Cavity at Completion of Second and Final Leaching Stage.

the development stage. The design called for drilling the access wells to the total depth rather than to the anticipated cavity roof depth. The concept is to leach a small cavity around each well and later the coalescence of these cavities will form a single large cavity. Based on this concept, 3-well and 2-well designs as well as the traditional single well design were developed for the SPR cavities. The single wells contained a 20″ final cemented casing. The 2-well cavities have 16″ final cemented casings and the 3-well cavities have 13⅜″ cemented casings. All these cavities would meet the same leach, fill and withdrawal requirements.

The advantage of the multi-well concept is the higher leaching efficiency which is resulted initially from dividing the circulation rate among multiple wells. Figure 1 can be used to estimate roughly the leaching efficiencies for the development of a 1 MMB cavity. For example, for a 1200 GPM total circulation rate, a 2-well system can be as much as 15% and a 3-well system as much as 20% more efficient. The efficiencies are reduced upon coalescence due to the inherent losses of salt surfaces. The overall leaching efficiencies will be quite smaller than the above pre-coalescence values. The leaching efficiency of the multi-well concept is far out weighed by its many inadequacies. Studies have compared the various leaching techniques and have found multi-well leaching, 3-well in particular, inadequate. Aside from the excessive drilling and completion costs for 3 standard size wells in comparison to the cost of a single large well, there are other shortcomings associated with the 3-well leaching concept.

3-Well Cavity Leaching Design. After the authorization of the Strategic Petroleum Reserve in 1975, there was an urgency to store a large quantity of crude oil in the shortest possible time. As a part of the Early Storage Program, large brine cavities were acquired by the government and plans to develop more cavities quickly were being drawn out. Under such circumstances the concepts of simultaneous leach/fill and multi-well leaching were adopted and drilling and completion of wells at the selected sites got underway. In the late seventies when the stock piling had all but disappeared, the leaching designs were reviewed by the various engineering and research organizations. Their unanimous conclusion was that 3-well leaching should be eliminated from any further consideration for future expansion programs.

This multi-well leaching design calls for drilling three wells in a 75-foot equilateral triangular arrangement. 13⅜″ final cemented casings would be positioned 500′ into the salt below the cap rock. Drilling would then be continued for another 2500′ to the total depth. The problem of maintaining the 75′ spacing between the wells is the first difficulty which surfaces early in the drilling stage. Deviation of the wells closer to each other, short of intersection, does not create a problem. On the other hand, if the wells drift farther apart, that would be a severe problem, affecting the leaching schedule and the pre-determined cavity spacing. The prolonged leaching of the wells to achieve coalescence, would alter the entire leach/fill design including the final shape of the cavity. State of the art technology was used in drilling the tri-lobe wells. However, the 75′ spacing could not be maintained and many wells had deviated from vertical.

The major concern over the 3-well cavity design was the formation of an undissolved mass of salt in the center. The coalescence of the wells at the bottom and the top

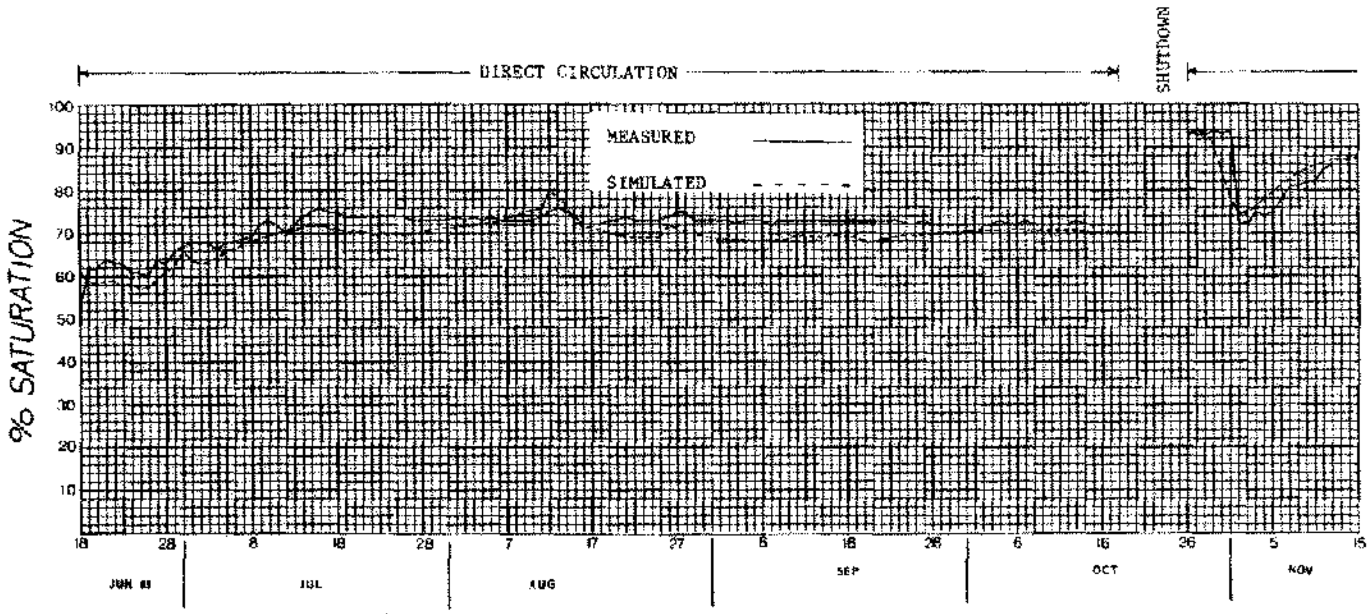
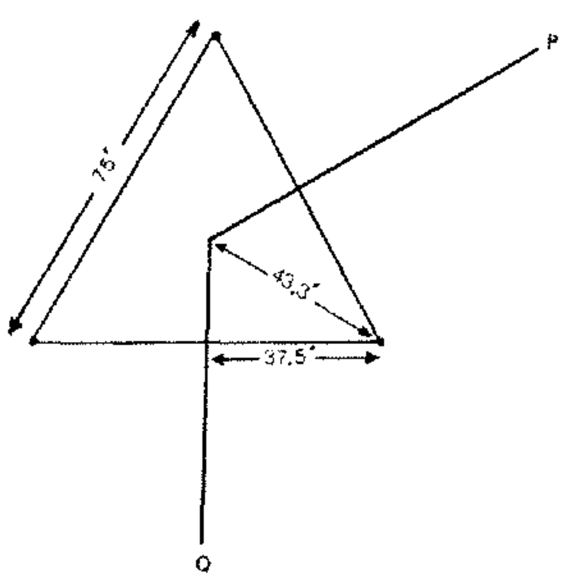


