Simulation of Gas Storage Cavity Creation by Numerical Methods

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ABSTRACT

A numerical model which simulates salt cavity development by solution mining processes has been developed from mass transfer basics as applied to salt dissolution. A simplifying hypothesis and its complements made for industrial application to gas storage use have been indirectly verified by the very good fit found between simulation results and field measurements. The final model provides the shape variation, bottom position, brine quality, and flow rate versus time according to successive injection flow rates. This model has been helpful in various studies ranging from performance projects to leaching surveys for cavity creation in any given salt layer. It could be a good supporting technique for accurate optimization.

INTRODUCTION

In 1968, one transmission line supplied the town of Lyon, (France), and its suburbs with natural gas. The increase in gas consumption, especially for domestic heating, progressively led to an increase in demand from the transmission line which was close to its maximal capacity. In order to avoid the construction of a new transmission line, it was decided to create a natural gas storage facility for use beginning in the winter of 1970–1971 which would have a high withdrawal capacity. Unfortunately, there was no useable acquifer known in the region of Lyon, but a geological opportunity was offered by the presence of subsurface salt deposits.

In considering the possibility of the storage facility in salt, the main concern very quickly became the possible mechanical behavior of the salt around the cavity to be used for storage where the cavity would contain natural gas at a pressure much lower than the overburden pressure, especially at times when the gas was near the end of the withdrawal cycle. The shape of the cavity appeared to be very important for the stress distribution. Under geological conditions a pear-shaped cavity seemed suitable for both mechanical and storage considerations. With this decision, it became necessary to institute a study on the growth of the cavern by leaching so as to sufficiently control the dissolution process and obtain the desired parameters including:

1. obtaining the desired pear-shape of the cavity.
2. location of the cavity in the correct place.
3. location of the cavity within the salt stratum of limited thickness.
4. location in the salt stratum correctly in spite of disseminated insoluble materials such as clay and anhydrite.
5. completion of all operation in the prescribed period of time.
6. correct implacement and movement of the injection tubes and performance of the planned shape survey.

Cavities are washed through one well only, with two concentric tubing strings and bottom injection.

THE MODEL

The model is described in terms of the basic information on the dissolution of salt on the cavity walls, general cavity dissolution including growth of the cavity, the leaching process and limitations of the model.

Dissolution on a salt wall

Basics. The theoretical basis for dissolution are given by Durie and Jessen (1964) in two articles. The first paper gives physical analysis, mathematical formulae and the resolution for salt removal from a smooth surface into brine through the laminar boundary layer which governs natural convection. Experimental results show a good correlation with the adjusted theoretical relationships (Fig. 1).

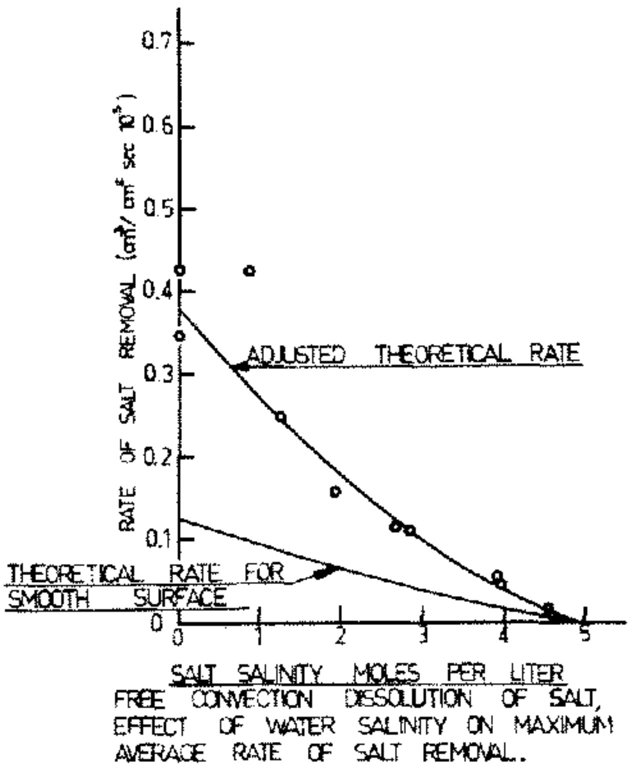


Figure 1.

The second paper shows the influence of dissolution on an inclined surface. The correlations with experimental results are excellent (Fig. 2). These papers are related to natural convection with a laminar boundary layer. The rate of salt removal for a given bulk brine concentration changes with position of the point under consideration on the vertical surface.

Complementary hypothesis. In keeping with the dimensions determined for the cavity in the field, a complementary hypothesis has been made by us which states that convection in a cavity during leaching is a turbulent process. The salt is removed from the walls through a sublaminar boundary layer into the brine in an eddy diffusion. The sublaminar boundary layer is thinner than the laminar layer. This fact, together with the occurrence of eddy diffusion in the bulk brine, probably leads to an increased rate of salt removal for a given brine concentration and this rate is the same on each point of a plane surface.

Assuming that the relationships established for laminar convection are useable for sublaminar boundary layers, the rate of salt removal in a cavity can be calculated versus brine concentration with a corrective multiplier, the value of which was found by experimentation and which is valid for any inclined plane surface (Fig. 2).

