# Underground Storages at Tersanne and Etrez: Prediction and Simulation of Cavity Leaching in a Salt Layer Charged with Insoluble Materials

Eric Pernette and Michel Dussaud

*Gaz de France,*
*Paris, France and*
*Sofregaz,*
*Paris, France*

*ABSTRACT*

*Since 1968, Gaz de France has been developing in southeast France two underground storages of natural gas in solution mined cavities. The Tersanne site, which is 90 km south of Lyon, will have by 1984 fourteen cavities, each 200,000 $m^3$ large and 1,450 m deep; the whole volume will be 475 million $m^3$ (n) of gas. The Etrez site, which is 85 km north of Lyon, will allow between 1979 and 1998 the realization of twenty eight cavities, 200,000 $m^3$ large and 1,350 m or 850 m deep each: the whole volume will be about one million $m^3$ (n) of gas.*

*For reasons of mechanical stability, the direct leaching method is used to create pear-shaped cavities. The composition of the salt layers led us to set up numerical programs able to simulate the leaching of salt layers charged with insoluble materials: the average content is 8 percent in Tersanne and 15 percent in Etrez. The deposit of insoluble materials freed by the leaching induces a rise of the bottom of the cavities which is important to control, at the risk of losing a non-negligible height of the salt layer. This is especially true during the first step of the leaching where layers containing up to 50 percent of insoluble materials risk creating superposed cavities. We have to take this into consideration in order to follow the leaching and the sedimentation at the bottom of the cavities.*

## INTRODUCTION

Since 1968, Gaz de France and its subsidiary Sofregaz have mastered the technique of and acquired experience in solution mining of salt cavities intended for underground storage.

The purpose of this paper is to present the major results of this experience.

The plan of this paper is as follows:

- Presentation of industrial installations carried out by Gaz de France and Sofregaz in terms of underground storage in salt cavities
- Presentation of computer means implemented to carry out and control these industrial installations
- Organization of the implementation and control of salt cavity leaching
- A special chapter in dealing with the means implemented to ensure the safety of storages in salt cavities.

## INDUSTRIAL INSTALLATIONS

### Tersanne and Etrez Underground Storages

The experience acquired by Gaz de France and Sofregaz is first of all based on two projects being carried out at present by Gaz de France in southeast France (Figure 1).

The first of these projects, now coming to an end, is at Tersanne, located 90 km south of Lyon. The second project is at Etrez, located 85 km north of Lyon.

At both sites, the cavities are leached out of salt layers belonging to tertiary evaporitic deposits (Oligocene) which are part of a succession of salt basins stretching from Alsace to the Camargues.

The leaching technique used is that of direct fluid circulation. The leaching fluid, fresh water in Tersanne and Etrez (seawater can be used just as well in the case of sites located by the sea), is injected through the bottom of the cavity and the brine produced is withdrawn at the top.

The main characteristics of these two projects of natural gas storage are shown in Table 1.