Figure 4A. Comparison of Simulated and Measured Produced Brine Saturations for a Typical LOOP Cavity.

would create a salt spire which would collapse at the time of total coalescence. The consequence of such a rock fall had become of a great concern. Under the sponsorship of Sandia Laboratories, the 3-well cavity development was numerically simulated using the specific leaching schedule which had been prepared for the actual operation. The programming effort and the simulation results are briefly discussed below:

Numerical Modeling of the 3-Well Cavity Leaching. Since the three wells were to be operated identically, one well was isolated and numerically modeled. To isolate one well, two imaginary vertical boundary planes were assumed as shown below:



During the course of leaching, three various conditions exists. As the cavity radius, r, at a given depth increases, the conditions can be identified as:

1) pre-coalescence $r \leq 37.5$
2) partial coalescence $37.5 < r \leq 43.3$
3) total coalescence $43.3 < r$

The wall surface area, A, for the height increment, Δh, varies for the different conditions.

$$A = 2\pi r(\Delta h) \tag{1}$$

$$A = 2\pi r(\Delta h)\left[1 - \frac{\arccos(37.5/r)}{\pi/2}\right] \tag{2}$$

$$A = 2\pi r(\Delta h)\left[0.833 - \frac{\arccos(37.5/r)}{\pi}\right] \tag{3}$$

The incremental volume, ΔV, for the height increment, Δh, also varies for the different conditions.

$$V = \pi r^2(\Delta h) \tag{1}$$

$$V = r^2(\Delta h)[\pi - 2\arccos(37.5/r)] + 75r\sin[\arccos(37.5/r)] \tag{2}$$

$$V = r^2(\Delta h)\left[\frac{5\pi}{6} - \arccos(37.5/r)\right] - 811.9 - 37.5r\sin[\arccos(37.5/r)] \tag{3}$$

The above relations were incorporated in a 1-well leaching model. A numerical scheme utilizing the dissolution factor in the model was used to account for the simultaneous oil filling of the cavity. The resulting computer simulation program was named SALT80.

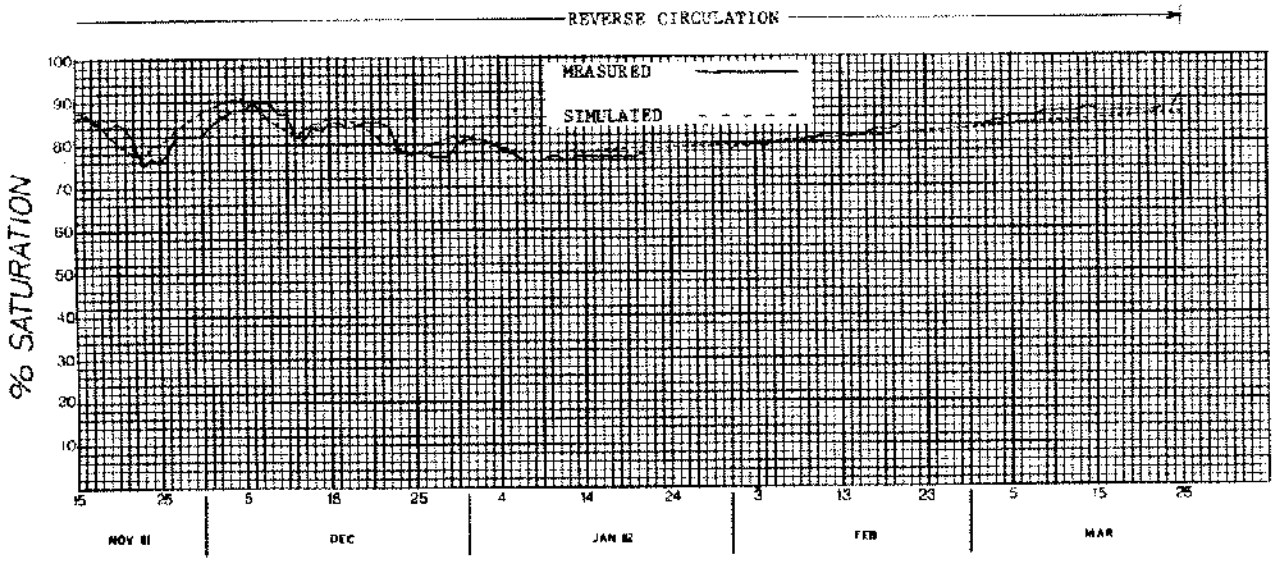


Figure 4B. Comparison of Simulated and Measured Saturations Continued.