Cavity dissolution

Geometrical approximations. The desired final shape and related intermediate shapes of the cavity are approximated by a combination of cylindrical and conical shapes (Fig. 3). The roof is assumed to be a cone. Movements of inert fluid in small amounts, calculated by special codes, allows control of this development of the shape of the cavity. The position of the roof is controlled by both inert fluid movement and the positioning of the insert tubing shoe. The bottom of the cavity is formed by fallen insoluble materials which are freed from the massive salt by

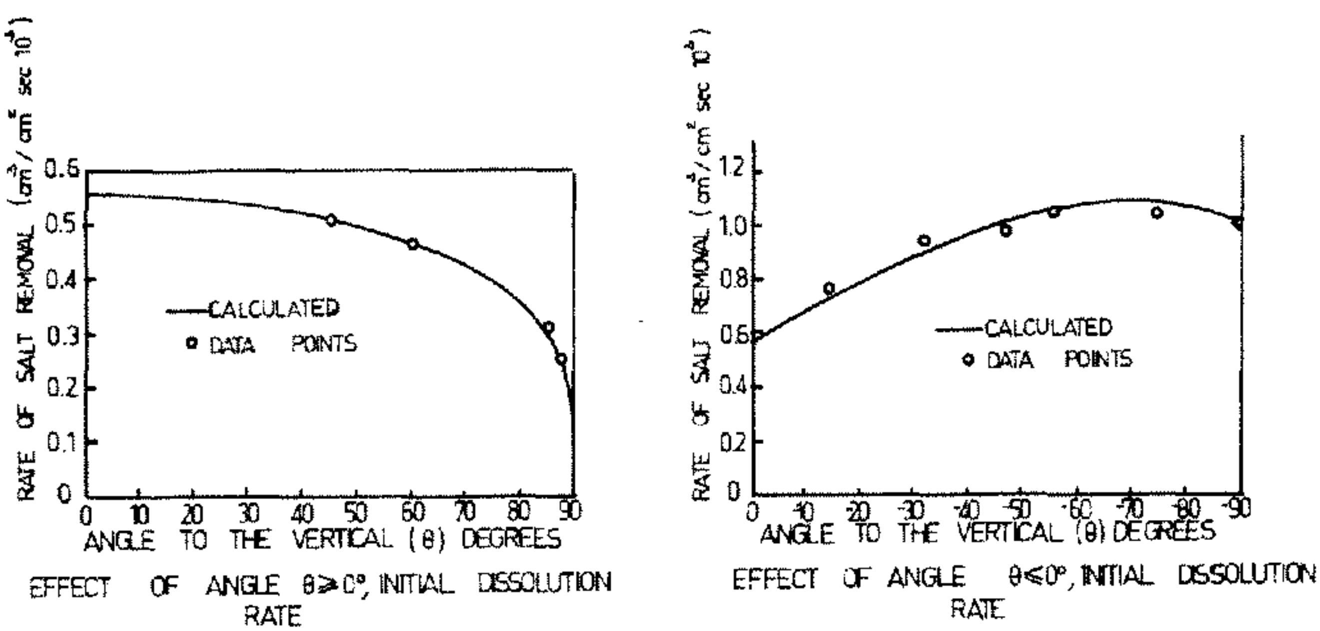


Figure 2.

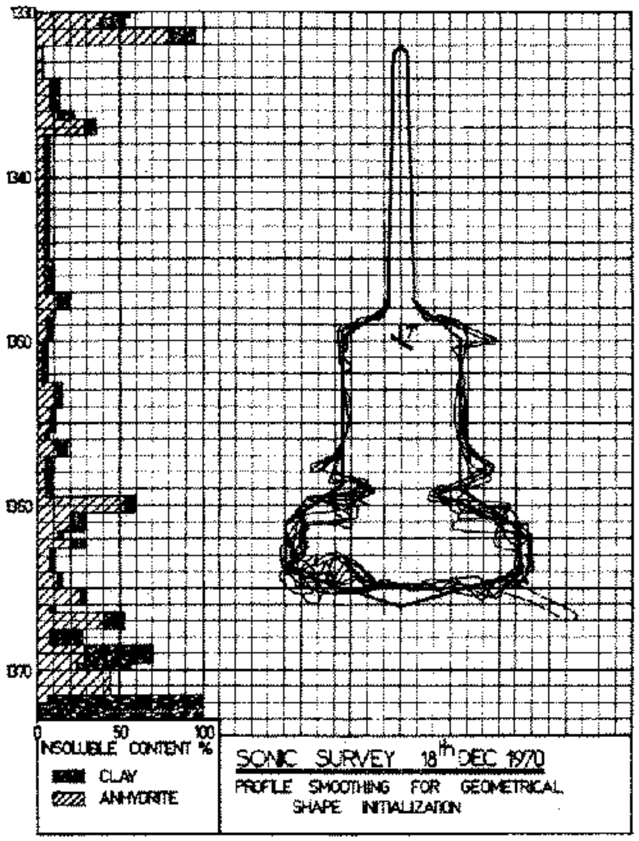


Figure 3.