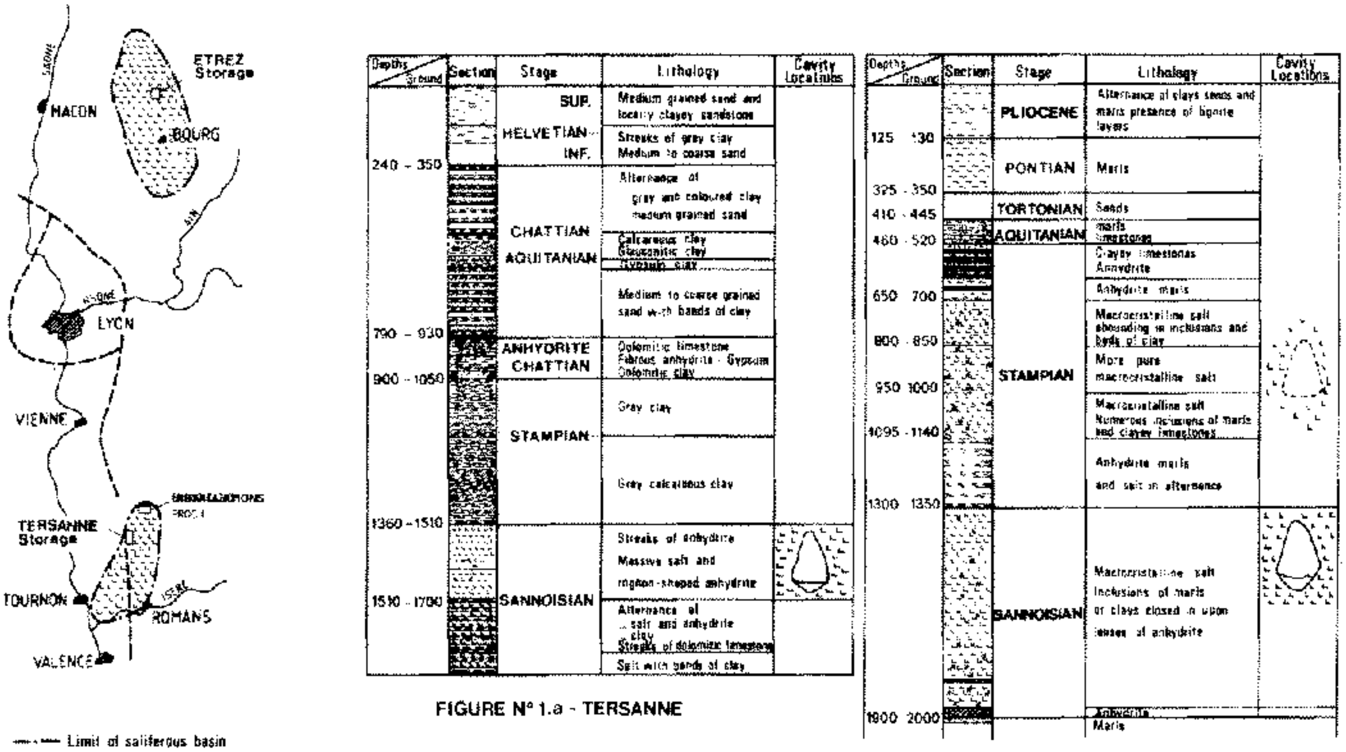


**Figure 1.** Saliferous Basins of Valence and Bresse.

TABLE 1

Characteristics of Terzanne and Etrez Gas Storage Projects

| | Tersanne | Etrez |
|---|---|---|
| Beginning of leaching operation | 1968 | 1977 |
| Expected final date | 1985 | 1998 |
| Final installation: | | |
| — number of cavities | 14 | 28 |
| — maximum storage capacity ($10^6$ Nm3) | 475 | 1 000 |
| Present installation: | | |
| — number of cavities being leached | 4 | 5 |
| — number of cavities being operated | 10 | 5 |
| Standard volume of cavities (m3) | 200,000 | 200,000 |
| Depth of cavity roof sub-ground (m) | ≈ 1 400 | ≈ 1 300 |
| Leached height of salt (m) | 140 to 180 | 140 to 180 |
| Height of standard cavity (m) | 80 to 120 | 80 to 120 |
| Maximum diameter of standard cavity (m) | ≈ 80 | ≈ 80 |
| Average percentage of insolubles in the salt layer | 8%* | 14%** |
| Variation intervals of operating pressure for gas storage (bar) | 80 to 220–240 | 80 to 210–230 |

*as compact layers.
**dispersed.

The main leaching equipment implemented on each site at Tersanne and Etrez is shown in Table 2. The surface equipment relating to natural gas storage operation is not discussed in this paper.

Each site has a central control room provided with a synoptic panel. At Tersanne, the flow, pressure and temperature measurements carried out on water injected and brines produced are sent to the control room. At Etrez, the leaching installation, being more recent and therefore more modern, enables the direct transmission to the control room of the sodium chloride concentrations of the brines produced as well as the direct acquisition of all these measurements into a mini computer. In addition, the control valves that regulate the various injection flows on the wells being leached simultaneously are remote controlled from the central control room.

On each site, at Tersanne and Etrez, each platform of a well being leached is provided with skid-mounted equipment (valves, pumps, meters) intended for the fuel[1] injection and withdrawal operations required by the leaching control at the cavity roof (cf. paragraphs Local Follow-up of "Implementation of Salt Cavity Leaching"). This equipment, called "fuel skids," is operated in automatic

[1] Fuel is used both at Tersanne and Etrez as inert fluid for leaching control at cavity roofs.

