Techniques for Developing Predetermined Shaped Cavities in Solution Mining[1]

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ABSTRACT

The problem of obtaining specific configurations in massive salt during solution mining is presented. Techniques are described which provide means of obtaining various shaped cavities. Such cavities have certain advantages over those obtained generally by present-day operations. Spherically-shaped cavities offer advantages as storage caverns. Laboratory investigations have proven the feasibility of forming cavities and numerous models were developed in the program to determine the most feasible manner for forming spherically-shaped cavities. Methods are outlined for obtaining specific types of cavities in massive salt by the solution mining technique.

An increasing number of utilities, gas transmission companies, producers, and refiners are looking underground for safe and economical storage of hydrocarbons. Underground storage capacity in the United States has increased tenfold during the past decade, and projects in the planning stages indicate a continuation of the upward trend. Solution cavities, mined caverns, natural reservoirs, and abandoned mines, reservoir, and tunnels make up nearly 90,000,000 bbls. of storage facilities. Roughly 87% of this space is in salt caverns which cost less than $2.00 per bbl. of capacity to construct (1).

Besides being attractive to the industries involved, underground storage has proved to be of substantial benefit since it affords broader coverage of the LPG supply over the winter months and permits wider domestic and industrial use. It conserves energy resources because without vast storage facilities the gas would go to less economical uses, and it conserves critical materials such as steel for other applications in the national interest (2).

At present, the prime and often only consideration in the design and construction of solution cavities is storage capacity. As the applications and use of these caverns become more widespread and investment in them continues to increase, other considerations such as ease of operation, stability, areal extent and prevention of product loss in traps caused by uneven or irregular solution become more important. Many of these requirements may dictate chambers of particular shapes such as spheres, cylinders, ellipsoids, or cones.

This investigation was undertaken to determine the mechanics of the solution process in order to establish the feasibility of leaching cavities of predetermined shapes. The methods of circulation currently being employed by industry were reviewed and all laboratory work was done with a view of applying information gained to the construction of large-scale field cavities.

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Feasibility of Controlling Cavity Shape

In initial model studies, using both direct and reverse circulation, attempts were made to duplicate actual field cavities whose dimensions were known through sonar log surveys. Figure 1 depicts the type of cavities obtained (3). Reproducibility of exact shapes was not achieved, though it was possible to duplicate the general configurations in every case. This inability to reproduce the exact shape of the field cavities in the laboratory models undoubtedly was due to the large reduction in the scaling factor.

Through the use of quarter and half sections, which permitted visual observation of the washing process, flow lines were traced by the addition of colored dyes to the inlet water. In the case of reverse circulation, the inlet water rises and tends to remain near the top of the cavity due to gravity segregation. Continued circulation displaces it towards the sides. As the fluid increases in density it flows down the sides of the cavity. While the process of solution continues, convection and diffusion take place simultaneously, causing flow towards the center of the hole. Reverse circulation generally affords the most efficient use of the circulating water due to its tortuous path in the cavity.

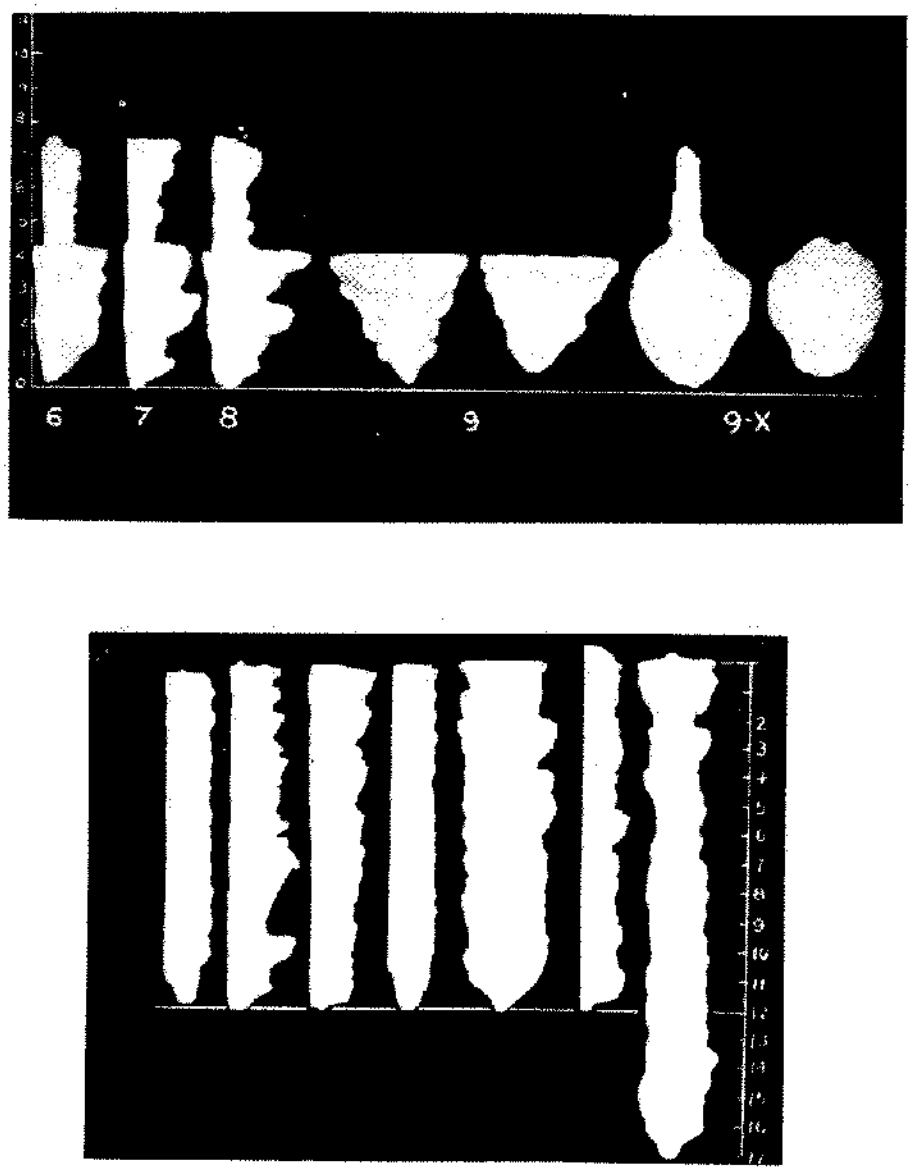

Figure 1. Casts of Model Cavities.