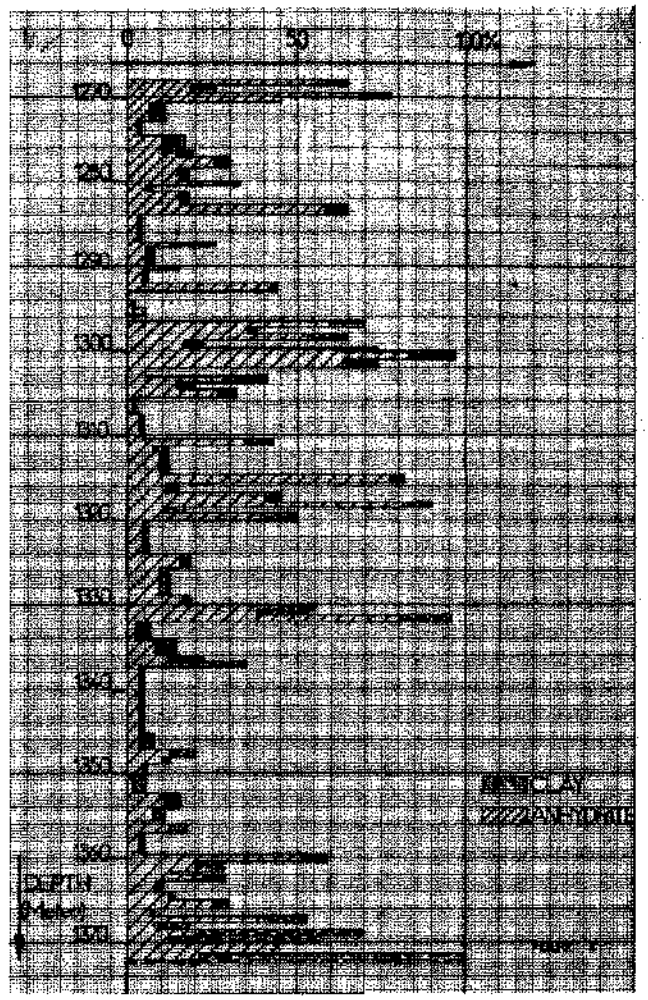


Figure 4.

dissolution of the walls. The bottom takes on a conical shape, sloping down from the cavity edge.

Growth of the cavity. Normal displacement of any inclined plane is related to normal displacement of a vertical plane or wall. Accordingly, it is possible to determine, step by step, the new progressive positions of each wall portion being dissolved, the volume of the freed insoluble material and the progressive position of the bottom. The volume of the freed insoluble material is calculated from the previously determined amount of insoluble material contained in horizontal slices of the salt layer (Fig. 4). It is assumed that the insoluble material is evenly disseminated in the salt and that no dissolution occurs under the rubble pile at the base of the cavern. This kind of model, regardless of the development time connected to brine concentration, can be used to verify the approximation to the desired shape and volume of the cavity in the given target salt layer.

Leaching process. Normal displacement of the vertical wall versus time is related to the brine concentration. With bottom injection and turbulent convection, brine concentration is assumed to be the same around all of the cavity. Where displacement of the vertical wall is known with respect to the brine concentration for each time increment, the position of the walls at the end of each time increment can be calculated. The procedure provides:

1. mass of the salt removed by dissolution.
2. amount of insoluble materials freed by dissolution.
3. position of the bottom.
4. the volume of brine removed and brine concentration at the end of each time increment.
5. by material and volume balances for each time increment for:
   a. salt removed from the wall,
   b. salt contained in the cavity brine,
   c. water injected (directly or as sea water or brine),
   d. water contained in the cavity brine,
   e. volume of the cavity.

By repetition of this procedure, the values for each variable involved in the leaching process are obtained for each time increment. The data needed for the calculations are:

1. insoluble material concentration for horizontal slices of the target salt.
2. initial shape of the cavity and position of the cavity in the salt layer.
3. initial concentration of the brine in the cavity.
4. successive positions of the injection and insert tubings and test values for change.
5. successive injection flow rates and injected fluid concentrations.

The results available for any increment of time include the position of the cavity walls and bottom and the concentration of the brine produced and flow rates.

Limitations of the model

In the salt layer it is assumed that all walls are exposed to leaching and must have same capability of dissolution. In addition, it is assumed that the insoluble materials are evenly distributed. Interestingly, these conditions are very often verified for halite layers. The general shape of the cavity must be round enough, or the injection must be so adapted, as not to invalidate the assumption of homogeneity made for the turbulent convection calculation. Bottom injection is required because bottom injection does not change the brine homogeneity. Injection at the top of the cavity would cause density segregations, even with turbulent convection, and the model would not be useable.

EXPERIMENTAL RESULTS

Various measurements were made in the experimental verification of the model. First the characteristics of the salt layer were obtained for the three minerals halite, anhydrite and clay which were recognized in the salt layer cores. The concentration of insolubles was computed for slices 0.5 m thick from two logs (either gamma-gamma density and neutron or sonic) which were calibrated with the core data. Secondly, the produced brine was evaluated from a survey of washing operations which included brine flow rate measurements by a positive displacement meter with an accuracy of 2%. Chemical analysis was made on brine samples and salt content was determined with an accuracy better than lg/l. Finally, the cavity shape and its dimensions were periodically measured by a sonic device called the "Echo-Log" (developed by PRAKLA). This device provides an orientation for the vertical cross sections or a reference orientation for the horizontal cross sections. Using it, the dimensions of the cavity can be measured with a 2% accuracy.