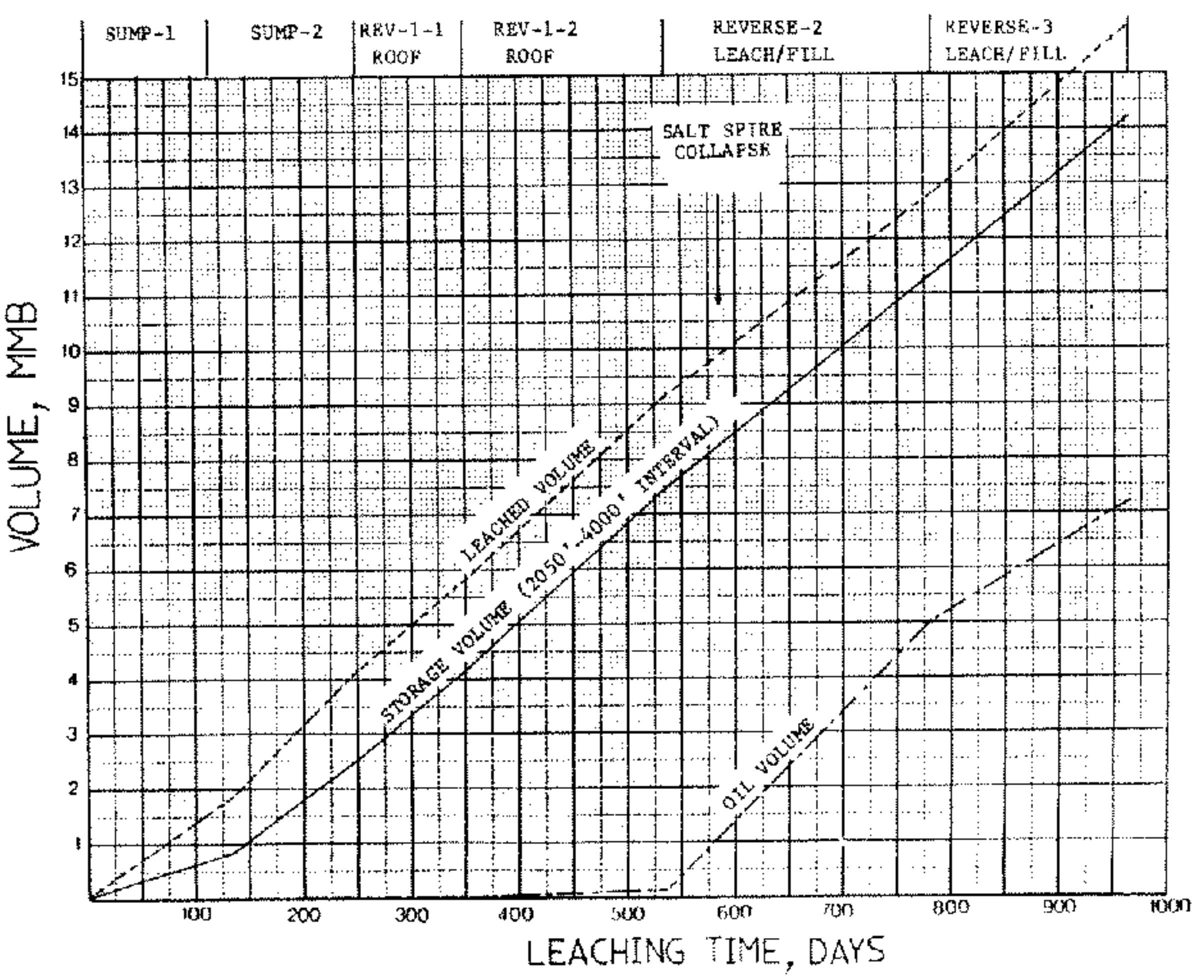


Figure 5. Simulation Results for Various Leach and Leach/Filling Stages of 3-Well Cavity Design.

A detailed 3-well leach/fill schedule which had been prepared for the SPR cavities was subjected to verification. Leach and leach/fill operations were simulated step by step according to the schedule. The simulation results are shown in Figures 5 to 13. The schedule called for 964 days of leach and leach/filling operations with another 208 days for contingencies, sonar surveys and oil fill. The simulated leached and storage volumes are shown on Figure 5.

The results indicate that under such a schedule a far larger cavity would be developed. The objective was to leach a 12.4 MMB cavity, 10 MMB for the storage, 1 MMB for cushion brine and 1.4 MMB for the insolubles accumulation. The simulation shows a leached volume of 15.9 MMB which is 28% larger than the intended size. Figures 6 to 9A show the cavity shapes at various stages of leaching. These cross sections are taken along a vertical plane that contains the axes of two wells. Such cross sections do not reveal a great deal about the undissolved salt spire. For example, Figure 9A, only shows the thickness of salt which is holding the salt spire. A more informative cross section is shown on Figure 9B. This vertical plane contains the axis of one well and is perpendicular to the vertical plane containing the axes of the other two wells. The simulation indicated that some 50 days into the reverse-2 leaching stage, the salt spire would fall. The pre-fall horizontal and vertical cross sections of the salt spire are shown in Figures 12 and 13. The spire would have a maximum thickness of 27′ and be some 900′ long.