Due to the prominent salinity gradient initiated by the setting of certain dimensional relationships of the inlet and outlet pipe positions, field cavities formed by this method are usually wider in the upper region, or "coke bottle shaped" when multiple stages are used. Effects of pipe positioning on cavity shape are depicted in Figs. 2 (a) and 2 (b). Since gravity segregation can be influenced by the relative positions of the water inlet and outlet, almost any desired shape, as long as it is a solid of revolution about its vertical axis, may be formed by the proper use of floating liners and inert blanket material.

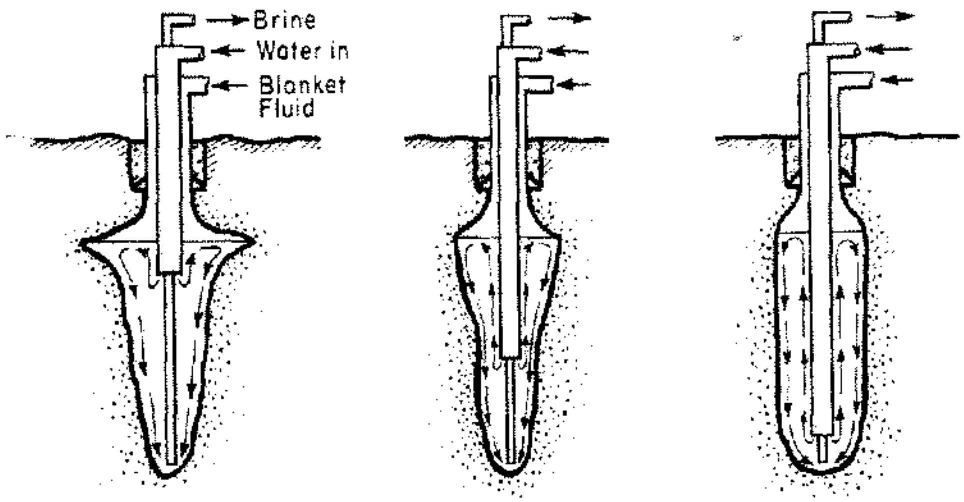

Figure 2 (a). Effects of Pipe Positioning on Cavity Shape Using the Reverse Circulation Method.

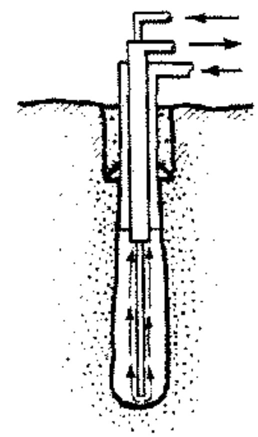

Figure 2 (b). Direct Circulation.

In the direct circulation method there is a flow of water in the upward direction. This results in an increase in salinity from the point of injection to the point of discharge, and from the center line of the cavity to the salt boundary. The effluent usually remains slightly undersaturated. The characteristic shape associated with this method is a slightly wider diameter in the lower region or a nearly cylindrical "jug type" cavity.

Controlled Washing Methods

Salt blocks, ranging in size from 8 ft.^{3} (2'×2'×2') to approximately 45 ft.^{3} (3.5'×3.5'×3.5') were obtained from the Morton Salt Company, Grand Saline Mine, Grand Saline, Texas, Carey Salt Company, Winnfield Mine, Winnfield, Louisiana, and the United Salt Company, Hockley Mine, Hockley, Texas. A total of 48 cavities, ranging in size from 8 to 18 inches in diameter, were washed in these blocks. In order to permit visual observation of the washing process, many of the cavities were washed in half-section. A transparent Lucite plate was cemented to the salt face and the initial hole was drilled adjacent to the Lucite plate. Figure 3 illustrates the mode of washing.

In order to maintain a basis of comparison and continuity between the various techniques and the individual experiments, the experiments were limited to the formation of a spherical shape. Each technique was evaluated according to its utility in forming this particular configuration. The criteria for forming spherical chambers may not be applicable to other shapes while certain techniques, cumbersome in some applications, are well suited to others. However, much common ground exists in the basic considerations of controlled washing. For example, the utilization of gravity segregation and limitation of the surface of salt exposed by an inert blanket material must be considered in arriving at a procedure to attain a cavity of particular size and shape.

The reverse circulation method seemed better adapted to the formation of spherical shapes and was used exclusively.