Comparison of measurements and model results

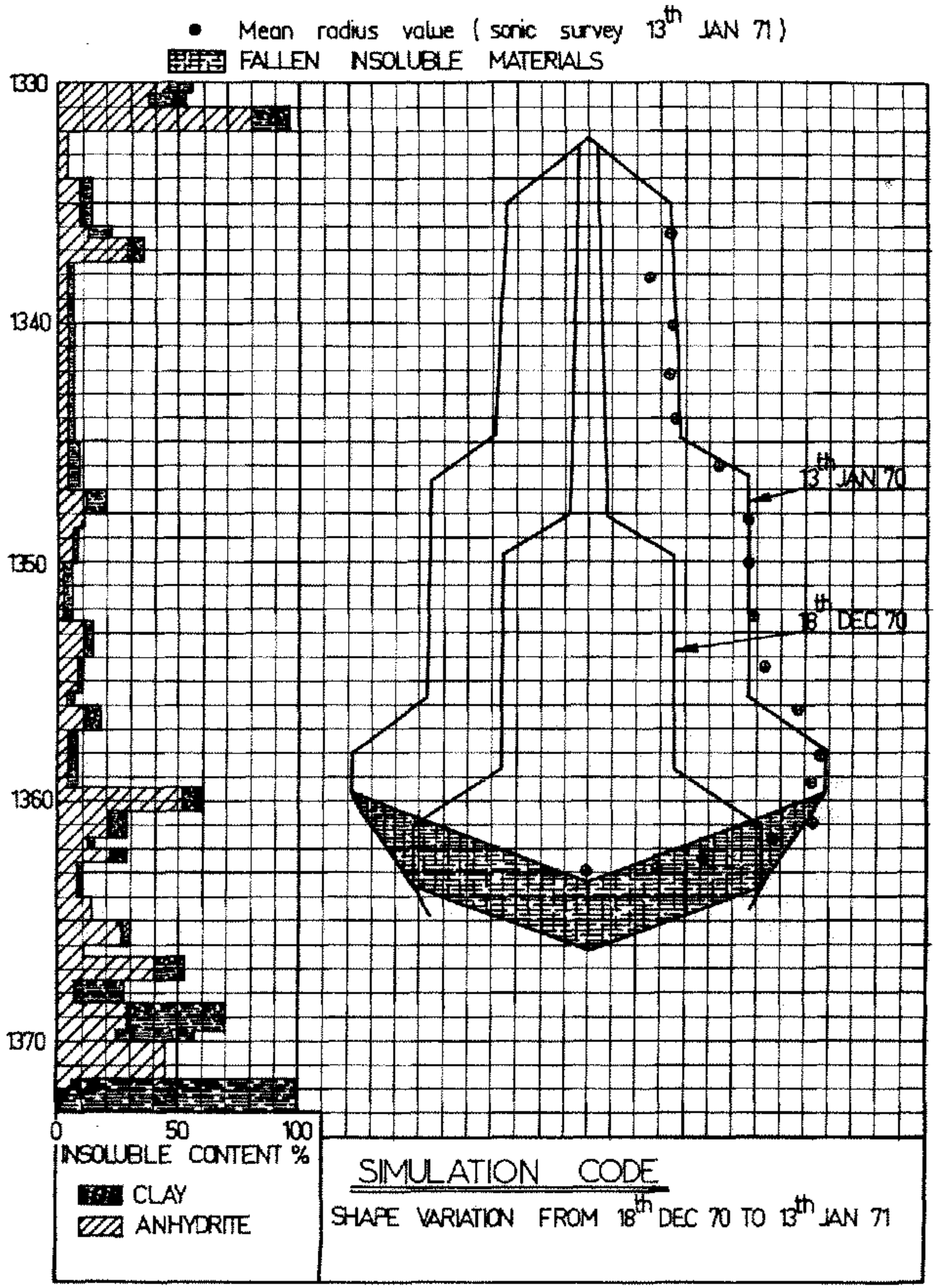
Cavity shape. Beginning with the initial data on the content of the salt layer and its insoluble concentration in terms of anhydrite and clay (Fig. 3), the initial shape, dimensions and position of the cavity, the injection flow rate for postsimulation has been calculated by the model from the produced brine flow. The initial shape is smoothed into cylindrical and conical portions for the model (Fig. 3). A simulation for two-months-long washing was made using a real succession of flow rate injections. The calculated new positions of the walls and bottom are shown on Figure 5 where they are compared with the mean value of the cavern radius as measured on horizontal cross sections (dots). Figure 6 shows all measured vertical cross sections as compared with the calculated cavern radius and bottom position. The small differences can be explained by the dip of salt layers and non-collapse of layers with a high content of insoluble material (e.g. at a depth of 1,360 m).

In the same way, the new measured vertical cross sections are smoothed (Fig. 7) and used for a new simulation intialization. As an illustration of the accuracy attained, the calculated bottom position has been kept on the illustration. The figure shows the results of the new calculation compared with the mean cavity radius of measured positions (dots). Conservative estimation of the bottom position remains with the same depth difference as in preceeding calculations. All vertical cross sections are on Figure 8 with dots showing the simulation results. Mean differences between measured and calculated positions are around 0.3 meters for a growth of more than 3 m in radius. At a depth of 1,330 m the difference is large because the high insoluble content layer did not fall.

Brine quality. The calculations have been made with the known succession of changes in injection flow rate. Corresponding to the changes in shape shown from Figure 3 to Figure 6, changes in brine concentration with time can be seen on Figure 9. Calculated values are shown as dots. The model sensitivity can be appreciated readily. A good agreement exists between the calculated and measured brine content except on days when irregularities occur in the injection flow rate which can not be taken into account in the calculations. For example, on December 21, 1970 there was a two hour electric power interruption. Again on December 30th and 31st the same occurred. There was some increase in injection flow rate from the 8th to the 11th of January, 1971.

The main values for changes in injection flow rates, at the right time, have been used for the calculation and the results are in good agreement with measured values even with transient interruptions. Another example can be seen on Figure 10 where a more constant injection flow rate was applied for five weeks. The calculated values correspond to shape changes shown from Figures 6 to 8.

