Accomplishments of SMRI-sponsored Salt Dissolution Research since the Fourth Symposium on Salt

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ABSTRACT

Since 1973, salt dissolution in unsaturated brine, a turbulent natural convection mass transfer, has been further studied and through laboratory experiments it was conclusively shown that dissolution is affected by many factors such as solvent concentration, temperature and velocity as well as salt surface inclination, roughness and amount of impurities. The dominant factor in dissolving a salt cavity is the injected fresh water plume which was studied with and without the lateral confinement conditions. As a result of the above studies, a numerical model for simulation of cavity leaching was first developed in 1974. Through continuous research more advanced versions of this model were developed and have been successfully utilized by the salt and storage industry. Other experiments have proved that lateral jet injection can be utilized for directional enhanced dissolution and the reach of a jet stream as a function of fluid velocity and local buoyancy was formulated. A side product of this study was multiple jet injection method which when applied in the field resulted in excellent results in overcoming the plugging problem when the injection tube was buried under insolubles. Useful information about salt dissolution in bedded salt and collapse of the insoluble stringers has been acquired through model studies performed in the laboratory. The model studies for fracture-connected multiple well systems were initiated by conducting dissolution experiments in horizontal conduits; and essential information for numerical modelling of such systems has been obtained.

INTRODUCTION

The problem of prediction of cavity shape and produced brine concentration has been studied in some detail for the past several years. Laboratory scale model studies employing salt blocks, and computer modelling utilizing data inputs from this work have been used to formulate relations capable of predicting the shape of a cavity and the produced brine concentration as a function of time and other variables, such as inlet-outlet position, rate of injection, height of salt exposed to dissolution, etc. Valuable information about the mechanics of solution mining had been gained through laboratory and field experiments[5,6,7,28]. However, development of a suitable computer model first required understanding of the mechanics of fluid flow and mass transport in the cavity. For the case of top injection-bottom production, the fluid flow in the cavity can be approximated as a plug flow throughout the washing period. For the other cases of intermediate injection (reverse circulation) and direct circulation, the mechanism of fluid flow in the cavity varies with time during the leaching operation because of buoyant rise of lighter fluids. For instance, for the direct circulation method, the flow can be described in the beginning as annular flow. The rate of salt dissolution would be found to be dependent on the velocity of flow as well as on brine density, etc. As the cavity diameter increases to several times the original bore hole diameter, the flow, although still momentum-dominated, cannot be classified as annular flow, since the fluid exhibits vortices or whorls caused by buoyancy. Finally, when the cavity has enlarged (mature cavity), the walls of the cavity have little effect on the rise of the fresh water, and buoyancy controls fluid flow in the cavity. At this stage, two distinct systems of mass transfer co-exist in the cavity: first, the entrainment or mixing of cavity brine into the rising fresh water (buoyant plume), and second, dissolution along the walls of the cavity and convective transfer of salt into the cavity brine. These two systems of mass transfer co-exist in the systems unified by the brine in the cavity.

SALT DISSOLUTION MECHANISM

It is generally agreed, based on the analogous technology of heat transfer, that in free convection boundary layer flow, turbulence begins when the product of the Grashof and Schmidt numbers exceeds 10^9. Based on this and the work done since last Symposium in this area, it has been shown that salt dissolution at the walls of a cavity may be described as turbulent boundary layer transfer[1].

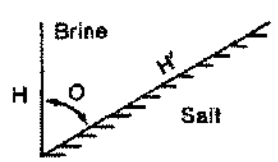
Dissolution data for vertical salt surfaces gathered by previous investigators[3,29] were used to derive an empirical relation between brine concentration (density) and the rate of mass transfer at 24°C solvent temperature.

$$\frac{1}{\rho_{SALT}}\left(\frac{dm}{dt}\right) = \frac{C_1}{\rho} + C_2 + C_3\rho + C_4\rho^2 + C_5\rho^3 + C_6\rho^4$$

The effect of surface inclination. The convective dissolution for non-vertical salt surface can be divided into two categories based on the attitude relationship of the salt-brine interface:

1. the stable condition—brine above the salt face.
2. the unstable condition—brine under the salt face.

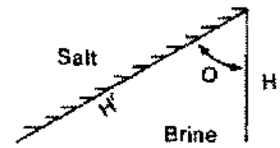
Durie[4] showed that the rate of dissolution decreases as θ increases, where θ is the acute angle between vertical and the salt surface, ranging from zero to 90 degrees.



Analysis of Durie's data yielded the following relation:

$$\left(\frac{dm}{dt}\right)_{\theta > 0} = \left(\frac{dm}{dt}\right)_{\theta = 0} (\cos\theta)^{1/2}$$

For the unstable condition, where the salt surface is above the brine, previous work[4] proved inconclusive and a new series of experiments was conducted. Initially, data were obtained for horizontal surfaces ($\theta = -90°$) where θ is the acute angle between vertical and the salt surface ranging from zero to $-90°$.



Experimental salt dissolution rates for cellular flow are plotted in Figure 1. A smooth curve fitted through the points showed that the two curves for $\theta = -90°$ and $\theta = 0°$ are related by a proportionality constant which was calculated to be 1.44.

Dissolution rates were also measured for attitude angles of $-30°$, $-45°$ and $-60°$ employing different brine concentrations. Results are plotted in Figure 2. The data points revealed that there is a significant increase in the dissolution rate between inclinations of $-40°$ and $-50°$. Experiments showed that the flow trajectory changed significantly at this surface inclination range.

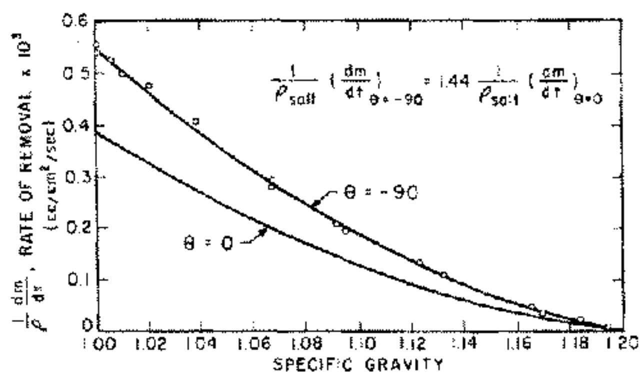


Figure 1. Volumetric rates of salt dissolution vs. specific gravity of the solvent (brine).

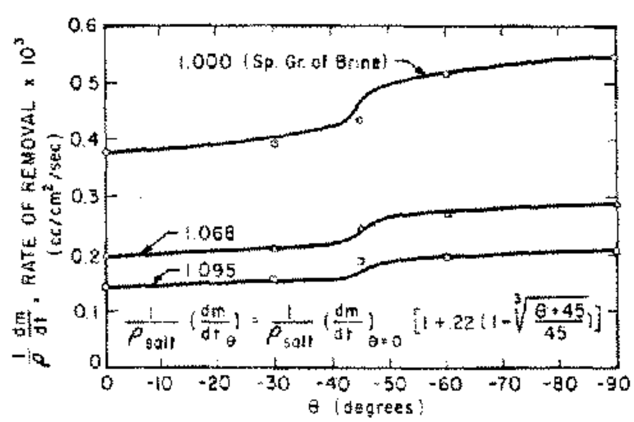


Figure 2. Effect of salt surface inclination on the rate of dissolution.