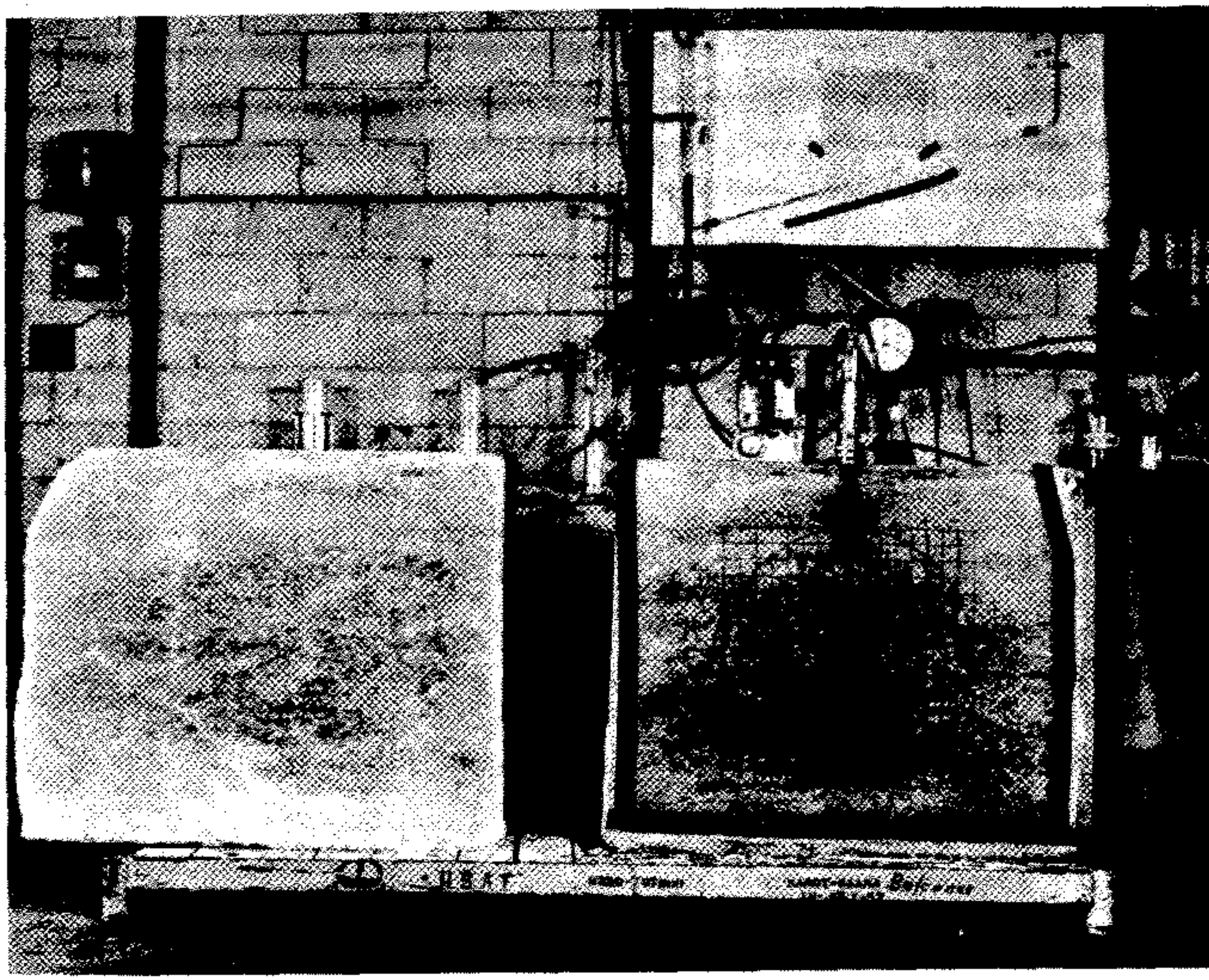

Figure 3. Equipment Set Up for Washing.

Floating String Technique

The Floating String method utilizes two concentric circulation pipe strings, a stationary outlet string and a movable or floating inlet string. The distinguishing characteristic is that the floating string is always positioned so that the point of water injection coincides very closely with the position of the blanket-water interface. The outlet string remains bottomed at total depth throughout the process. Figure 4 depicts the method of operation and progression of a cavity washed by this technique. Close control requires that the cavity be washed in a number of stages. The number of pipe manipulations increases with the complexity of the desired shape. However, the number of pipe manipulations can sometimes be reduced by using a number of concentric floating liners, as shown in Fig. 5.

As leaching progresses, any point on the surface of the exposed salt section proceeds along a path normal to the surface at that point. The rate at which that point progresses is proportional to the salinity of the water opposite that point. A prediction of progressive configurations is then possible by extrapolating from one washing stage to the next, as illustrated.

One of the complexities of this procedure arises from the fact that the final cavity configuration is the result of the alteration of each washing stage by every successive stage. Therefore, cavity shape is greatly affected by the uniformity of the salt, flow rate and pipe setting. This renders precise control very difficult.

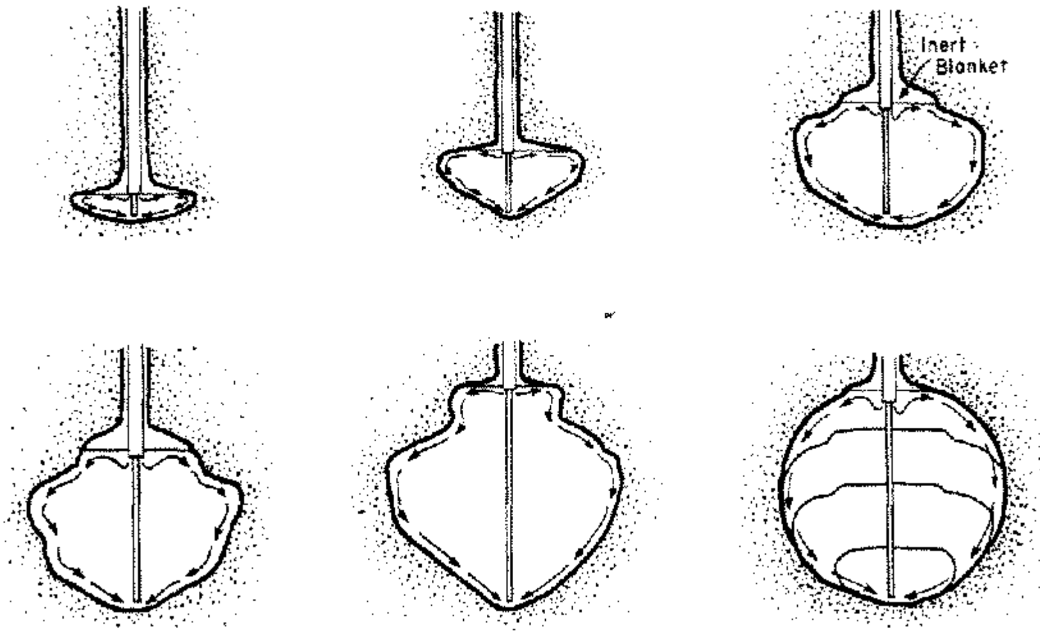

Figure 4. Progression of Cavity Washing by Floating String Technique.

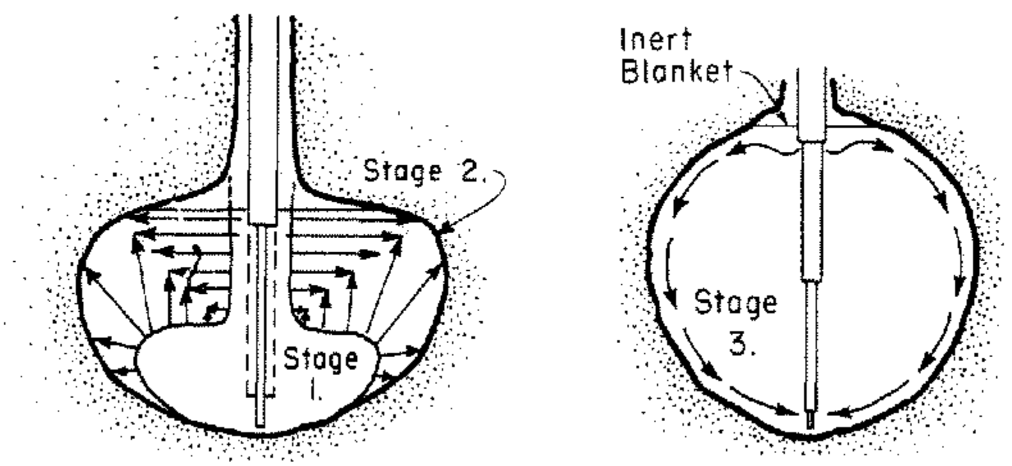

Figure 5. Cavity Progression Using Concentric Strings to Minimize Pipe Manipulation.