Model sensitivity. If incorrect data are used for calculations, especially for values of injection flow rates or mean insoluble content, the calculated values of brine quality and consequently shape variations slowly become different from the measured values and the differences increase with time. This sensitivity and the verifications given above substantiate the validity of the model and subse-



● Mean radius value (sonic survey 13th JAN 71)
FALLEN INSOLUBLE MATERIALS
1330
1340
1350
1360
1370
13th JAN 70
18th DEC 70
0
50
100
INSOLUBLE CONTENT %
CLAY
ANHYDRITE
SIMULATION CODE
SHAPE VARIATION FROM 18th DEC 70 TO 13th JAN 71

Figure 5.

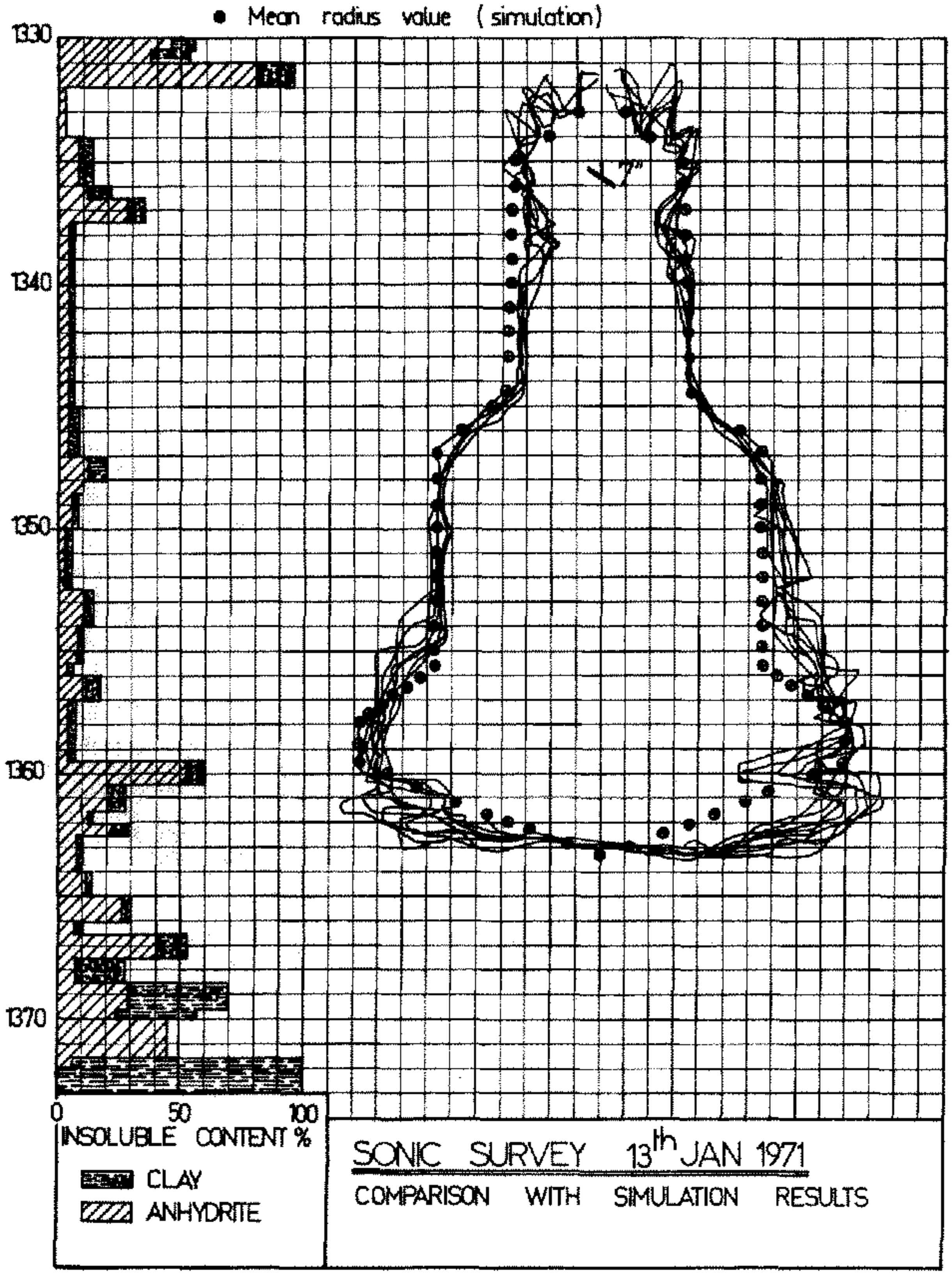
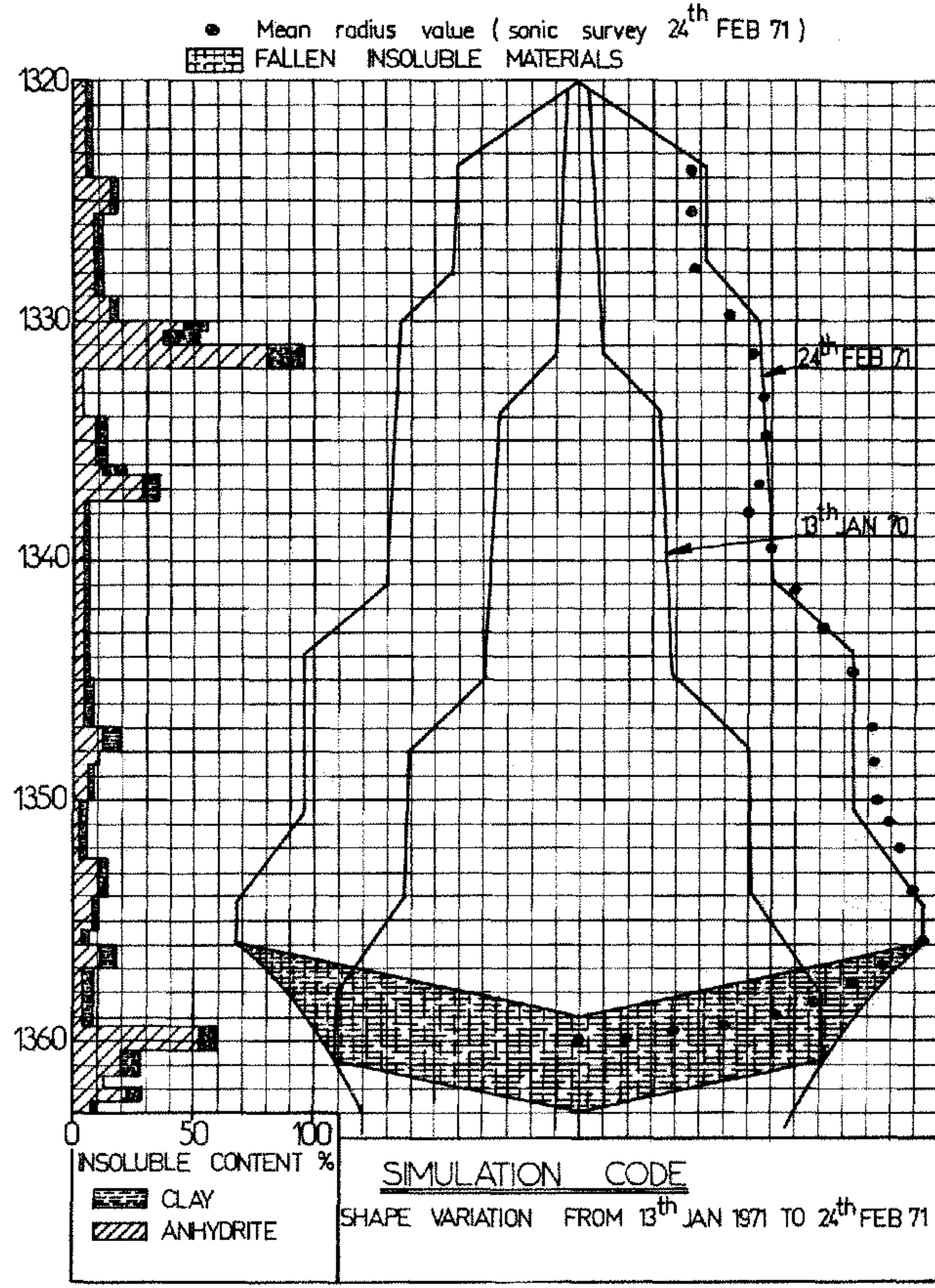