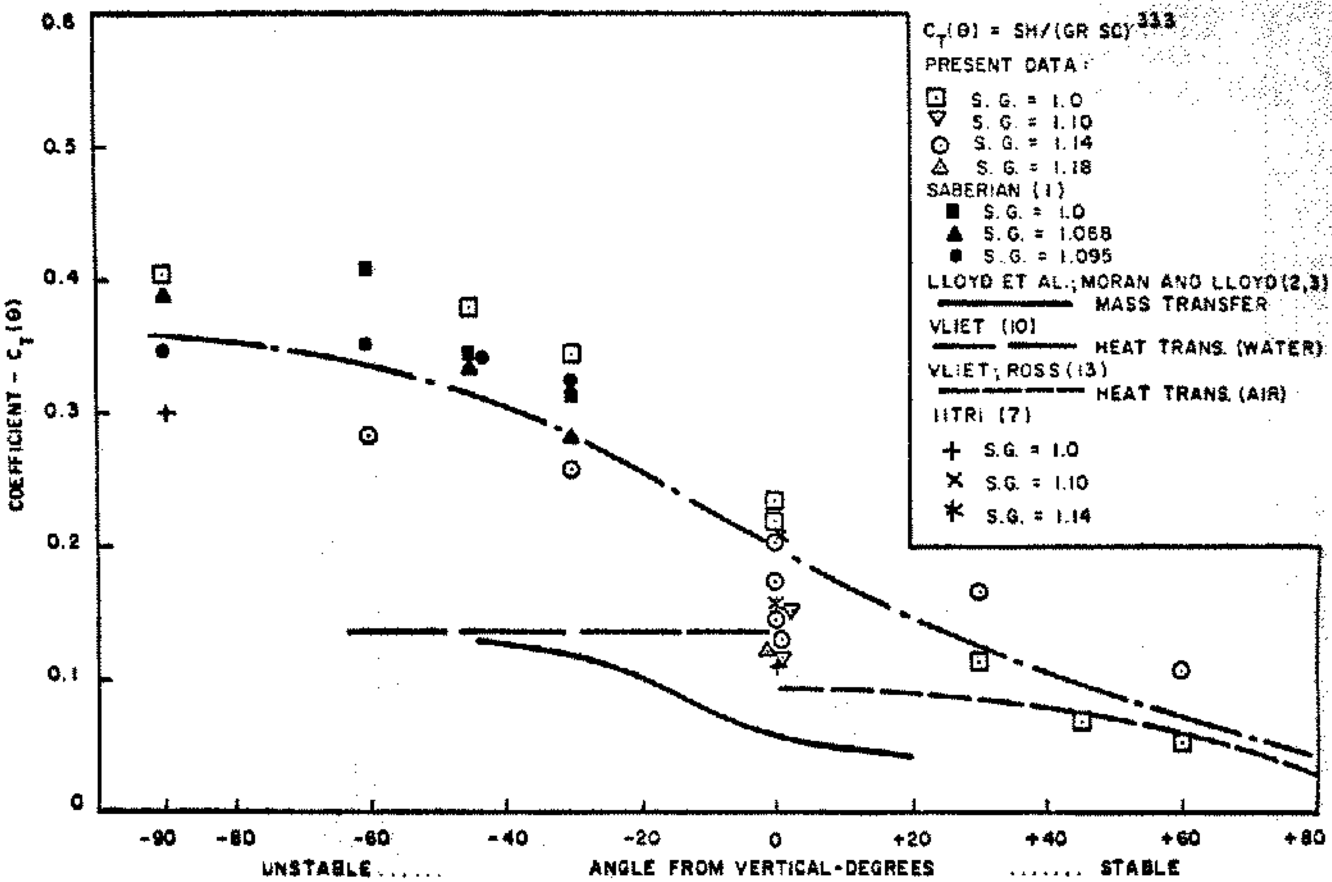


Figure 3. Angle dependent correlation coefficient.

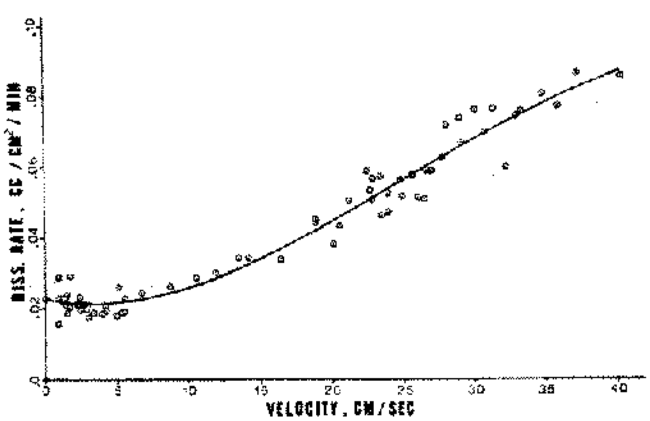


Figure 4. Effect of solvent (water) velocity on rate of dissolution.

The following relation best fits the data points:

$$\frac{1}{\rho_{salt}}\left(\frac{dm}{dt}\right)_{\theta} = \frac{1}{\rho_{salt}}\left(\frac{dm}{dt}\right)_{\theta=0}$$

$$\left\{1 + .22\left[1 - \sqrt{\frac{\theta + 45^\circ}{45^\circ}}\right]\right\}$$

In a different dissolution study[1], on large salt samples (1 meter long) similar results were obtained (Figure 3).

Effect of the solvent velocity. Experiments were conducted for small samples suspended in a flow tube and the results indicated that dissolution rate increases with solvent velocity and an empirical relation was derived (Figure 4).

Effect of temperature. Experiments were conducted to evaluate the effect of temperature on the rate of dissolution. 6 salt samples were used for 3 different solvent concentrations in the 75 to 120°F temperature range (Figure 5). Later the range of 40 to 75°F was also covered. The results indicated that the rate increased proportional to the temperature.

PLUME RISE MECHANISM

Since the Fourth Symposium the mechanism of fresh water injection in brine and performance of the resulting plume was further studied. Convective flow in a medium motivated solely by buoyancy is commonly known as simple plume flow. A simple plume is characterized by zero vertical velocity at the origin of the flow. On the other hand, a forced plume is characterized by the momentum of the fluid at the source.

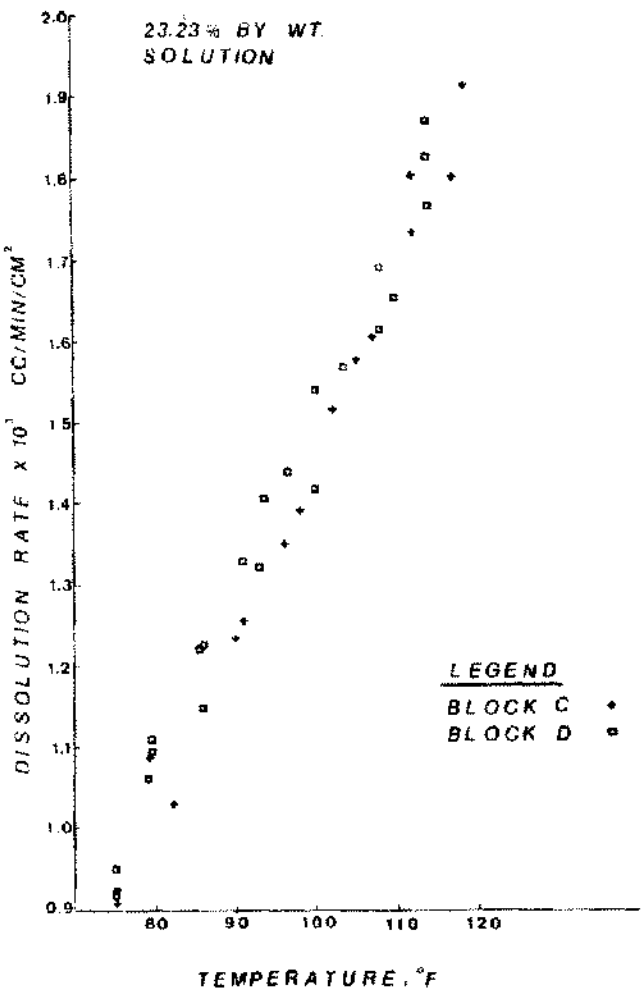


Figure 5. Salt dissolution rate vs. brine temperature.