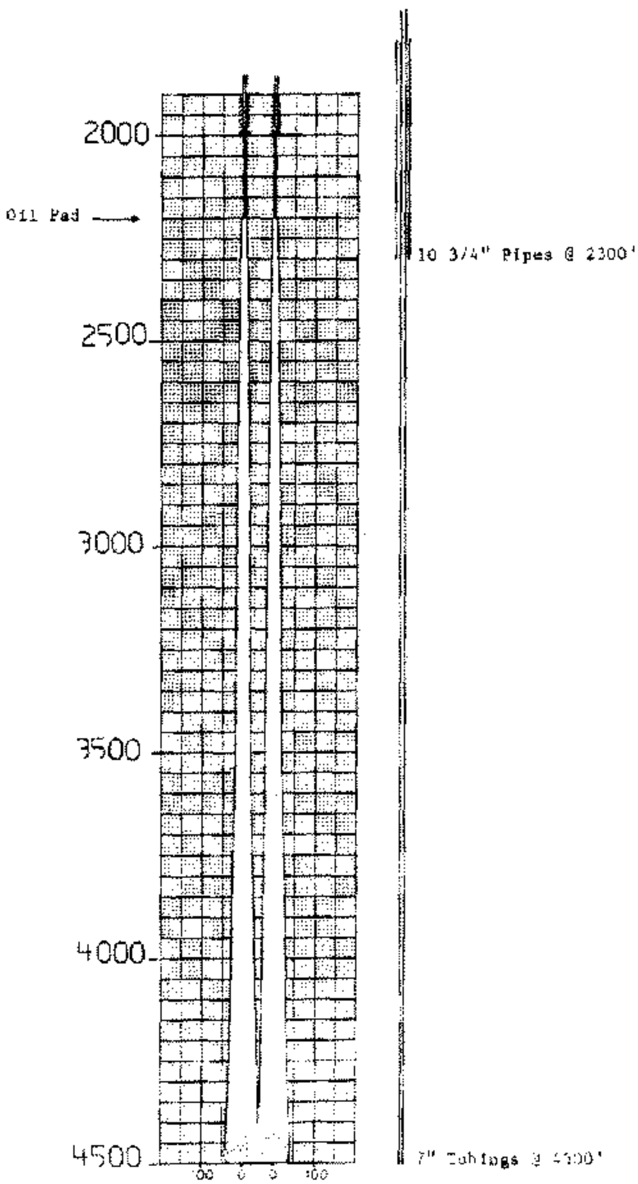


Figure 6. Vertical Cross Section of 3-Well Cavity at Completion of Sump/Chimney-1 Leaching Stage.

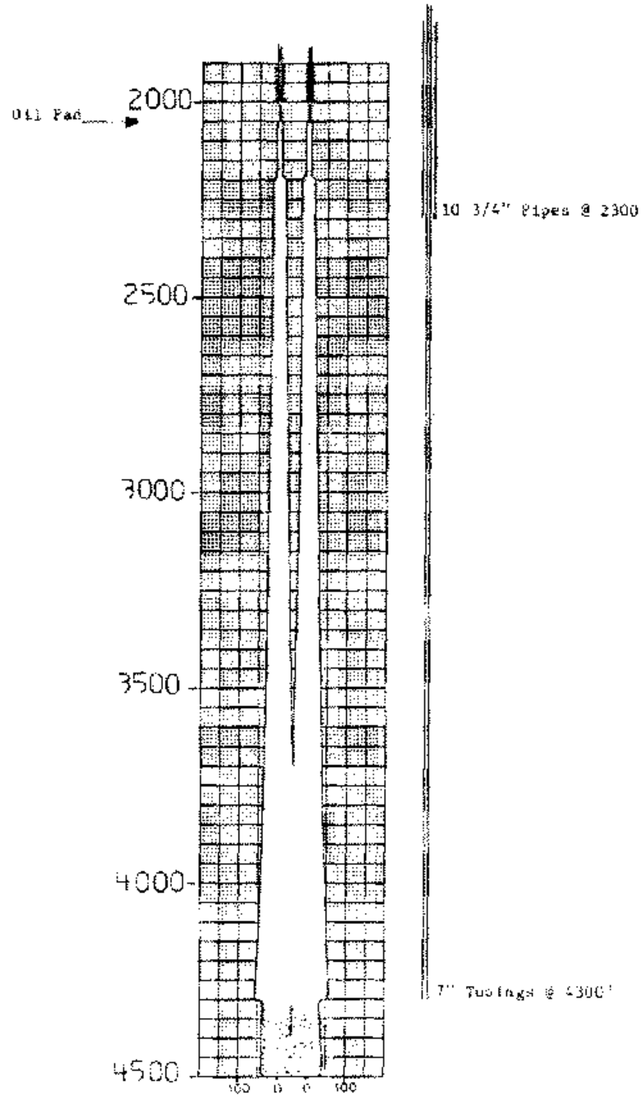


Figure 7. Vertical Cross Section of 3-Well Cavity at Completion of Sump/Chimney-2 Leaching Stage.