TABLE 2

Leaching Equipment at Terzanne and Etrez Gas Storage Sides

| Sites | | Tersanne | Etrez |
|---|---|---|---|
| Fresh water supply | Coming from | Miocene sands −150 m/ground level | Tortonian sands −350 m/ground level |
| | Immersed pumps | 5<br>Unit flow rate: 100 m3/h | 5<br>100 m3/h at 10 bar |
| | Storage | 1 × 800 m3 open air basin | 10 × 100 m3 tanks under nitrogen top accumulation |
| Leaching pumps (centrifugal type) | Medium pressure header | 4 × 70 m3/h pumps at 55 bar | 4 × 70 m3/h pumps at 55 bar |
| | High pressure header | 2 × 100 m3/h pumps at 80 bar | 3 × 130 m3/h pumps at 120 bar |
| Completion of well for leaching | | 7″–4″ | 7⅝″–5″ |
| Brine evacuation | Storage | 1 × 2,000 m3 open air | 10 × 100 m3 tanks under nitrogen top accumulation |
| | Pumps (centrifugal type) | 4 × 80 m3/h pumps at 15 bar | 3 × 250 m3/h pumps at 50 bar |
| | Average sending flow rate | 200 m3/h | 300 m3/h |
| | Destination* | Compagnie Industrielle & Minière at Hauterives | Société Solvayat Poligny |
| | Brine pipe | cast iron<br>Ø 250 mm − L = 7 km | steel<br>Ø 400 mm − L = 75 km<br>automatic system for oxygen reduction |

*For saturation, then removal to a chemical plant for chlorine and soda extraction.

sequences and is remote controlled from the central control room.

In addition to these "fuel skids," the following equipment is found on each platform of wells being leached:

- four fuel storage tanks of 30 m$^3$ and one tank for decantation
- one separator used for separating fuel from the brine produced by leaching in case of overflow and equipped with a fuel detector (cf. paragraph "Computer Control for Leaching Control at Cavity Roof" and "Implementation of Salt Cavity Leaching Follow-up").

All this equipment installed on each platform of a well being leached is represented in Figure 2.

### The Other Projects of Gaz de France and Sofregaz

In addition to these two projects being carried out at present by Gaz de France, the following projects must be mentioned:

- In the 1970s, construction of a propylene storage cavity of 60,000 m$^3$ at Grand-Serre, near Tersanne, led by Gaz de France on behalf of Rhone-Poulenc
- Planning and early engineering of the project of natural gas storage cavities at Hornsea, Great Britain, with the assistance of Sofregaz on behalf of British Gas Corporation
- A construction project of five salt cavities for the storage of LPG at Kirkuk, Iraq, led by Sofregaz on behalf of Northern Petroleum Organization is in progress.

## COMPUTER IMPLEMENTATION

### Setting Up of the LOGSEL Program

In order to carry out and control the solution mining of salt cavities, a knowledge as precise as possible of the materials forming the salt massif to be leached and of their distribution within the massif is required.

At Gaz de France and Sofregaz, such knowledge is synthesized in the LOGSEL program, which gives the clay and anhydrite contents in relation to the depth of the well to be leached (Figure 3). These components are automatically determined by a computer programme combining two by two the results of the following well logs: gamma-gamma (formation density), and neutron and sonic, after calibration of these well logs based upon the analyses carried out on samples taken *in situ*.