Stationary Pipe Technique

This technique consists of keeping the number of pipe manipulations to a minimum and moving only the inert blanket to achieve control. Both the tubing and casing are positioned only once for a given series of stages. Due to the physical set up of the circulation system, gravity segregation is not as pronounced as in the previous method and cavity progression is more cylindrical. However, enough divergence is achieved in the upper regions of the cavity to facilitate the formation of spherical shapes. Figure 6 shows the technique and type of cavity formation obtained.

The desirable feature of this type operation is that it facilitates the formation of various circulation patterns within the cavity by simplifying operational functions identified with pipe manipulations. The undesirable feature of the interdependence of washing stages is inherent in this procedure. Whereas this may be a distinct disadvantage when attempting spherical shapes, it may not be detrimental when constructing cavities of less complex configuration.

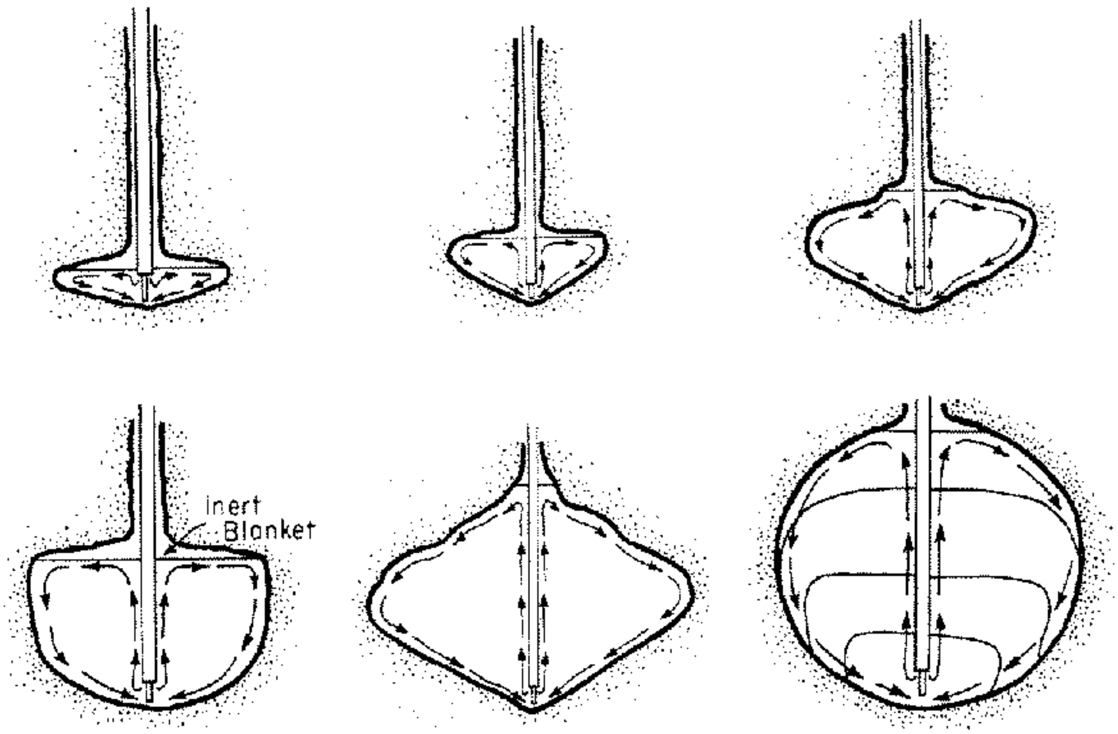

Figure 6. Progression of Cavity Washing Using Stationary Pipe Technique.

Movable Pipe Technique

This procedure consists of washing the cavity in a series of horizontal layers. The vertical extent of each layer is limited on the bottom by saturated brine and on the top by an inert blanket. Figure 7 shows the typical advance made in cavity formation using this technique.

It affords a higher degree of control than the two previous methods since the layers can be made very thin rendering almost any shape possible. However, this greater accuracy is obtained at the expense of more time consuming pipe manipulations. Moreover, precise pipe positioning is very critical.

Any one of the aforementioned systems may be used for the construction of relatively simple shapes such as cones or cylinders. Cylinders can also be formed by the direct circulation method but with less economical use of the circulating water. For more complex shapes, such as spheres, the layer technique, described below, was found to be most satisfactory.

Layer Technique

In order to visualize this process, consider the volume element formed by revolving the quadrilateral ABCD (Fig. 8a) about the vertical axis X. A series of area strips can then be revolved about this same axis, as in Fig. 8b to form concentric thin-walled segments around the original volume element. If these strips are such that their widths are very small, making the number of strips revolved very large, and the horizontal and vertical progressions are controlled, it is possible to obtain a geometric shape that closely resembles a sphere (Fig. 8c).

By utilizing this process over a wide range of flow rates and pipe settings, a cavity is formed through expanding the frustum of a conic section. The greatest diameter of the frustum of the cone always coincides with the blanket-water contact. Leaching begins with the blanket (air, natural gas or a liquid hydrocarbon) at the top of the proposed cavity. As the cavity is enlarged, the blanket is gradually lowered by an amount dictated by the geometry of the projected shape so that the blanket-water interface always coincides with the surface of the projected shape. Almost any desired shape can be constructed in this manner as long as the sides of the cavity below the blanket are confined within the limits of the superimposed shape.

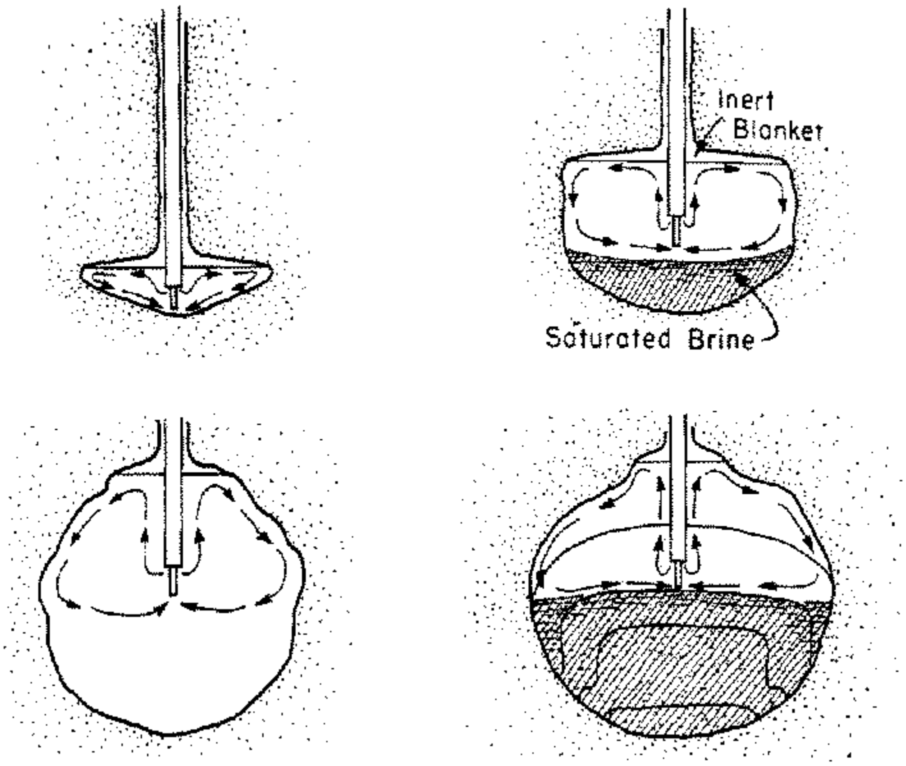

Figure 7. Progression of Cavity Washed by Movable Pipe Technique.