Among the extensive plume studies available in the literature, only a few cases were reported where the direction of flow from the outlet was opposite to the buoyancy direction.

In cases where the buoyant rise of the plume is opposed either by a rigid surface or a density barrier, vertical movement is redirected laterally. In this case, the term "vertically confined plume" has been used in the literature[27]. Four distinct flow regimes are recognized in vertically confined forced plumes as shown in Figure 6:

1. In the laminar flow zone (for low rates of injection), little or no mixing is observed.
2. The second zone, known as the positive entrainment region, includes the zone of turbulent mixing.
3. The third zone includes the transition between the positive entrainment and drift regions. This zone is limited in extent if the ambient brine is uniform in density. However, in stably stratified brine, this zone is most extensively developed and is known as the negative entrainment region.

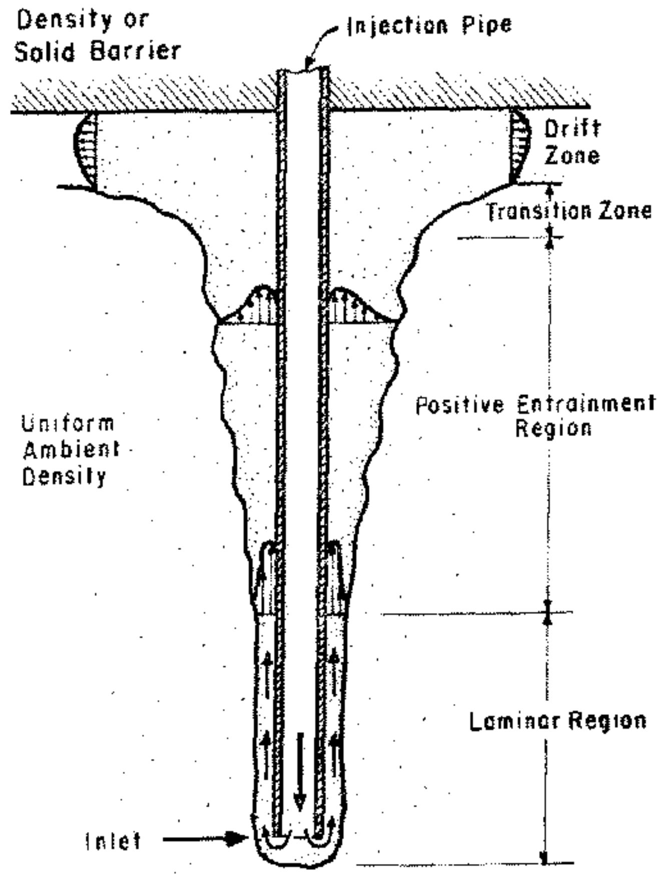


Figure 6. Schematic diagram of a vertically confined plume ($F_d < 1$).

4. The drift region is the zone which is developed due to the existence of cavity roof or other vertical rise confinement (pad or blanket).

Lateral confinement of the plume affects its rise similarly to the way vertical confinement does. The hydro-dynamic regime of plume rise in a confined environment is limited by the distance to the lateral confining boundary and the distance between the inlet and the vertical confinement level. In the process of solution mining, the diameter of the cavity (lateral confinement) and the distance from injection level to the roof (vertical confinement) determine the flow characteristic of the plume.

The importance of lateral confinement stems from the fact that it causes the inversion of the brine density gradient, creating a transient situation in which denser brine overlays lighter brine.

In order to study this aspect of the problem a laboratory model study was undertaken[5,28]. A half-cavity was leached by reverse circulation in a two-meter-high salt block. The model cavity was characterized during development by the ratio of L_p, the distance from the inlet to the blanket fluid

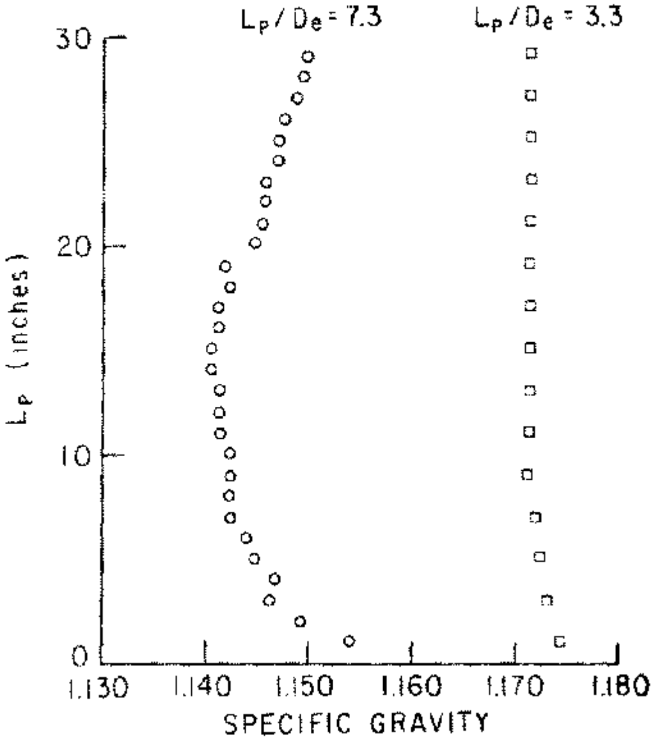


Figure 7. Variation of the brine concentration profile in a model cavity as a function of L_p/D_e.

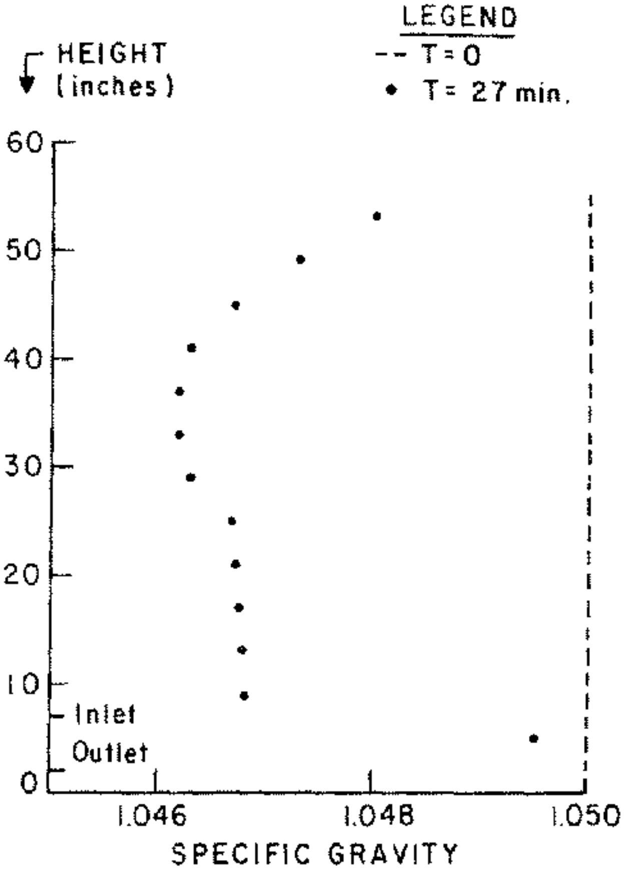


Figure 8. Gravity inversion caused by the lateral confinement in a plume rise experiment[13].

level, to D_e, the average cavity diameter over the distance L_p. The initial L_p/D_e was 57.5 and decreased to 2.9 when the washing was terminated due to enlargement of the cavity diameter to the edge of the salt block. Measurement of cavity brine concentration at L_p/D_e of 7.3 indicated a gravity inversion in the brine as shown in Figure 7. When L_p/D_e decreased to 3.3 through cavity enlargement as the result of continued dissolution, the inversion disappeared. Uniformly concentrated brine occupied about 75% of the distance, L_p, and the rest of the brine in the cavity exhibited a negative concentration gradient. If dissolving could have continued, resulting in further reduction of L_p/D_e, it is expected that the measurement would have indicated a negative gradient throughout.