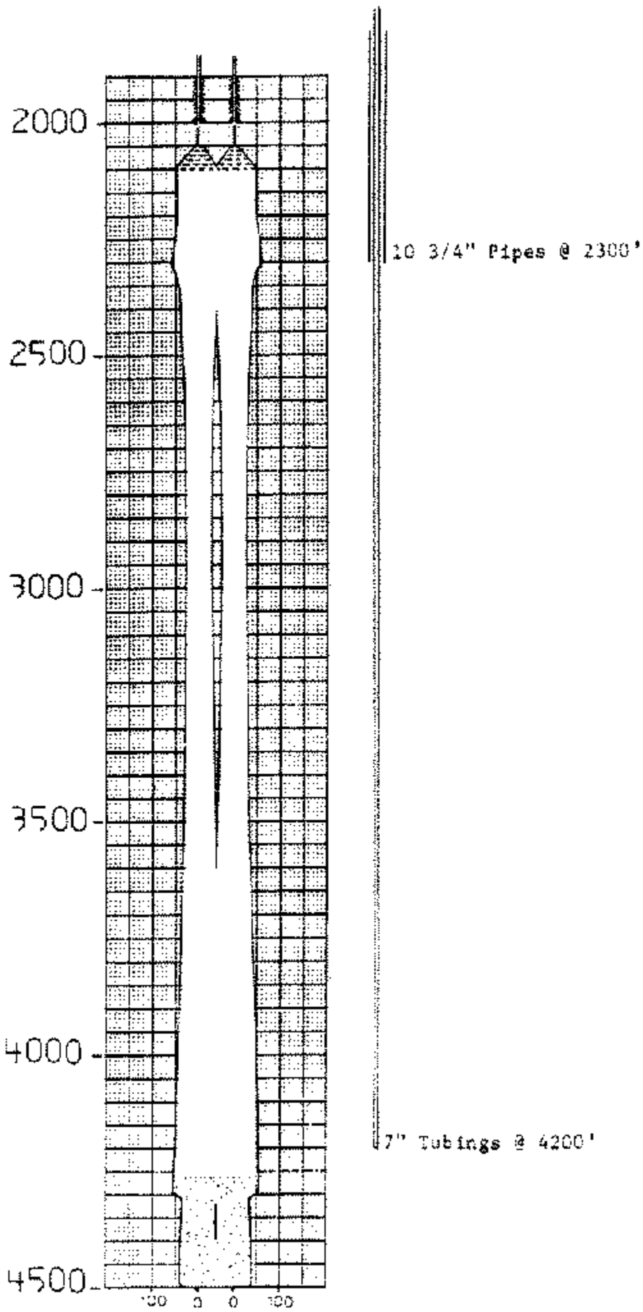


Figure 8. Vertical Cross Section of 3-Well Cavity at Completion of Reverse-1-1 Leach/Filling Stage.

The volume of the spire would be about 92,000 cubic feet. This corresponds to 1.2 million pounds total weight.

The fall of such massive body of salt would undoubtedly be hazardous. Rock falls, which are not uncommon in bedded salt cavities, do cause problems generally by knocking off or damaging the leach strings. Replacing the damaged tubing is a tedious and expensive task. It should be pointed out that the average size of a fallen rock in a bedded salt cavity would represent only a fraction of the spire in the 3-well design. The existence of 1.1 MMB of oil in the cavity at the time of the spire collapse, makes the fall even more hazardous.

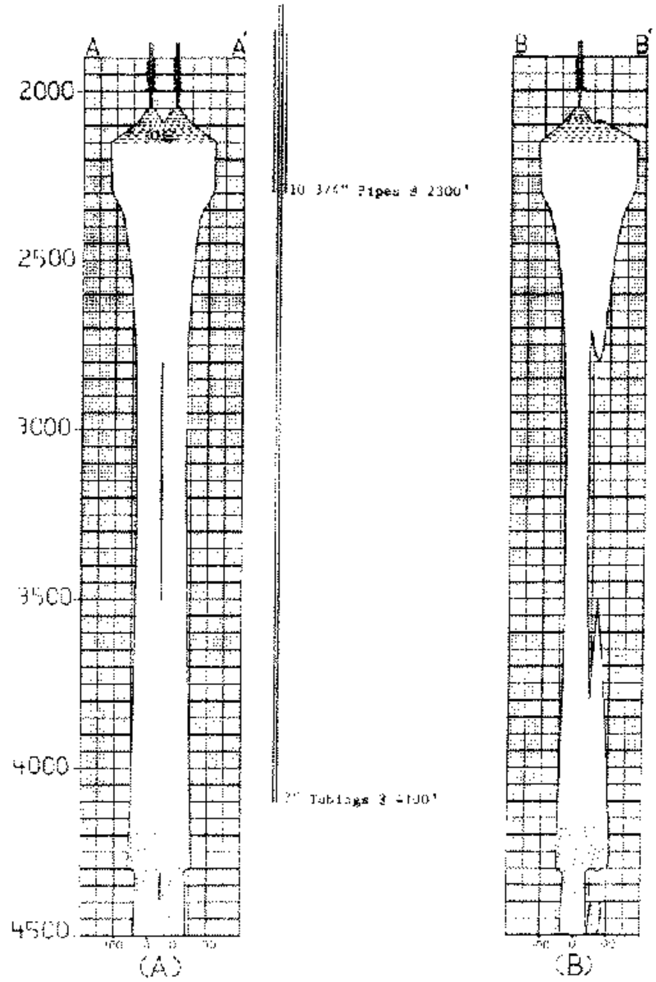


Figure 9. Vertical Cross Sections of 3-Well Cavity at Completion of Reverse-1-2 Leach/Filling Stage.

Modified 3-Well Cavity Leaching. As stated earlier, many of the wells for the 3-well design had been drilled and completed before the design came under scrutiny. Therefore, any modification to the design had to be in the area of leaching procedure and not the well arrangement area. Under the sponsorship of Sandia Laboratories the following design modification was recommended by the specialists:

- Leach all three wells according to the 3-well design until all coalesce at the bottom (sump/chimney stage)
- For the reverse circulation stage, select one well as the injector and the other two as the producers. Remove the 7″ tubing from the injector well and position the 10¾″ pipe at a pre-determined depth, in the uncoalesced, upper part of the cavity. The two