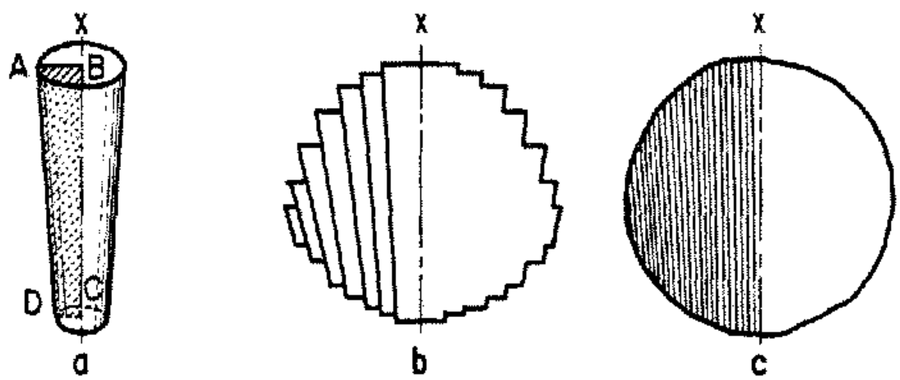

Figure 8. Formation of Spherical Shape by Revolution of Concentric Quadrilaterals.

In order to facilitate multiple staging without the disadvantage of pipe movement, the circulation system may consist of three or more concentric pipe strings as depicted in Fig. 9. When circulation is being maintained through the upper strings, insoluble material is removed by periodically switching the effluent to the tubing by means of a manifold at the circulation head. The tubing should be of a size to assure sufficient velocity for particle removal.

Determining the Position and Size of the Blanket-Water Interface

In order for this type of controlled washing to be effective in producing cavities of close dimensions, the progress of the cavity must be monitored throughout the leaching process. This can be done usually by establishing a relationship between the position of the blanket-water contact and the volume of space occupied by the blanket material in order to determine the diameter and position of the blanket-water contact.

Determination of the blanket position is relatively easy to accomplish. Since the inert blanket is usually a nonconducting material, the position of the blanket-water interface can be set by the use of resistance wires or electric probes.

The volume occupied by the blanket material is more readily ascertained when a relatively incompressible fluid is used. The volume of space occupied by the inert blanket material and the amount of mass removed below the blanket material are much more difficult to ascertain. Material balance techniques derived by Remson (4) and Kazemi (5) are available, but the practical application of equations developed has not been proven in large-scale operations. See Fig. 10.

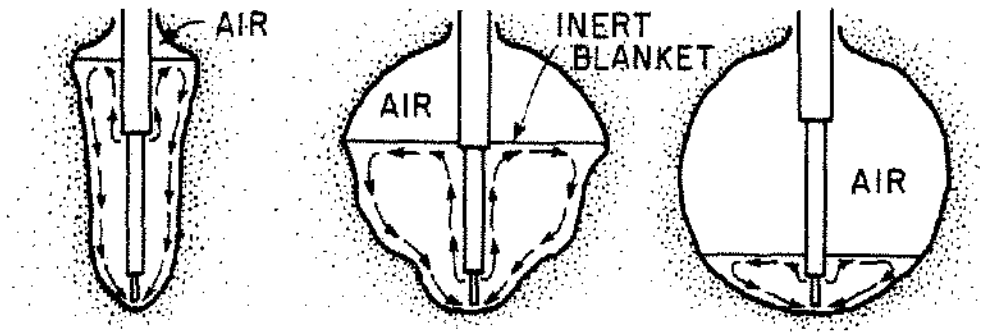

Figure 9. Concentric Washing Strings to Facilitate Formation of Spherically-Shaped Cavities Using the Layer Technique.

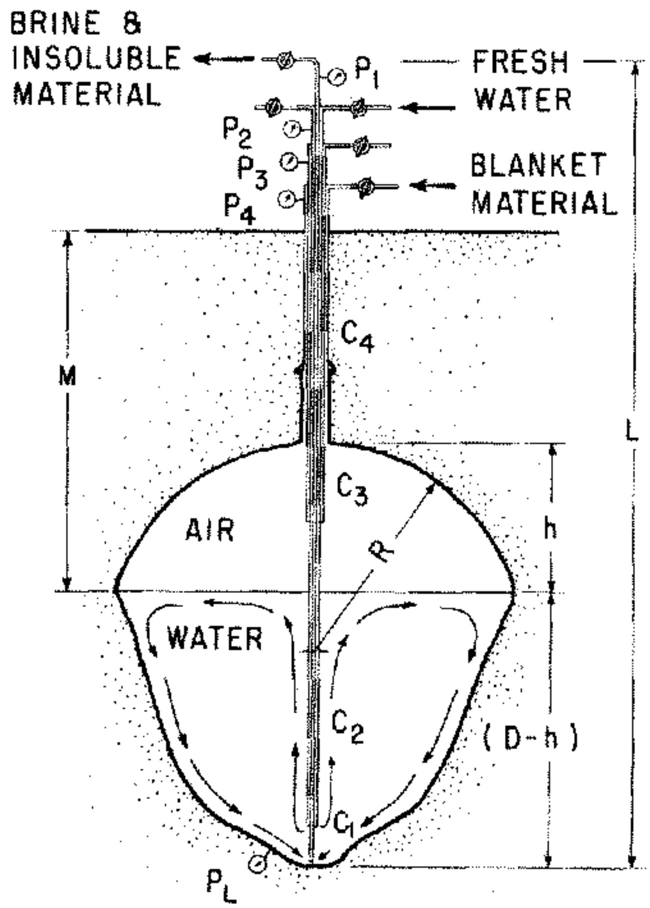

Figure 10. Schematic Diagram of Washing Process.