It was concluded from experiments conducted in a 1.5 m high, 30 cm diameter plexiglas cylinder that the level at which the gravity inversion was observed corresponded closely with the location where the cavity walls restrained the rise of the plume. It was also concluded that plume characteristics can be described on the basis of the densimetric Froude number (F_d), defined at the outlet.

For $F_d < 1$ buoyancy is the dominant force. The length of the laminar region increases to a maximum and then decreases to zero as F_d increases from 0 to 1.

For $F_d > 1$ the laminar region disappears, turbulent mixing is present from the outlet, and fluid momentum at the outlet contributes to the rise velocity.

In studies of the confined plume, the plume and the ambient brine were distinguishable below the level where lateral confinement affected the rise and growth of the plume. However, above this level such distinction could not be made. The onset of gravity inversion correlated with the level at which confinement was established. One example is shown in Figure 8.

LABORATORY STUDIES OF OTHER FACTORS IN LEACHING PROCESS

Effect of insoluble stringers on cavity shape. 1) Three Layer Bedded Salt Model[24]: The model consisted of three slabs of rock salt attached together by thin layers of cement. A cavity was leached in the model by direct circulation method (bottom injection-top production) during a 51 hour experiment. The cavity shapes are shown in Figure 9. The cavity brine gravity measurements showed an inversion throughout the leaching time.

2) Five Layer Bedded Model with Partially Soluble Stringers[26]: In constructing the model, a mixture of salt and cement (92% to 8% by weight) was used for stringers to facilitate the breakaway condition. A 65 hour leaching ex-

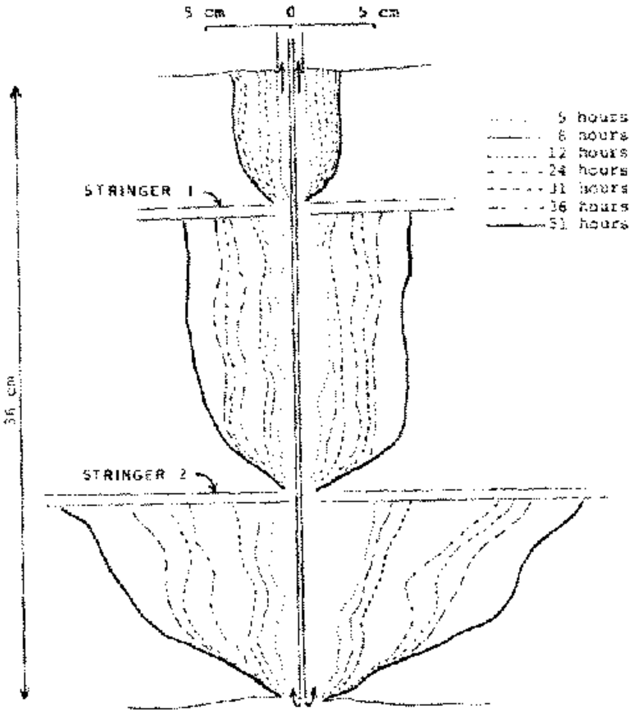


Figure 9. Cavity shape vs. leaching time[24].

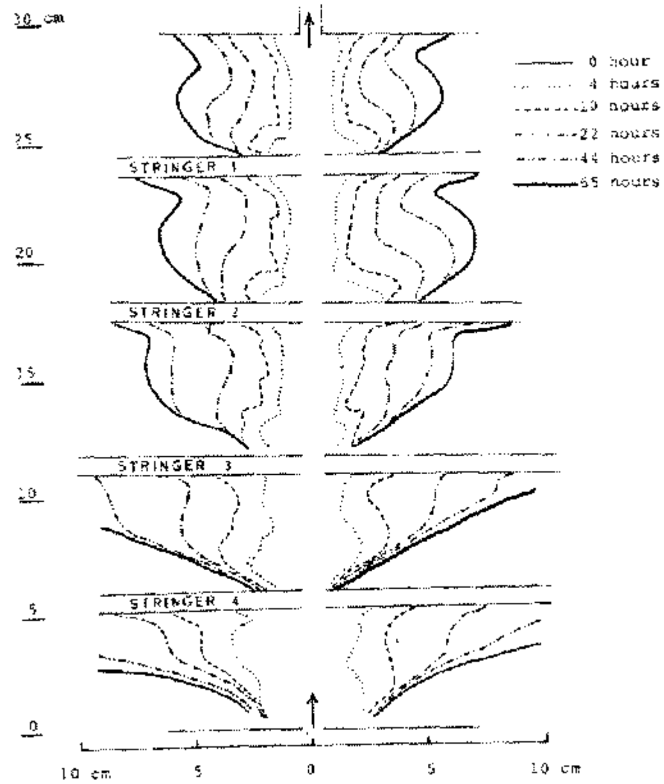


Figure 10. Bedded salt model, cavity shapes vs. leaching times[26].

periment was conducted and the recorded cavity shapes are shown in Figure 10.

The above experiments in conjunction with another leaching test in a bedded model with inclined stringers have provided valuable information which will be used in future numerical modelling work.

Cavity leaching in two well fracture connected systems. The mechanism of salt dissolution in galleries or connecting conduits in two well systems has been of great interest to operators of solution mining systems in bedded salt. The results of the few reported experiments are questionable, since the free air from the injected water (due to gain in salinity) had formed air pads and obstructed the true dissolution pattern. In field practice, pressures are thought to be high enough to keep the air in solution.

1) Salt Dissolution in Horizontal Conduits[25]: Experimental work began by studying the salt dissolution in a horizontal conduit, 6 mm tall, 1.5 mm wide and 80 cm long. An air gathering port had been constructed at the injection side to remove the freed air from the system. A 48 hour leaching experiment injecting 50% saturated brine at 30 cc/min was conducted. Resulting conduit shapes are shown in Figure 11.

2) Salt Dissolution in a Horizontal Fracture: A leaching experiment was conducted in a horizontal fracture model 25 cm wide, 1 mm tall and 60 cm long. An air gathering system had been constructed on the injection side. The experiment began by circulating water at 5 cc/min to obtain saturated brine on the production side. The results indicated that by keeping the saturation line above the production level, there was little or no dissolution on the production side.

Additional fracture dissolution experiments have been planned, which should provide the needed data for development of a numerical model for multiple well systems.

Directional dissolution in cavity leaching. Leaching experiments[3,20] have indicated that directional dissolution can be achieved in a cavity by means of a horizontal jet, provided that the stream reaches the cavity wall (Figure 12).