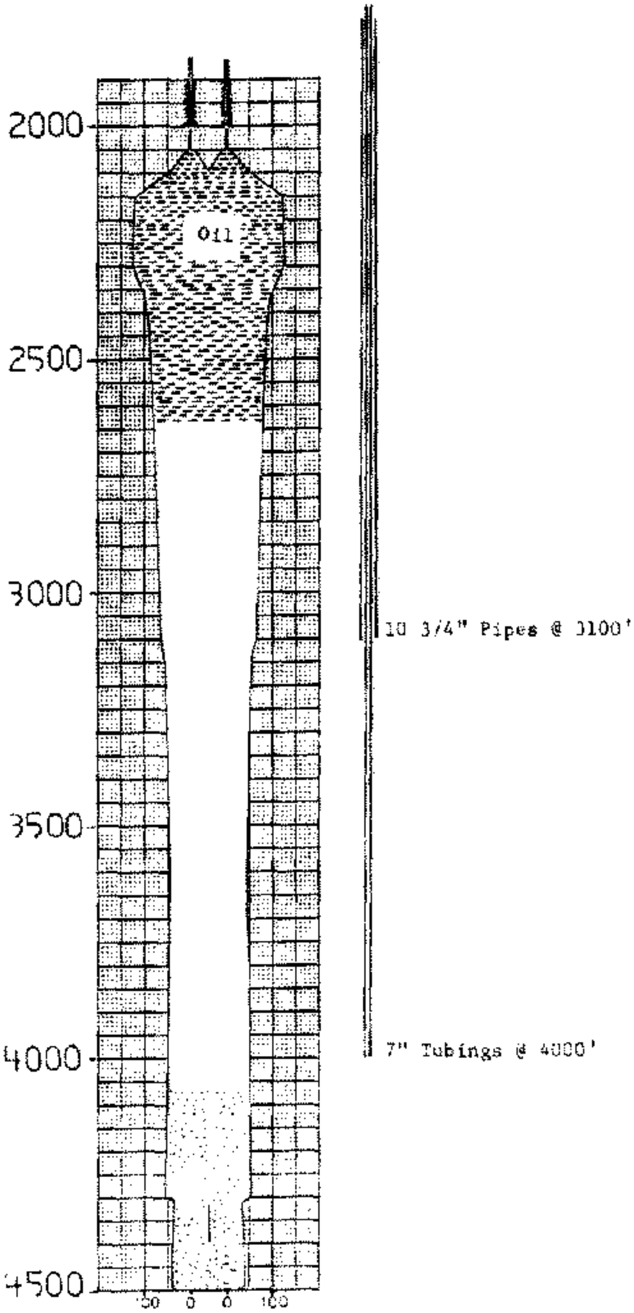


Figure 10. Vertical Cross Section of 3-Well Cavity at Completion of Reverse-2 Leach/Filling Stage.

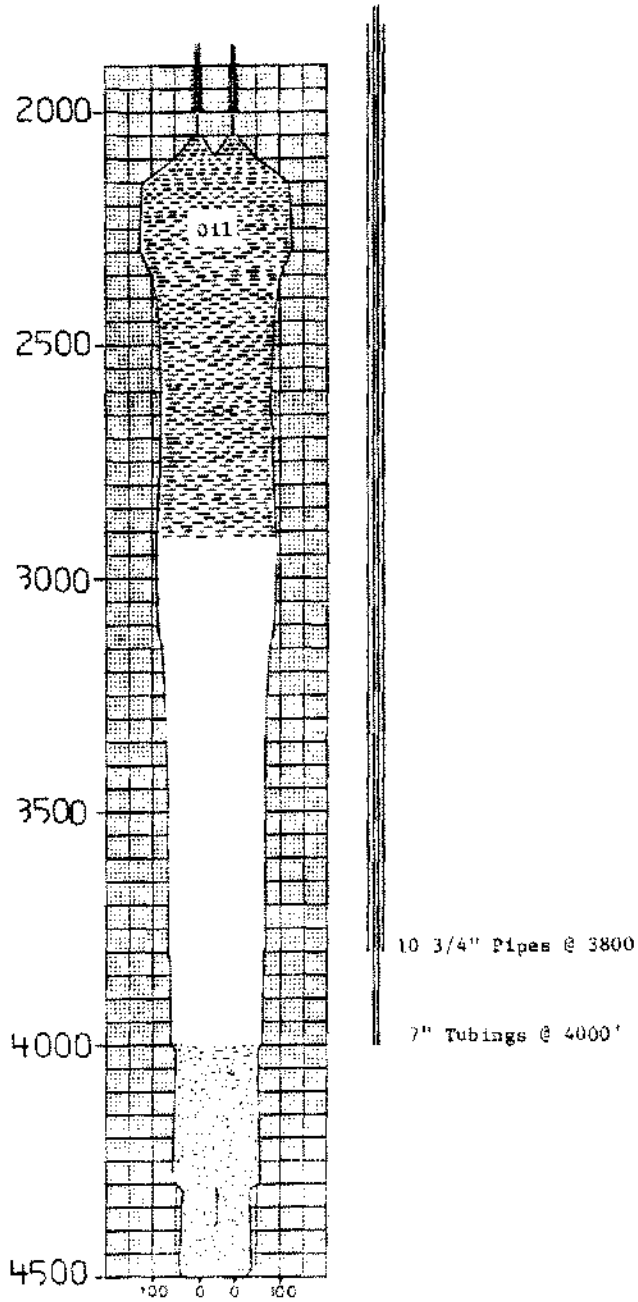


Figure 11. Vertical Cross Section of 3-Well Cavity at Completion of Reverse-3 Leach/Filling Stage.

7″ tubings in the producer wells would remain for brine production

The injector well will grow much faster than the producer wells, therefore, the formation of a massive salt spire is avoided. Any undissolved mass of salt resulting from the coalescence will be strongly attached to one wall. Figure 14 illustrates the growth sequence for the 3 wells in the upper regions of the cavity.