The most promising technique is an empirical relationship derived in the laboratory that has proved quite successful in laboratory specimens. Basically, the technique is simply an experimental relationship between blanket height and total mass removed which can be compared with the theoretical blanket space curve with any errors corrected as they occur.

In practice, the best available empirical wash curve is followed in removing salt, and blanket additions are made according to the following relation:

$$V_b = \pi \int_{R-H}^{R} (R^2 - Y^2)\, dY = \pi (RH^2 - H^3/3)$$

which relates the blanket volume V_b to the blanket height, H, for any given sphere of radius R. See Fig. 11.

The cumulative additions of blanket material made during the leaching process must equal the blanket volume V_b calculated at any given height, H. If less blanket additions were necessary, the segment under consideration was underwashed, and if more blanket volume was necessary, the segment was overwashed. In this manner, it is possible to form a spherical cavity in which the volumetric differences between the projected diameter and the overwashed section represents a maximum error equal to the sum of the overwashed segments which cannot be retrieved. Underwashed segments can be rewashed to leach additional salt as required. Figure 12 illustrates this principle graphically. The top curve is an empirical wash curve which is used only as a guide. The bottom curve is the theoretical blanket space curve which is used to control cavity shape. The cavity shown in Fig. 13 was leached according to this technique and the result was a fairly uniform spherical cavity which, except for the hidden crack, might have been 100% successful.

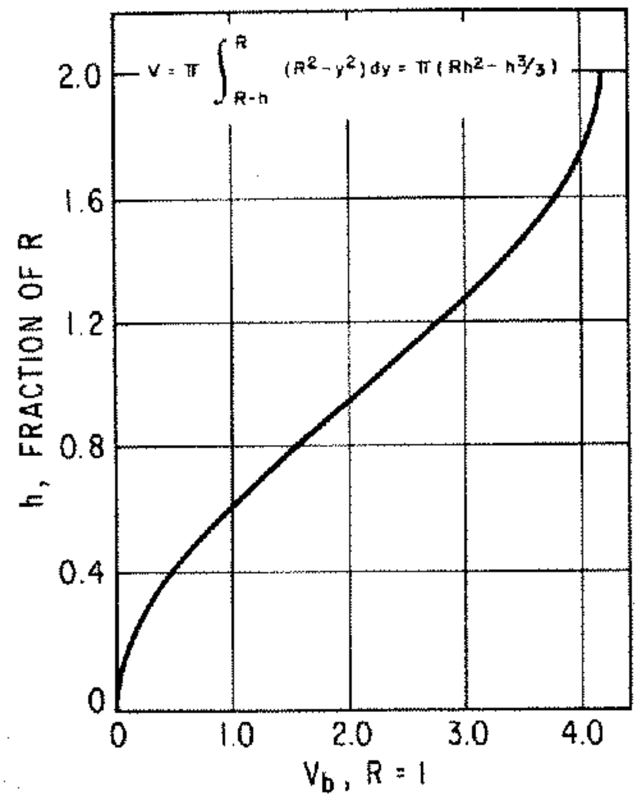

Figure 11. Position of Blanket-Water Contact as a function of Cavity Volume occupied by blanket material.

The procedure followed when using the material balance equation is given below:

1. By manipulating the blanket, find the greatest value of h such that V_b (calculated) is equal to V_b (from curve, Fig. 11).
2. Wash with blanket in this position for a certain time interval (based on experience).
3. Lower blanket by increment and again find greatest value of h such that V_b (calculated) is equal to V_b.
4. Repeat 2 and 3 throughout the process.

Figure 14 shows relation between specific gravity of brine solutions and weight per cubic foot.

By a similar technique, the water inlet can be closed and water displaced from the cavity by air. The amount of water displaced is measured and the change in water level is determined by the use of electric probes. Making the same assumption as above, the diameter of the blanket-water contact can be determined.

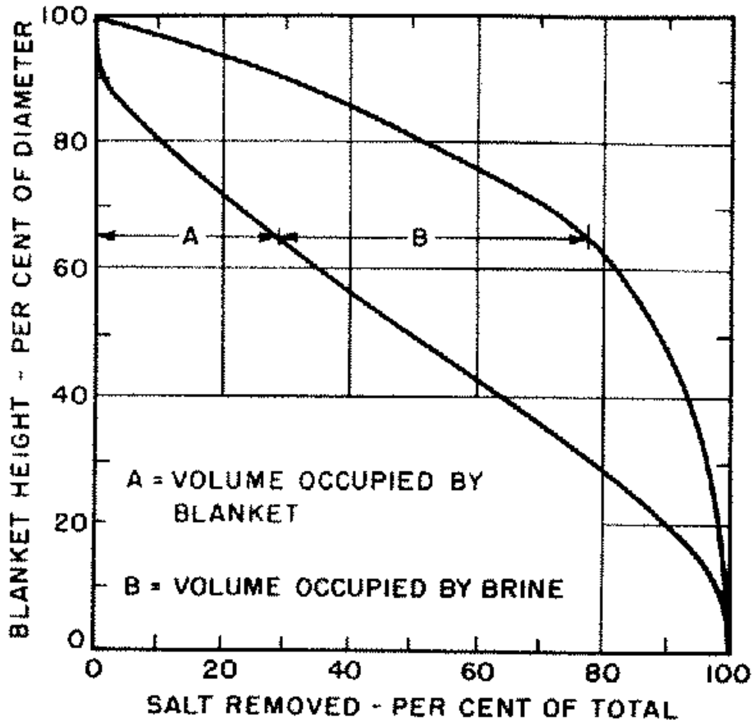

Figure 12. Washing Relationships as Analyzed from Several Cavities.