1. The Horizontal Penetration of a Buoyant Jet Stream in Brine: Numerous experiments, using three different diameter jets, were conducted. The results indicated that the densimetric Froude number at the jet outlet controls the reach of the jet stream (Figure 13).
2. Application of Jet Injection in Cavity Leaching: Multiple jet injection can lessen the chances of tubing plugup by insolubles, encountered in tubing injection. A comparison of data from field cavities, one leached by conventional tubing injection and the other by jet injection clearly confirms the above statement[23].

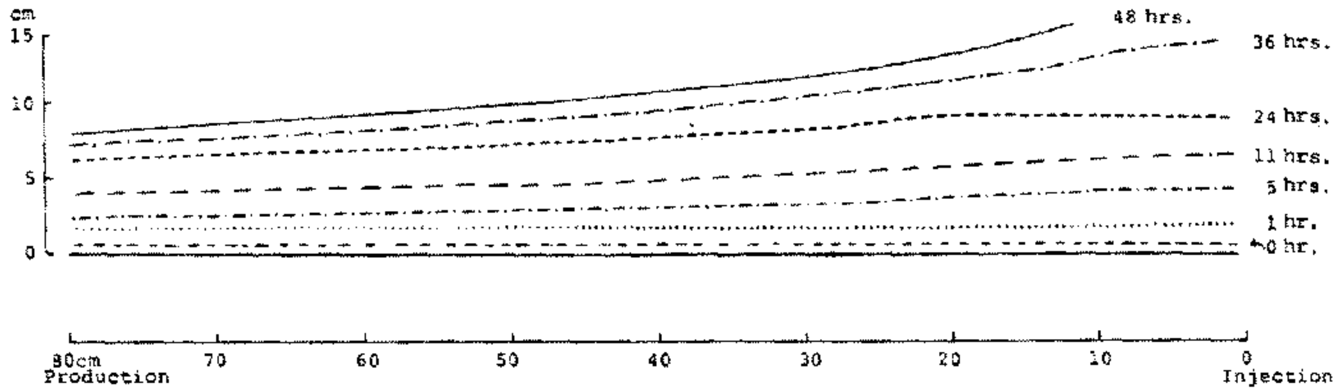


Figure 11. Conduit roof location vs. leaching time[25].

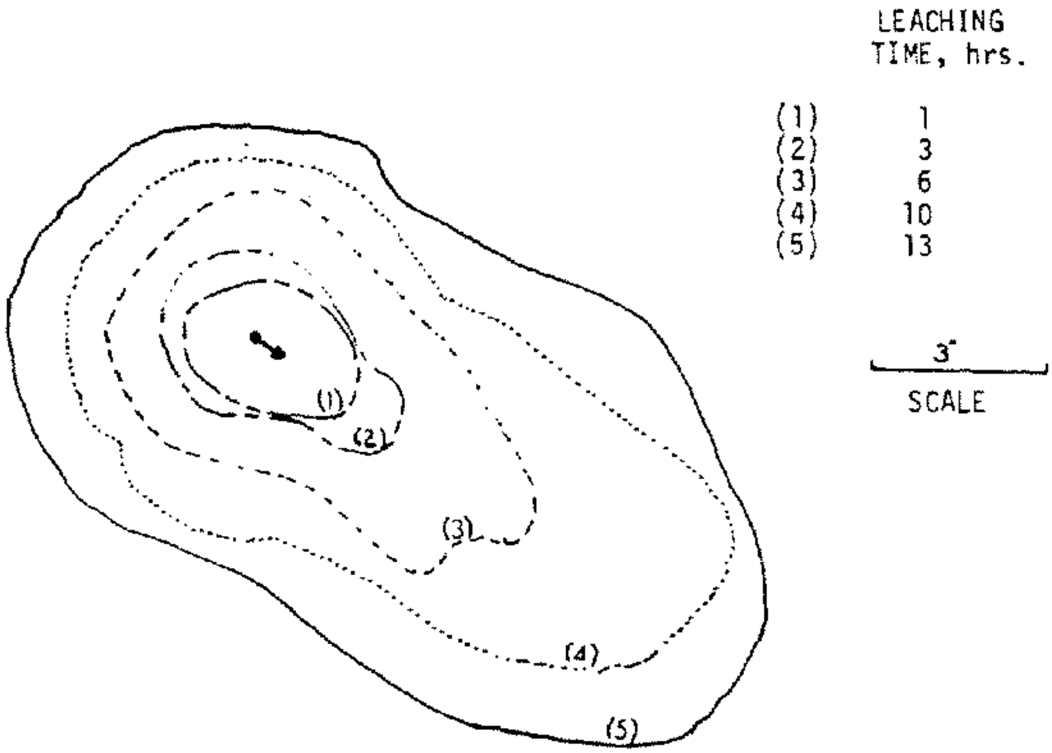


Figure 12. Cavity cross-sections at the jet level[9].

CAVITY DEVELOPMENT SIMULATION

In the majority of reported attempts at salt cavity simulation, the problem has been oversimplified to the extent that the application of these methods to a field case generally yielded large discrepancies between predictions and actual field measurements. A numerical model was used to simulate a nine-day leaching experiment of a 60 meter high cavity developed in a salt mine (top injection, bottom production). This experimental pilot-size cavity experiment was reported by Jessen[6]. The model treated the cavity as a tube with injection at one end and production at the other. In 1972, Jessen[5] reported the development of a method for shape prediction of a mature cavity. Under the assumption that brine concentration in a mature cavity was in a steady state, the concentration profile was used to evaluate dissolution rates and the cavity shape corresponding to an additional one year of leaching was calculated. Similar work was reported by Pottier and Esteve[10] in 1973. They used the results of numerous sonar surveys and production data to simulate numerically a period of 2 months of leaching. In 1974, Nolen et al.[8] reported the development of a three