Numerical Modeling of the Modified 3-Well Cavity Leaching. A computer simulation model was developed for the coalescence and in conjunction with the single well model, code SALT79, leaching was simulated according to the following steps:

1. Direct circulation, sump/chimney development

SALT 80

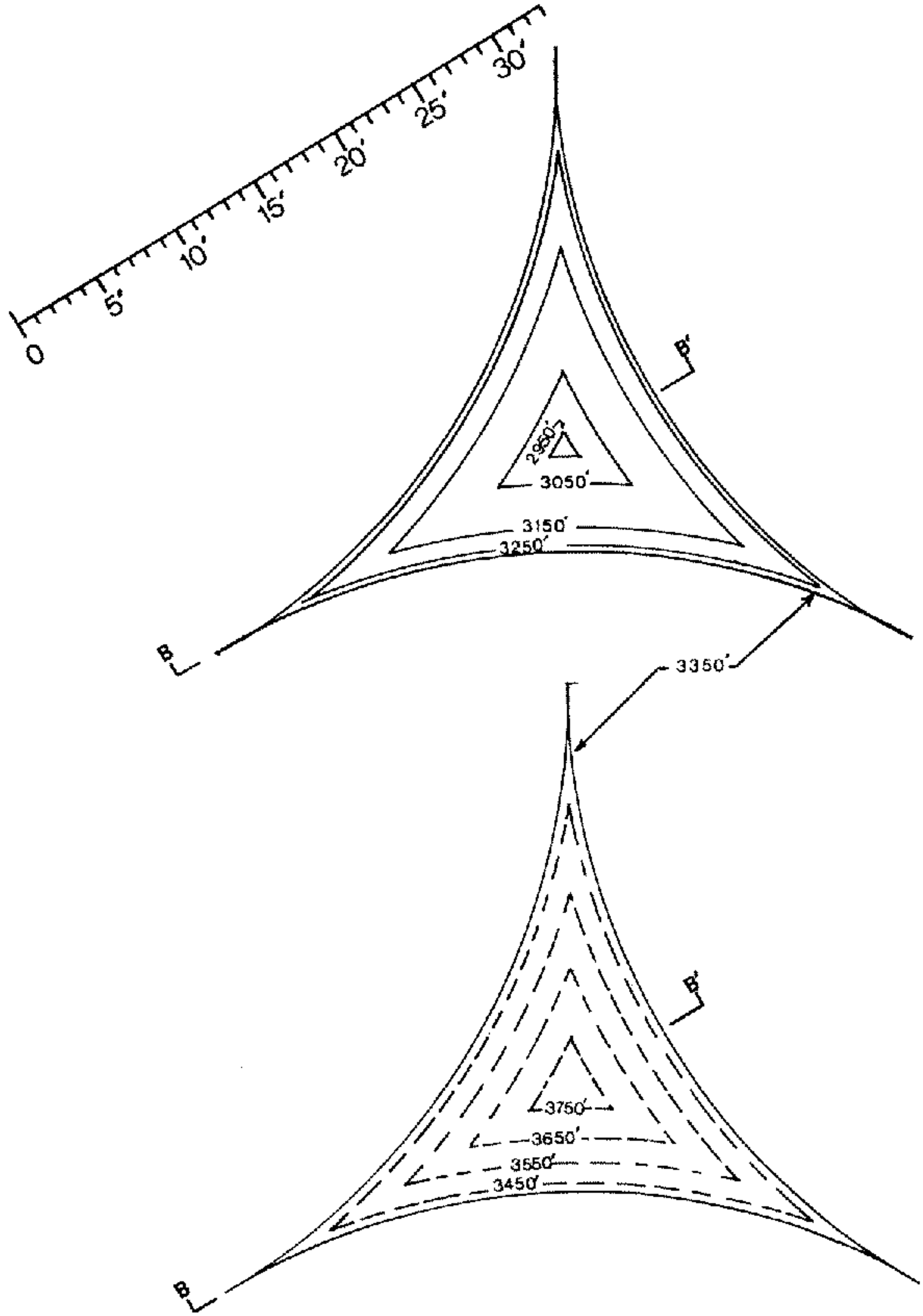


Figure 12. Pre-fall, Horizontal Cross Sections of the Salt Spire.