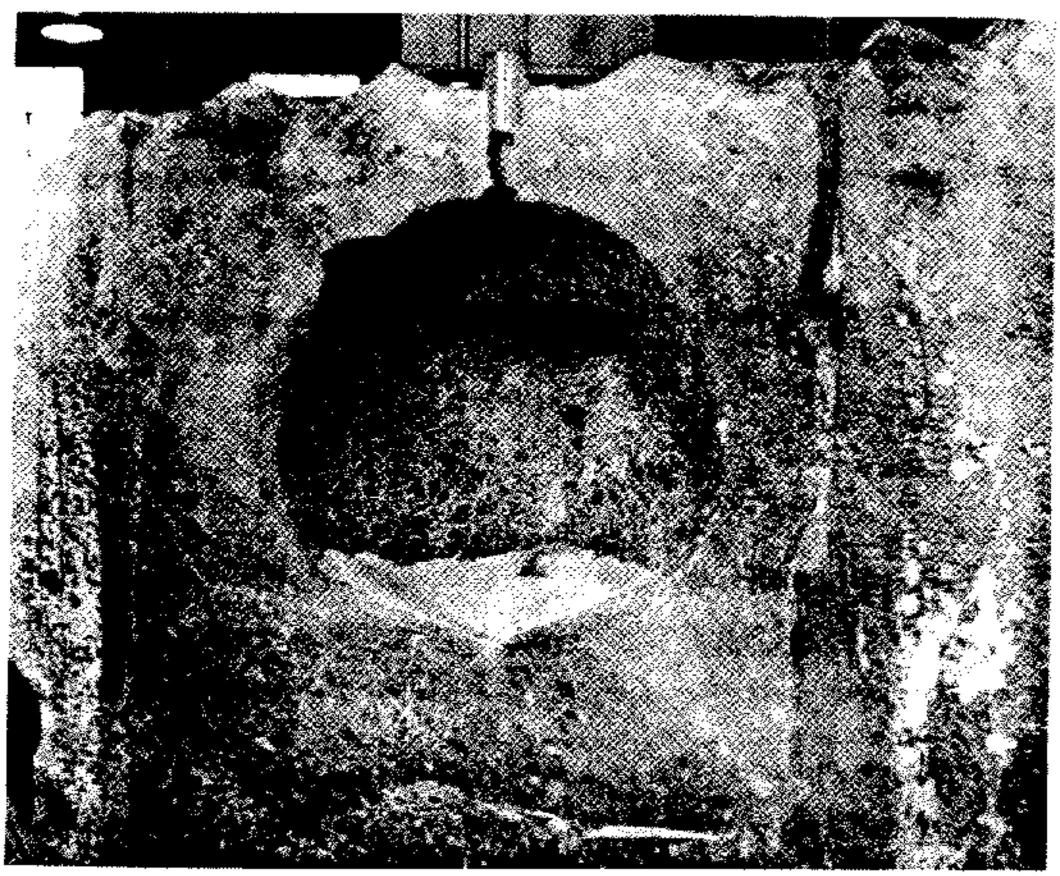

Figure 13. Cavity Leached by Using Material Balance.

Effects of Insoluble Material on Cavity Shape

The salt used in all experiments contained insoluble material, mainly anhydrite, in quantities from approximately 1% to more than 10%. The amount was fairly consistent in specimens from a given source. In several cases the bulk of the impurities was concentrated in parallel bands, several inches thick, as shown in Fig. 15.

The collection of this material on the cavity bottom acts as a barrier and greatly reduces the rate of solution in that area. If most, but not all, of this material is removed from the cavity while washing, the bottom of the cavity will assume a conic shape whose sides slope at an angle equal to the angle of repose of the insoluble material. In the case of anhydrite, this is approximately 34°.

Other effects of insoluble material on cavity shape tend to average out over the washing process and become relatively insignificant, except when the anhydrite stringers or bands are sufficiently thick to provide barriers. In such cases greater irregularity of the surface results. With severe banding of anhydrite, it would be

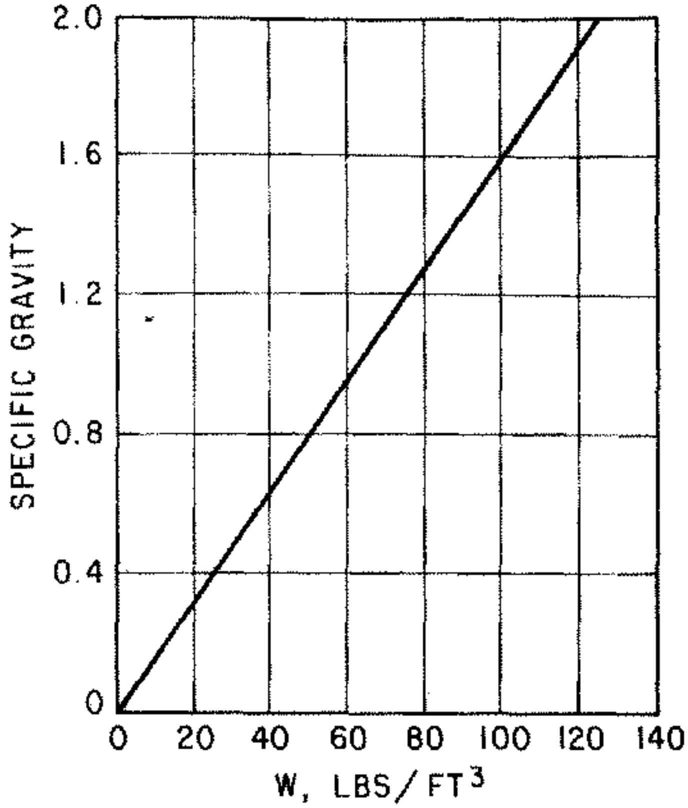

Figure 14. Specific Gravity vs. Specific Weight.

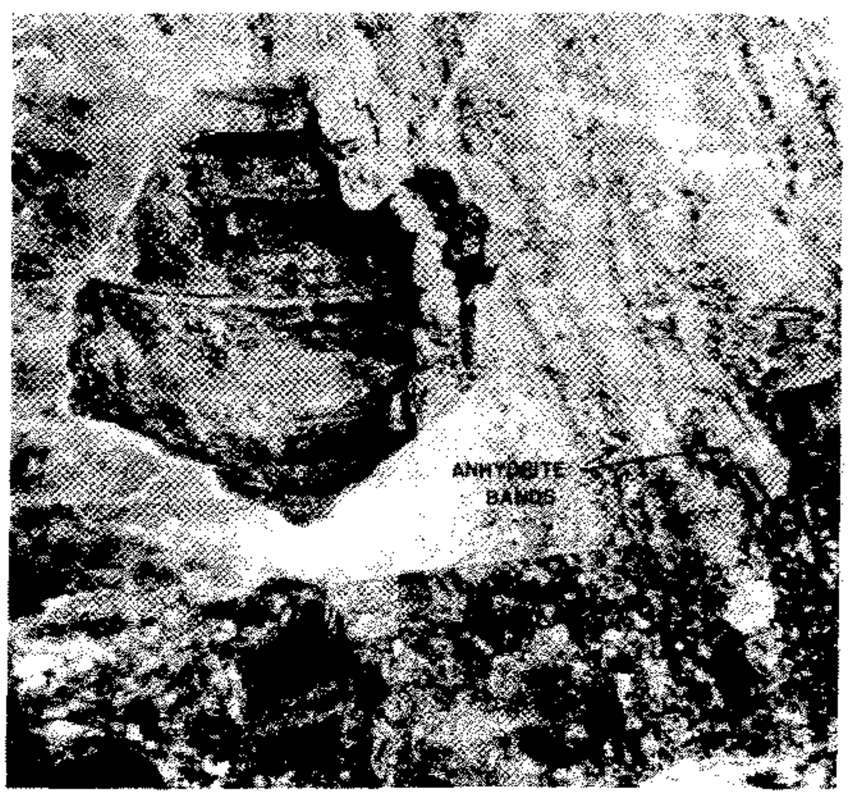

Figure 15. Occurrence of Insoluble Material.

difficult to obtain smooth surfaces. Generally, excess amounts of insoluble material in the bottom of the cavity may be removed by jetting through the tubing.