● Mean radius value (simulation)
1330
1340
1350
1360
1370
0
50
100
INSOLUBLE CONTENT %
CLAY
ANHYDRITE
SONIC SURVEY 13th JAN 1971
COMPARISON WITH SIMULATION RESULTS

Figure 6.



● Mean radius value (sonic survey 24th FEB 71)
FALLEN INSOLUBLE MATERIALS
1320
1330
1340
1350
1360
24th FEB 71
13th JAN 70
0
50
100
INSOLUBLE CONTENT %
CLAY
ANHYDRITE
SIMULATION CODE
SHAPE VARIATION FROM 13th JAN 1971 TO 24th FEB 71

Figure 7.

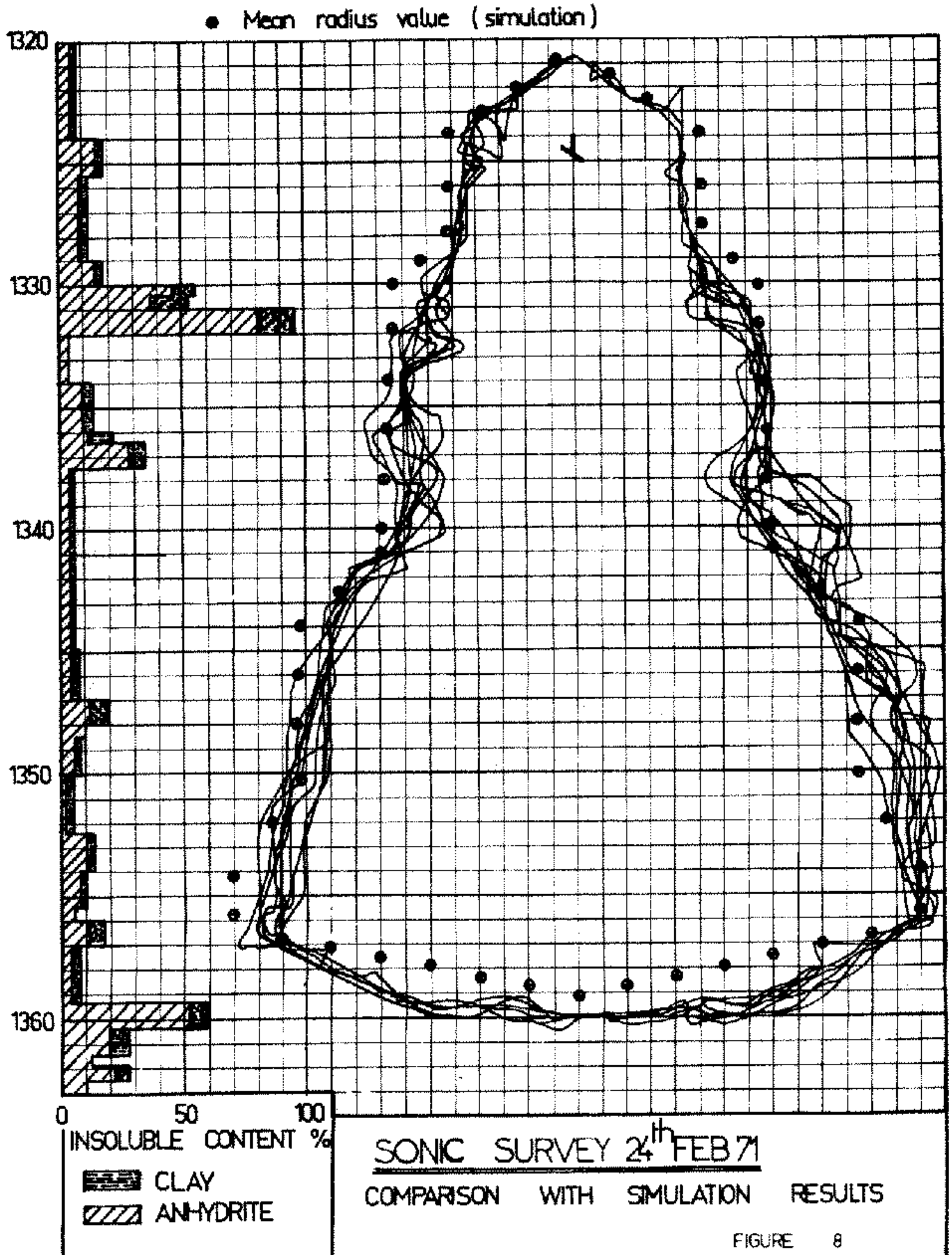

• Mean radius value (simulation)
1320
1330
1340
1350
1360
0
50
100
INSOLUBLE CONTENT %
CLAY
ANHYDRITE
SONIC SURVEY 24th FEB 71
COMPARISON WITH SIMULATION RESULTS
FIGURE 8

Figure 8.

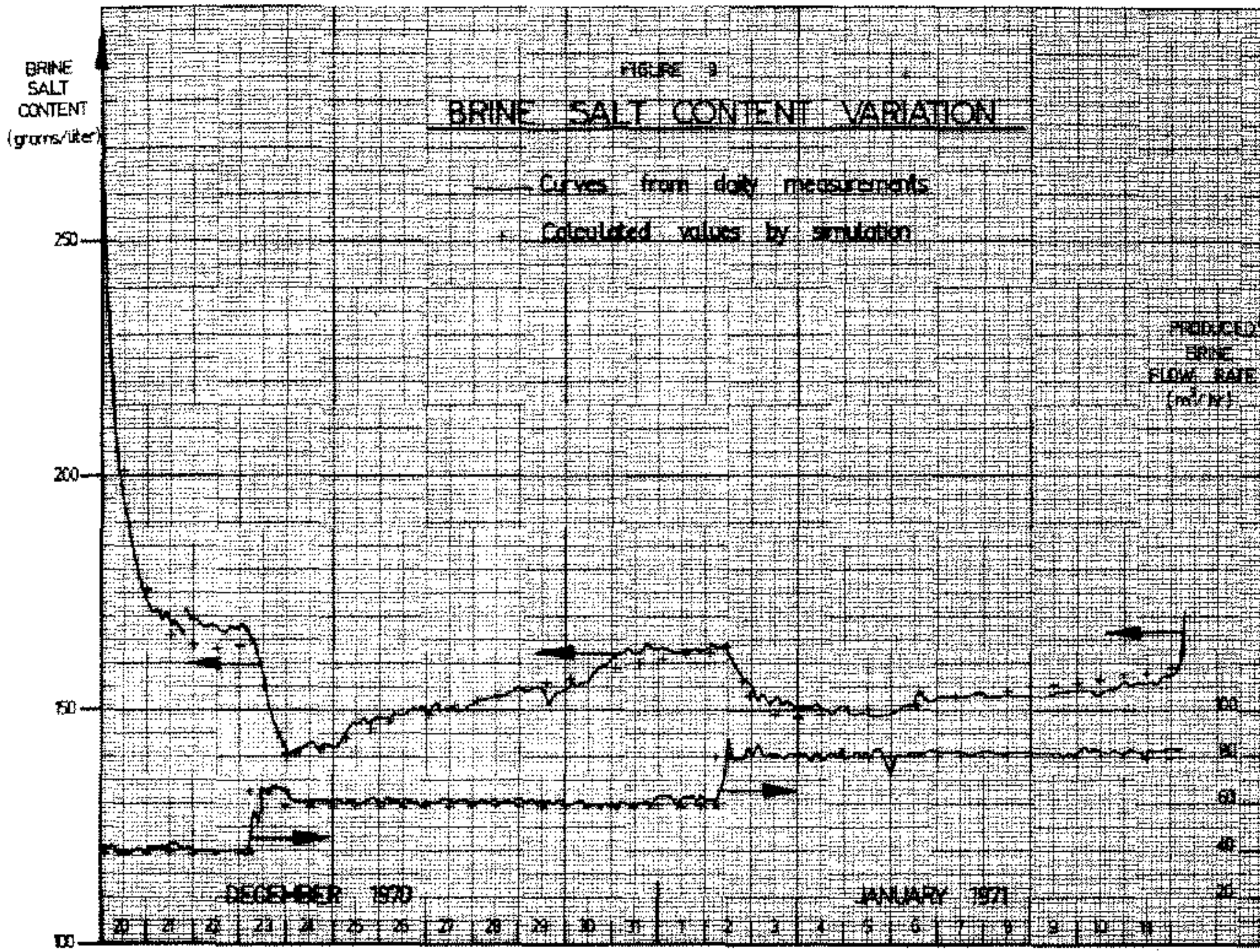


Figure 9.