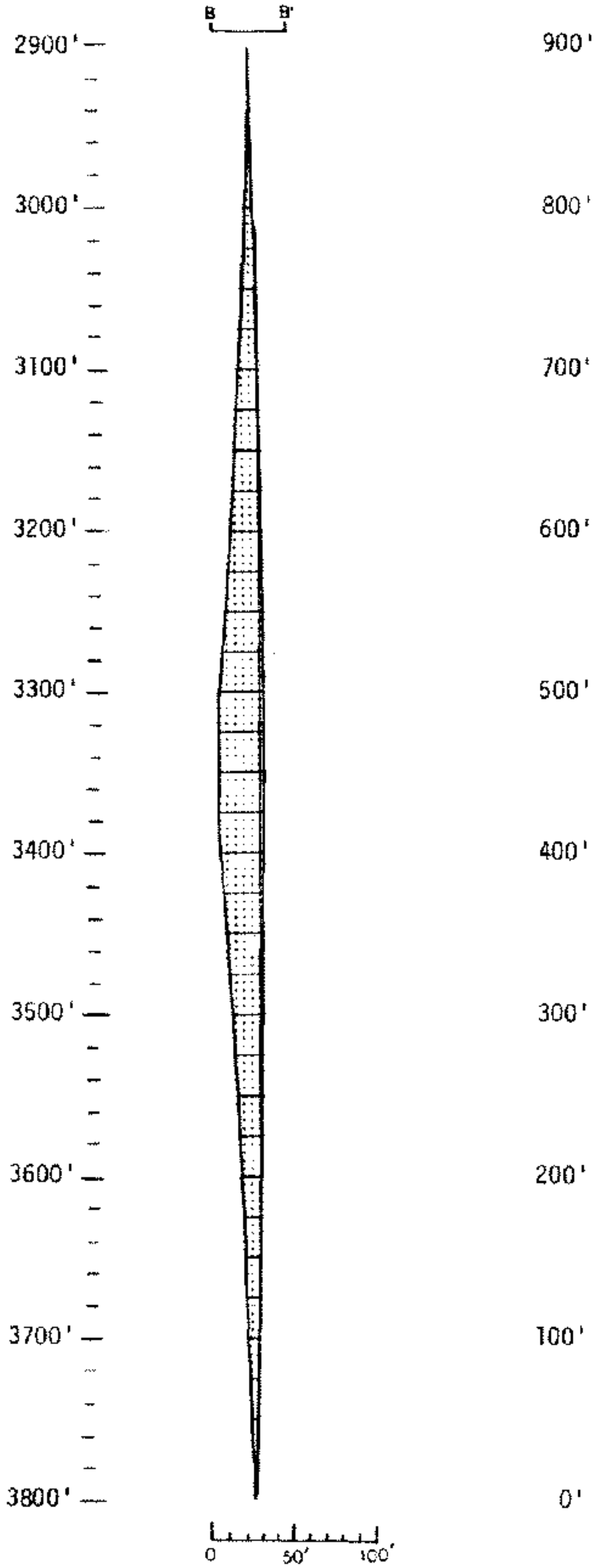


Figure 13. Pre-fall, Vertical Cross Section of the Salt Spire.

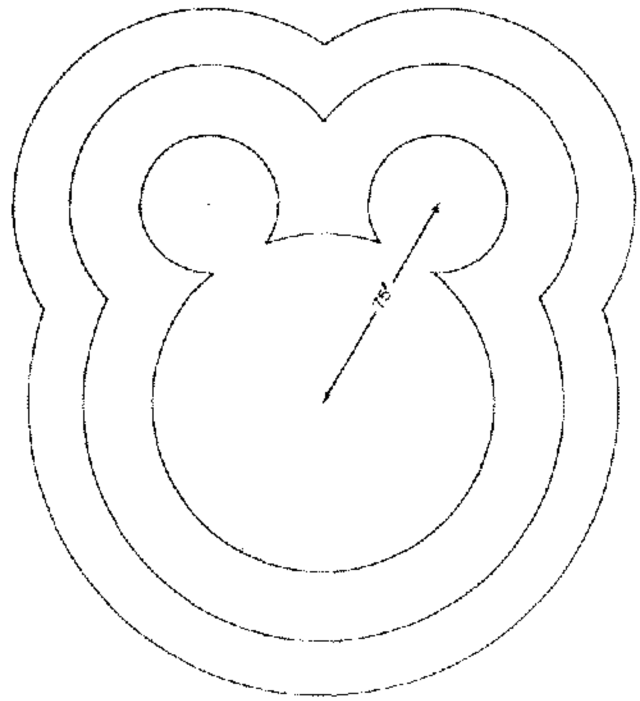


Figure 14. Horizontal Cross Sections Showing the Growth Pattern for the Modified 3-Well Cavity Leaching Design.

2. Reverse circulation
   (a) Before coalescence in the upper part
      - Injector well, injection at 10¾" pipe level, assumed production at the bottom coalescence level. SALT79
      - Producer wells, assumed injection of cavity brine at the bottom coalescence level, production at the 7" tubing level. SALT80
   (b) After coalescence in the upper part, SALT79 + XYZMMC.

The coalescence code, XYZMMC, calculates the cross sectional area enclosed by twin circles (producers) intersected by a larger circle (injector). The centers of the circles are located on the apexes of a 75′ equilateral triangle.

For the 3-well cavity, at a given depth after coalescence, the radial growth of the injector well is the same as the producer wells. Tables were generated by the code XYZMMC, showing the growth in the radii vs. the growth in the cross sectional area for the selected levels. The results from the single well leaching simulation together with the tables were used to evaluate the dimensions of the modified 3-well cavity.

OTHER LARGE CAVITY DESIGN CONSIDERATIONS

Large cavities, developed by high circulation rates, have characteristics somewhat different from the conventional size cavities developed by conventional rates. After completion of leaching, when circulation has ceased, salt dissolution in the cavity continues. Dissolution is terminated when the brine is totally saturated and temperature equilibrium between the cavity and the formation is established. The lag time between the cessation of circulation and the termination of dissolution is dependent on a number of factors and can vary widely. For a conventional size cavity this period may be as short as 3 days. On the other hand, for a large cavity, leached by high circulation rates, the lag time could be 30 days or more. The saturation lag time is directly proportional to the ratio of brine volume to the cavity wall surface area ($\pi hr^2/2\pi hr = r/2$). The cavity brine average saturation is partially controlled by the circulation rate. The method of circulation, direct or reverse, determines the salinity gradient or profile in the cavity brine.

Salt dissolution after shutdown, for a large cavity leached by high circulation rates, can be very extensive. Therefore, in designing such cavities, the saturation and the related cavity growth must receive the proper considerations. The cavity integrity test normally done by pressurizing the cavity must be scheduled after the cavity brine is in equilibrium. The final sonar survey will also be more reliable if the brine is calm and uniformly saturated.

CONCLUSIONS

1. Overall, utilization of high circulation rates is the most effective way of leaching large storage cavities in the shortest time.
2. High circulation rates require large wells; however, large wells are generally inherent in the design of large crude oil storage cavities.
3. Operational leaching during the life span of a cavity must be predetermined and incorporated into the overall design of the cavity.
4. The most effective method of preventing injection tubing plug-up problems during sump development is the maintenance of a continuous high circulation rate.
5. A conical roof adds to the stability of a cavity; however, except for a leach/fill type operation, the conical roof is not considered cost effective.
6. Multi-well leaching is costly both in terms of drilling and completion and operational cost. It can also create geotechnical problems such as the formation of a massive salt spire in the 3-well cavity design.

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