Conclusions

When fresh water is introduced into a solution cavity, gravity segregation of the circulating water takes place and a salinity profile is developed within the cavity. This salinity profile is influenced by the relative positions of the water inlet and outlet and by the flow rate. Cavity shape can be controlled by initiating the proper leaching conditions through manipulation of these parameters and a known rate of increase in the amount of blanket material.

Four controlled washing techniques are described. Each was found to be effective in forming cavities of various predetermined shapes. The effectiveness of these techniques is directly related to the accuracy with which the cavity progress is monitored.

The effects of insoluble material on cavity shape are not too serious and can be controlled to a large extent. Other problems which may arise, such as accumulation of insoluble material in the bottom of the cavity, can be minimized by correct planning and selection of pipe sizes to affect the required discharge velocity for adequate removal.

Expanded technology in leaching operations may be a contributing factor in meeting the complex requirements for future underground storage cavities.

ACKNOWLEDGMENT

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APPENDIX

Consider Fig. 10 where an intermediate step in the washing process is represented schematically. The shape of the portion of the cavity occupied by the blanket material can be determined by solving the relationship.

volume of cavity space occupied by blanket material	=	volume of material removed or dissolved	-	volume of brine remaining in cavity

in terms of the simultaneous equations listed below.*

$$P_L = P_1 + 0.00694\, W \left[\frac{V}{2g} + L\ (1 + ff)\right] \qquad \text{------------------------ (1)}$$

$$S_{WC} = \frac{P_L - P_4 \left[1 + \frac{M}{ZnRT}\right]}{(D - h)(0.434)} \qquad \text{------------------------ (2)}$$

$$V_v = V_{WO}\ (1 + F_{WO}) - V_{WI} \left[\frac{1}{1 - F_{WO}} + F_{WI}\right] + V_{WC}\ F_{WC} + V_I \qquad \text{---------- (3)}$$

$$\left[\frac{P_a}{W} + \frac{V^2_a}{2g} + Z_a\right] + H_A - H_L - H_E = \left[\frac{P_b}{W} + \frac{V^2_b}{2g} + Z_b\right]$$

$$\frac{P_a}{W} - Z_b(ff) = \frac{P_b}{W} + \frac{V^2_b}{2g} + Z_b$$

* All symbols defined at end of Appendix.

$$\frac{P_a}{W} = \frac{P_b}{W} + \frac{V^2{}_b}{2g} + Z_b + Z_b \ (ff)$$

$$P_a = P_b = W \left[\frac{V^2_b}{2g} + Z_b \ (1 + ff) \right] \frac{1}{144}$$

$$P_L = P_1 + 0.00694 \ W \left[\frac{V^2}{2g} + L \ (1 + ff) \right] \qquad \text{------------------------- (1)}$$

Also,

$$P_L = P_4 + (D - h) \ (0.434) \ (S_{WC}) + \text{Wt of air column}$$

So,

$$S_{WC} = \frac{P_L - P_4 - \text{Wt of air column}}{(D - h) \ (0.434)}$$

or finally,

$$S_{WC} = \frac{P_L - P_4 \left[1 + \frac{M}{ZnRT}\right]}{(D - h) \ (0.434)} \qquad \text{------------------------- (2)}$$

By relating the water input and effluent, and assuming water in = water out - water remaining in cavity, then

$$\frac{V_{WI}}{(1 - F_{WO})} - V_{WO} = V_{WC}$$

Furthermore, the volume of cavity = volume of salt removed from cavity + volume of salt in solution in water in the cavity + volume of insoluble material removed, or

$$V_C = V_{WO} \ F_{WO} - V_{WI} \ F_{WI} + V_{WC} \ F_{WC} + V_I$$

It then follows that the volume of cavity space occupied by blanket material = volume of cavity - volume of water in cavity,

$$V_b = V_C - V_{WC}$$

$$V_b = V_{WO} \ F_{WO} - V_{WI} + V_{FWC} + V_I - \left[\frac{V_{WI}}{(1 - FWO)} - V_{WO} \right]$$

$$V_b = V_{WO} \ (1 + F_{WO}) - V_{WI} \left[\frac{1}{(1 - FWO)} + F_{WI} \right] + V_{WC} \ F_{WC} + V_I \qquad \text{--------- (3)}$$

Determination of

P_1, P_2, P_3, P_4 -- from pressure gages

V_{WI}, V_{WO}, V_I -- from meters and direct measurements

h, S_{WI}, S_{WO} -- from direct measurement

Legend

C_1 -- innermost circulating string, extends to bottom of cavity

C_2 -- intermediate string, does not extend to bottom

C_3 -- outermost string, extends short distance below top of cavity

C_4 -- protective string, cemented through cap rock

P_1 -- surface pressure (psig @ wellhead), discharge pressure inside C_1

P_2 -- surface pressure C_1 - C_2 annulus

P_3 -- surface pressure C_2 - C_3 annulus

P_4 -- surface pressure C_3 - C_4 annulus

R -- radius of sphere (ft.)

h -- distance from top of cavity to blanket-water contact (ft.)

L -- distance from bottom of cavity to outlet, in effect length of C_1 (ft.)

V_{wo} -- volume of brine discharged from cavity

V_{wi} -- volume of fresh water pumped into cavity

V_I -- volume of insoluble material removed from cavity

V_b -- volume of cavity space occupied by blanket material

V_{wc} -- volume of cavity space occupied by water

S_{wo} -- average specific gravity of V_{wo}

S_{wi} -- average specific gravity of V_{wi}

S_{wc} -- average specific gravity of V_{wc}

F_{wo} -- salinity factor of V_{wo}

F_{wi} -- salinity factor of V_{wi}

F_{wc} -- salinity factor of V_{wc}

V -- velocity of outlet brine (ft./sec.)

q -- acceleration of gravity (32.2 ft./sec./sec.)

W -- specific weight of outlet brine (lbs./cu. ft.)

ff -- friction loss in (ft. head/ft. length)

V_c -- volume of cavity

M -- distance from the surface to the blanket-water contact

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