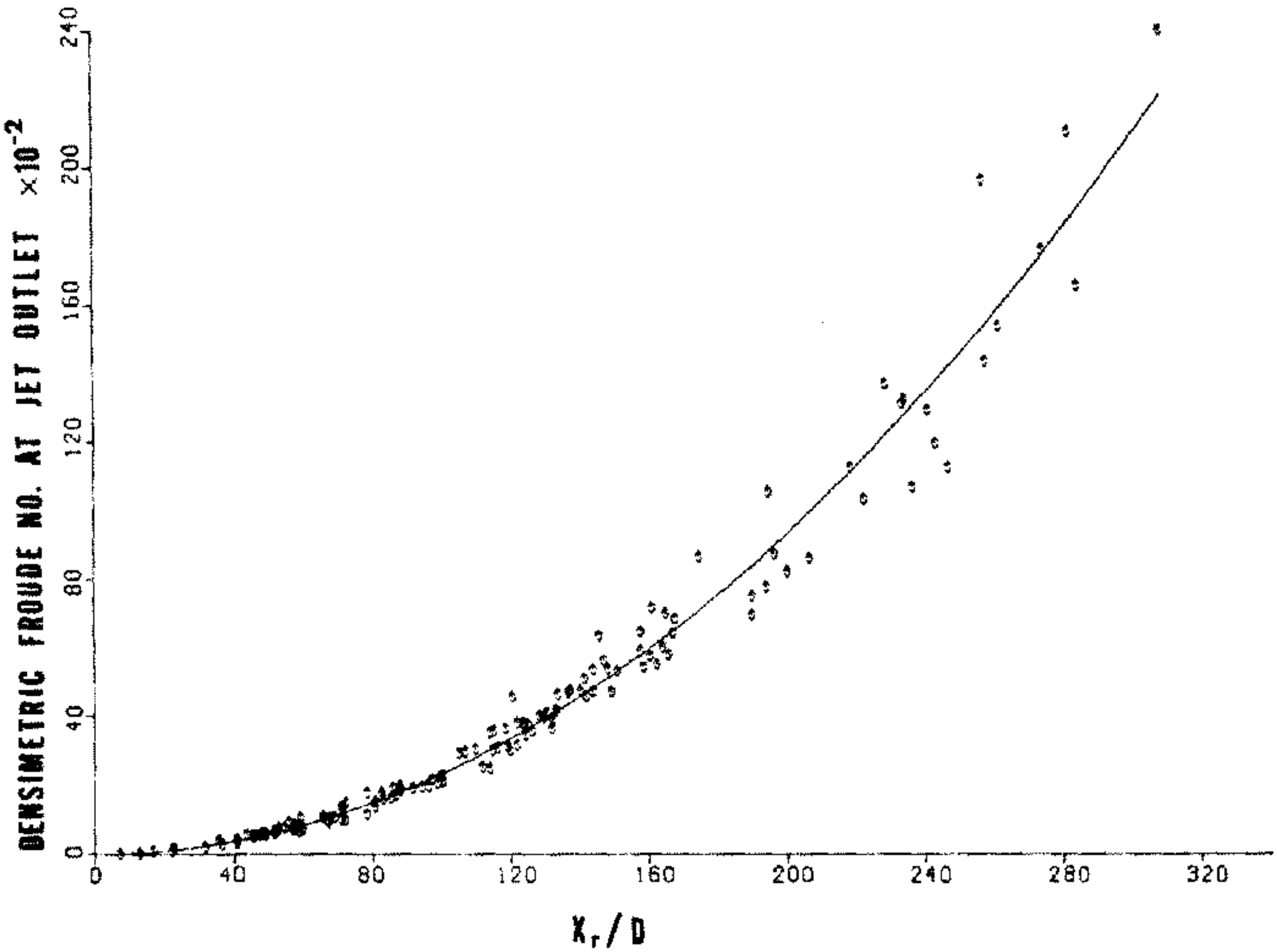


Figure 13. The reach of horizontal bouyant jet streams in brine[22].

dimensional numerical model for cavity development by solution mining. Basically, the model is an oil reservoir model which has been modified to simulate the solution mining process.

The numerical model, SALT77, today used in industry for planning single cavity leaching operations is the product of several years of SMRI sponsored research. The chronology leading to the development of SALT77 is as follows:

MIXING1 (1972–73)
MIXING2 (1973)
MIXING3 (1974)
SALT76 (1976)
SALT77 (1977)

The computer program MIXING1 was developed using the results of five different water-brine experiments[11] with reverse circulation in both uniform and stratified brine. Figure 14 represents the simulated and measured brine concentration for one of the five experiments.

For development of MIXING2, additional checking of the program, especially in reference to scaling, was obtained by simulating a mixing experiment in a large tank (125,000 gal)[13], which resulted in close agreement between the measured and calculated brine concentration profile in the tank (Figures 15a, 15b).

In Phase Three (MIXING3), simulation of the complete development of a cavity starting from a bore hole for either direct or reverse circulation with constant or variable injection rate was developed. The numerical model was designed with the minimum of limitations possible, allowing the simulation to be accomplished by integrating the salt dissolution and confined, or free plume mixing relations. The computer program consists of a main program and six subroutines and/or functions. Figures 16, 17a and 17b show the comparison between the model's cavity shape prediction and sonar measurements of two field cavities.

SALT76, a more advanced version of MIXING3 was developed after receiving feedback from the users of MIXING3. Added options included provisions for: 1) dis-

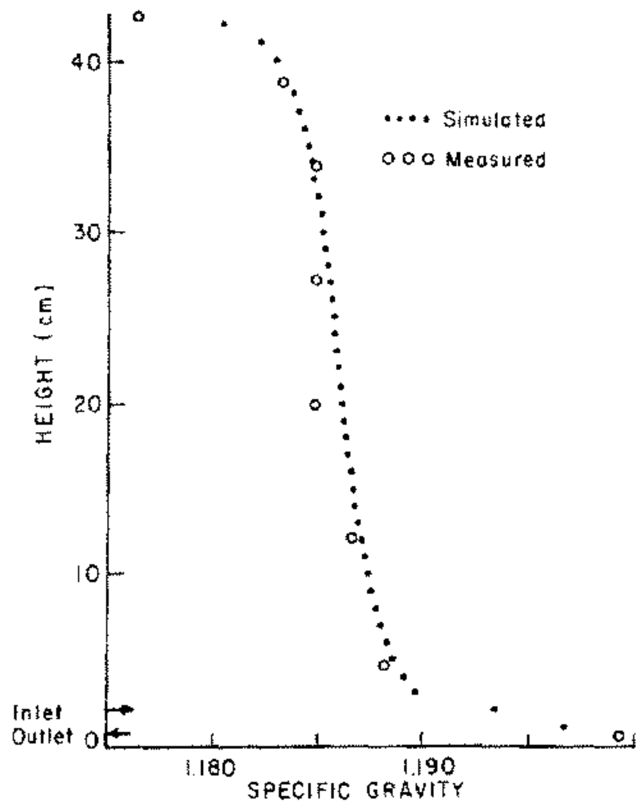


Figure 14. Comparison of measured and numerically stimulated (MIXING 1) brine concentrations after 47 hours of water circulation in originally uniform, saturated brine[13].