quently the validity of the initial hypothesis. Such sensitivity makes the interpretation of small differences between pre-calculated values which are used for planning surveys and measured values delicate. On the other hand, persistent large differences between calculated and measured values allows one to reasonably assume that something is happening which is not normal.

MODEL USES

All the objectives assigned to the model seem to have been attained. The model can be used for many engineering tasks involved in salt storage cavity creation. With the availability of necessary quantitative information on the composition of the target salt layer, it is possible to determine cavity characteristics, leaching performance, plan dates for surveys and estimate projected delays in injection flow rates. It is also possible to anticipate some of the probable difficulties occasioned by special geological conditions. With all interrelated technical variables known, it is possible to attempt optimization.

REFERENCES

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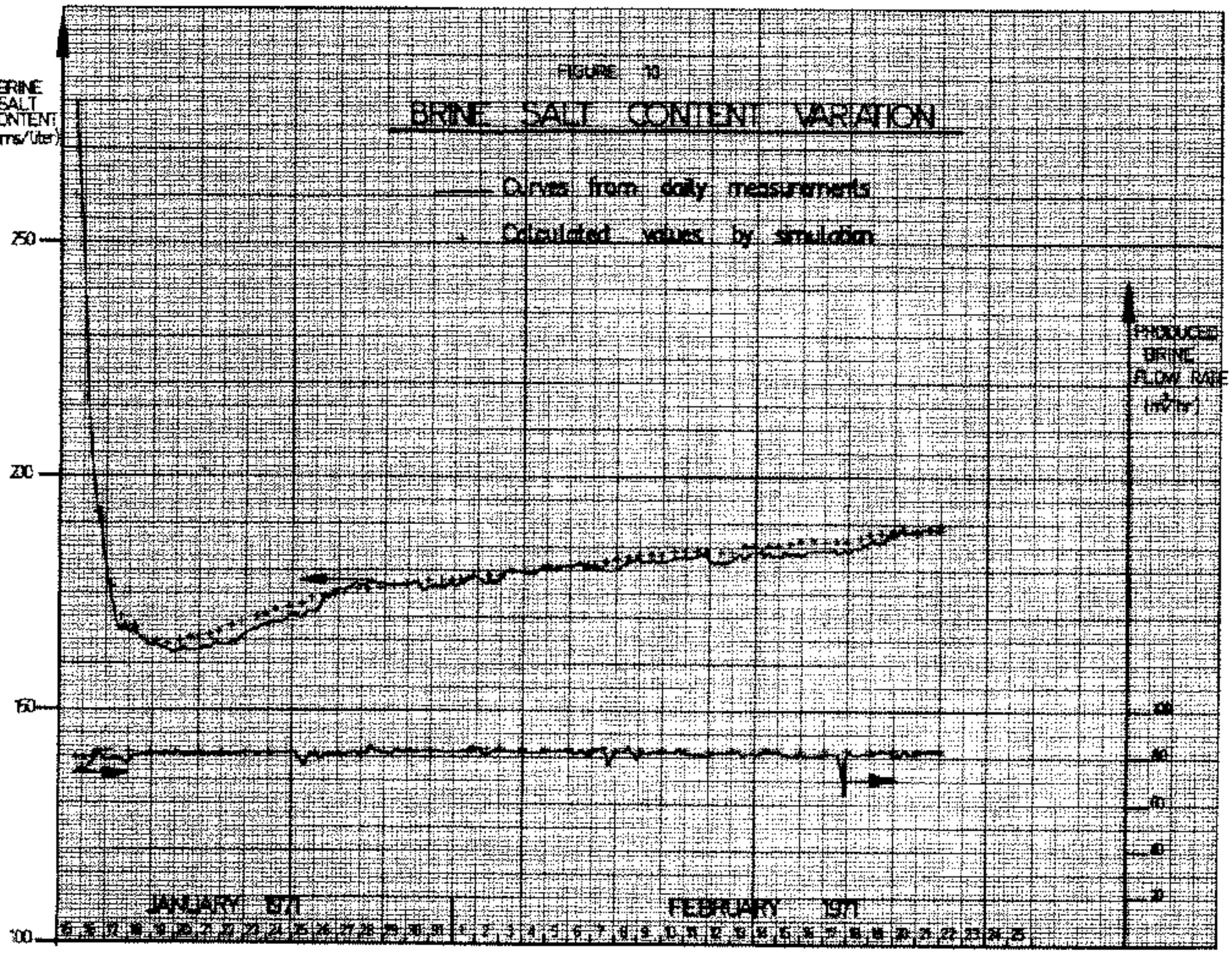
FIGURE 10
BRINE SALT CONTENT VARIATION
Curves from daily measurements
+ Calculated values by simulation
BRINE SALT CONTENT (grams/liter)
PRODUCED BRINE FLOW RATE
JANUARY 1971
FEBRUARY 1971

Figure 10.