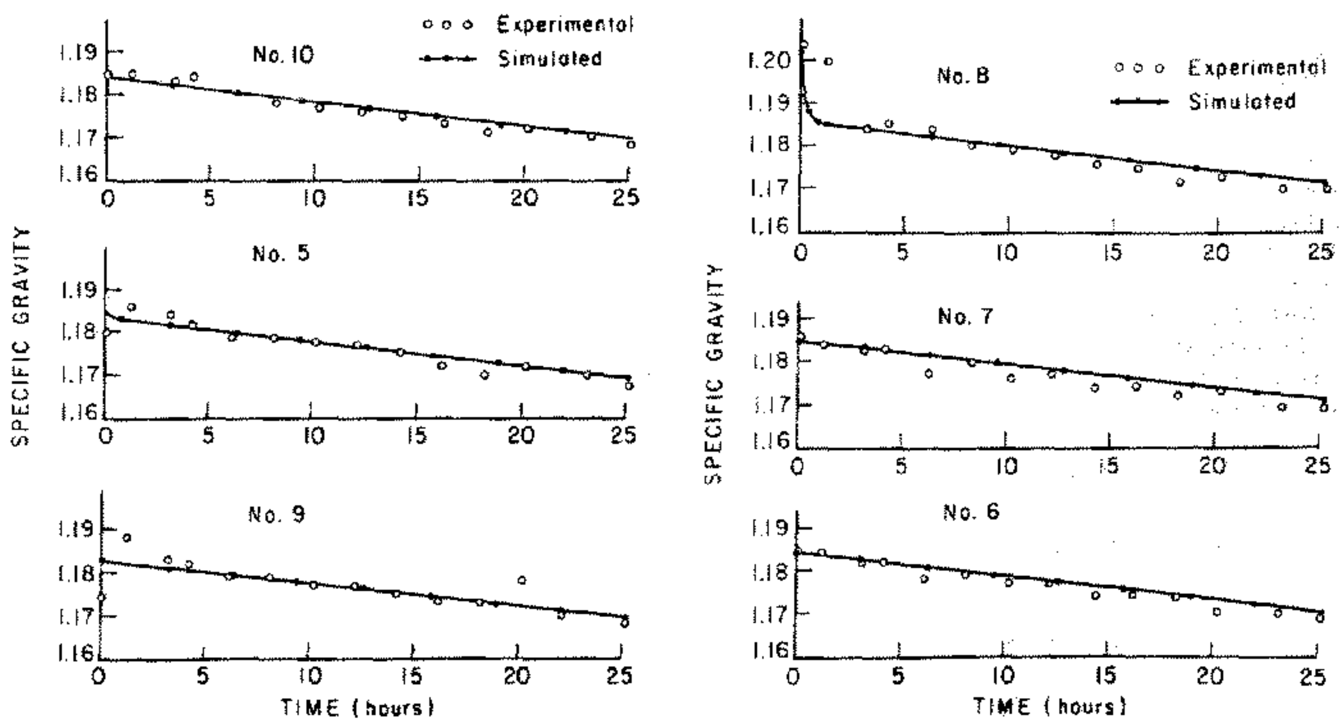


Figure 15a. Comparison of measured and simulated (MIXING 2) brine concentrations at sampling levels 10, 5 and 9 of the mixing experiment in a 125,000 gallon tank[13].

Figure 15b. Comparison of measured and simulated (MIXING 2) brine concentrations at sampling levels 8, 7, and 6 of the mixing experiment in a 125,000 gallon tank[13].

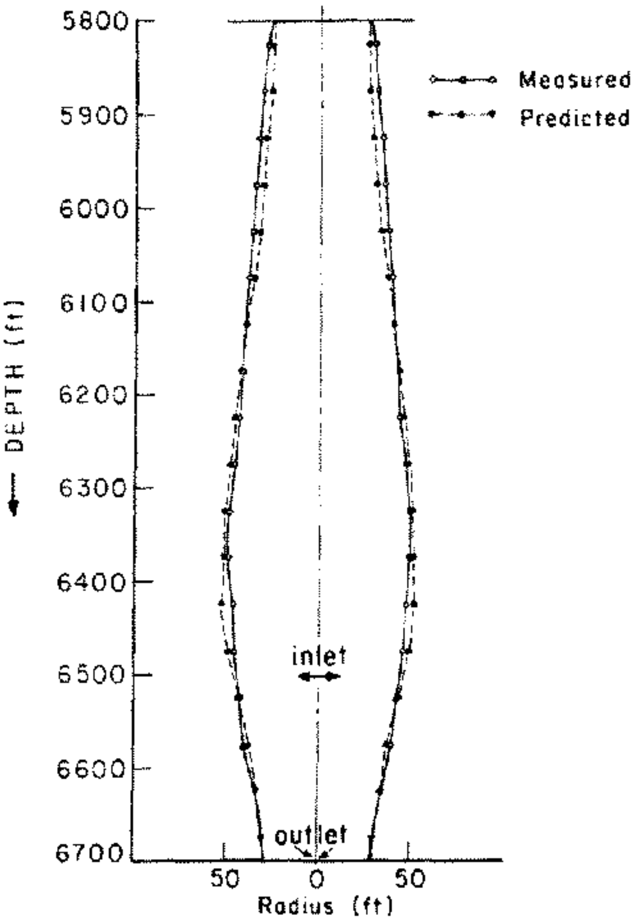


Figure 16. Measured and simulated (MIXING 3) shapes for a field cavity developed by reverse circulation[13].

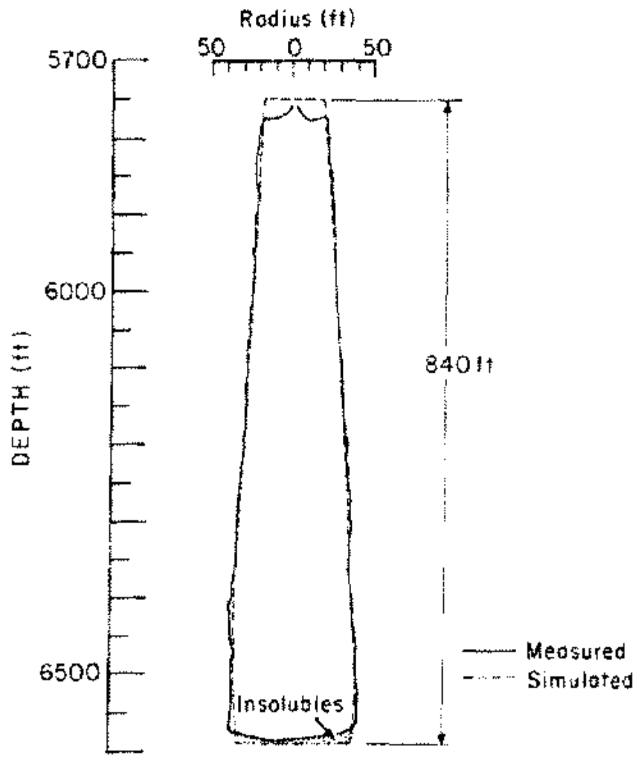


Figure 17a. Measured and simulated (MIXING 3) shapes for a field cavity leached by bottom injection-top production (halfway through completion)[13].

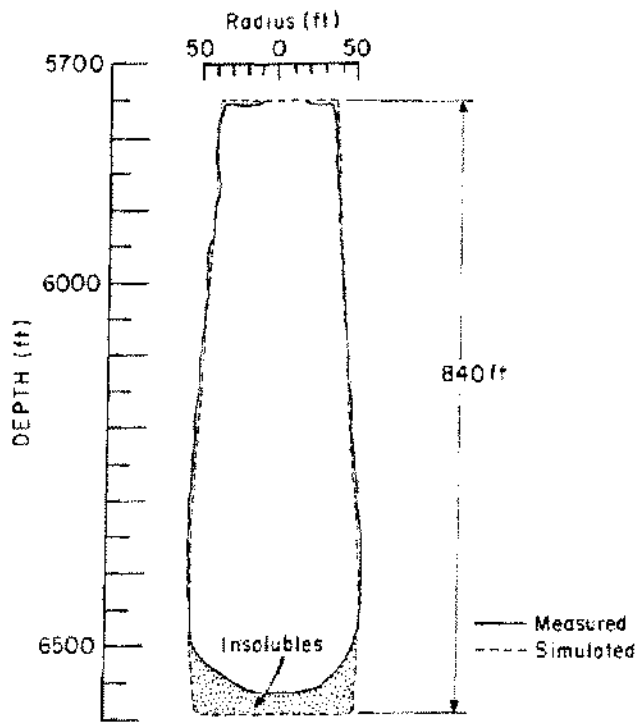


Figure 17b. Measured and simulated (MIXING 3) shapes for a field cavity developed by bottom injection-top production[13].

solving (unprotected) roof, 2) bottom injection-intermediate production, 3) variable salinity injection fluid.

Figures 18 and 19 show the comparison between cavity shape predictions by SALT76 and sonar measurements for two field cavities[18].

SALT77, the latest version of the numerical model, has the following added options: 1) injection-production switch over, 2) heterogeneous salt, 3) circulation pressure calculation and power consumption.

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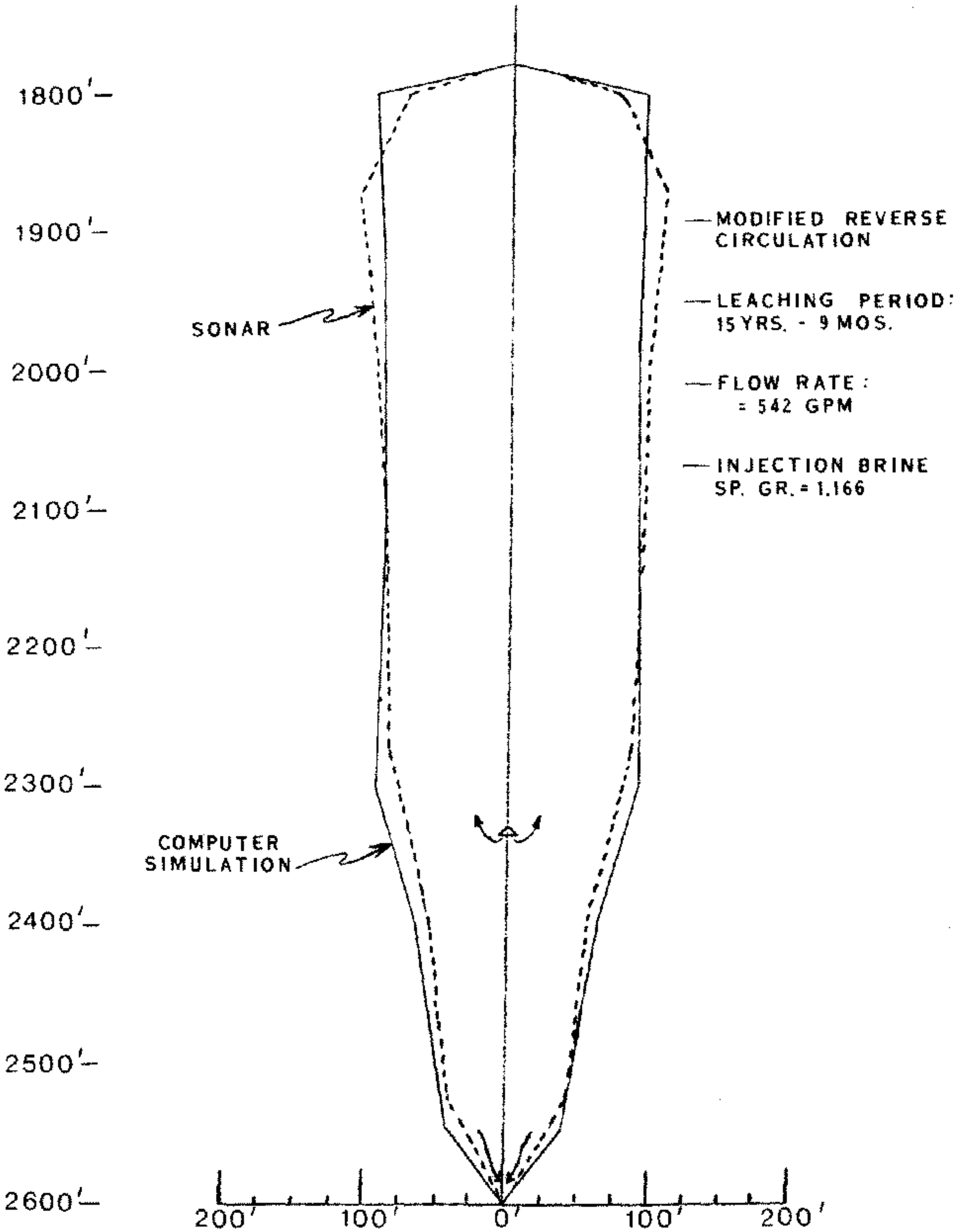

Figure 18. Measured and simulated (SALT 76) cavity shapes for a topping well[6].

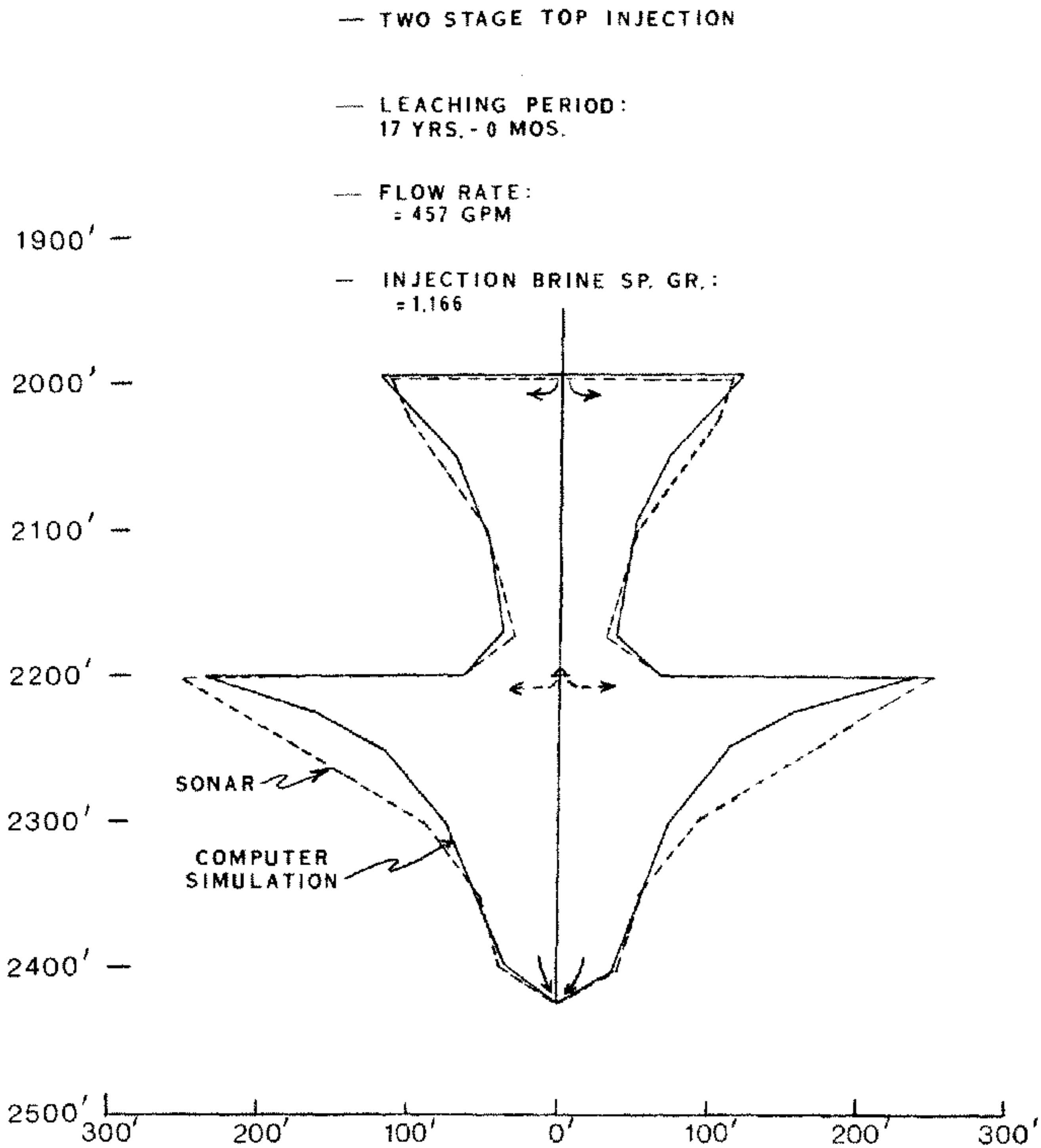

Figure 19. Measured and simulated (SALT 76) cavity shapes for a topping well[16].

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