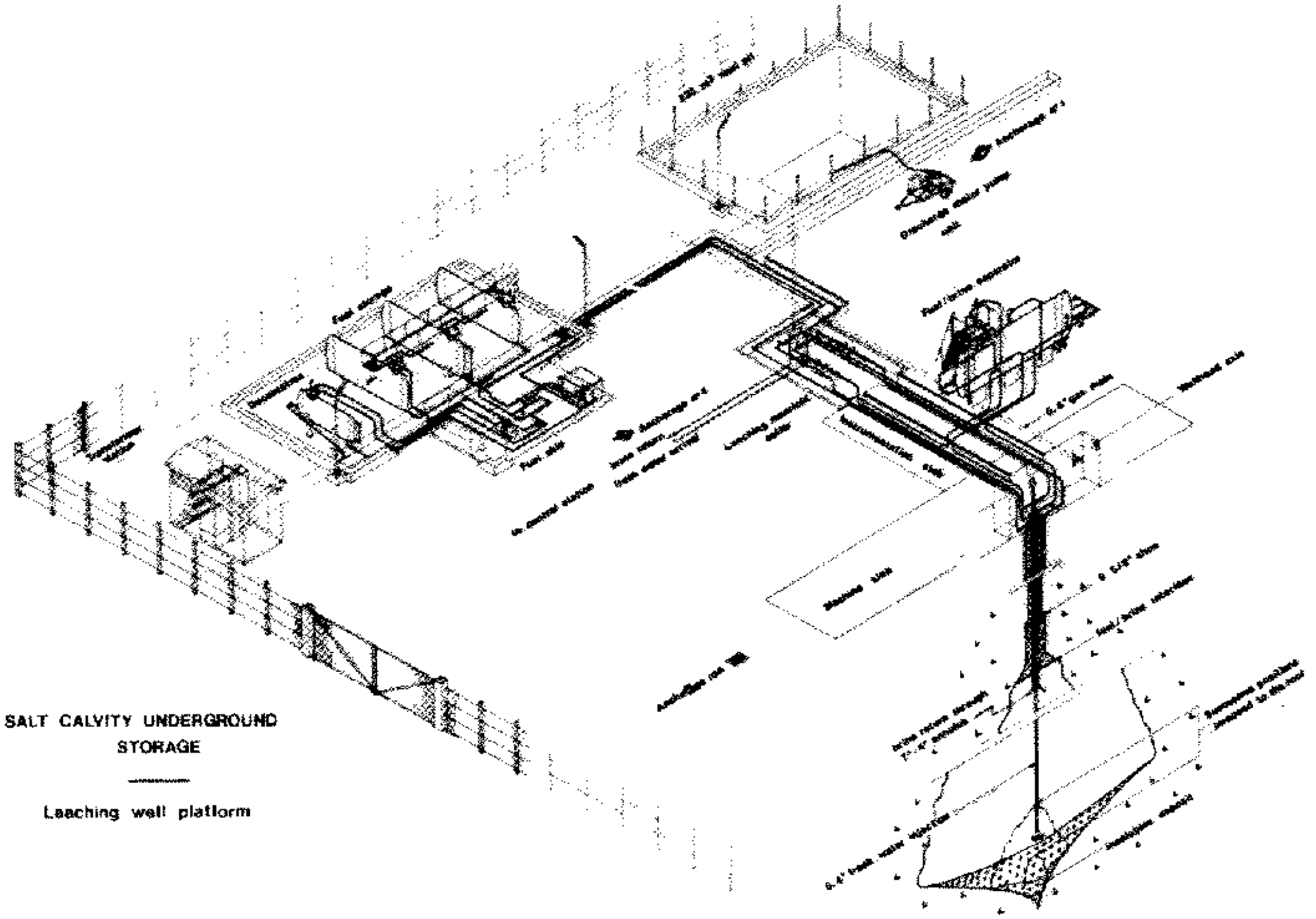


Figure 2.

**Theoretical Bases of the Computer Programmes Relating to Leaching**

The theoretical bases of the computer programmes used by Gaz de France and Sofregaz are based upon the work of Durie and Jessen (1964) on the dissolution of salt by natural convection at laminar flow. Results were transposed to the case of turbulent flow with sub-laminar boundary layer, which corresponds to the conditions found in a cavity leached directly. It is important to note the homogeneity of brine along the walls of a cavity directly leached.

**Cavity Geometrical Development Simulation Computer Programme**

The original characteristics of the techniques developed by Gaz de France is that they enable making ogival-shaped cavities, a shape which in terms of mechanics is considered the most stable.

In order to obtain such a shape, cavities are mined out in successive steps (Figure 4). At each step, a truncated cylinder and a truncated cone are added to the previous shape. From one leaching to another, the fresh water injection and brine evacuation tubing string shoes are raised by a set height, the distance between both shoes increasing as the cavity develops. The number of steps and the positioning of the tubing string depend on the salt composition and the shape wanted, which, while remaining within the same geometrical family, can be more or less elongated.

Applying the dissolution laws deduced from the work of Durie and Jessen to this mining principle allows calculation of the geometrical development of a cavity being leached in relation to the development of the vertical walls radius. Based on factors such as salt composition (LOGSEL), position of the fresh water and brine evacuation tubing string shoes and vertical wall progression during the various steps, the geometrical simulation computer programme developed by Gaz de France and Sofregaz enables forecasting of the cavity shape development and more particularly the rise of the cavern bottom (Figure 4), depending on the sedimentation of the insolubles released by leaching.

**Cavity Kinematic Development Simulation Computer Programme**

Adding to this computer programme, the solution of the mass flow balance equations giving an account of the

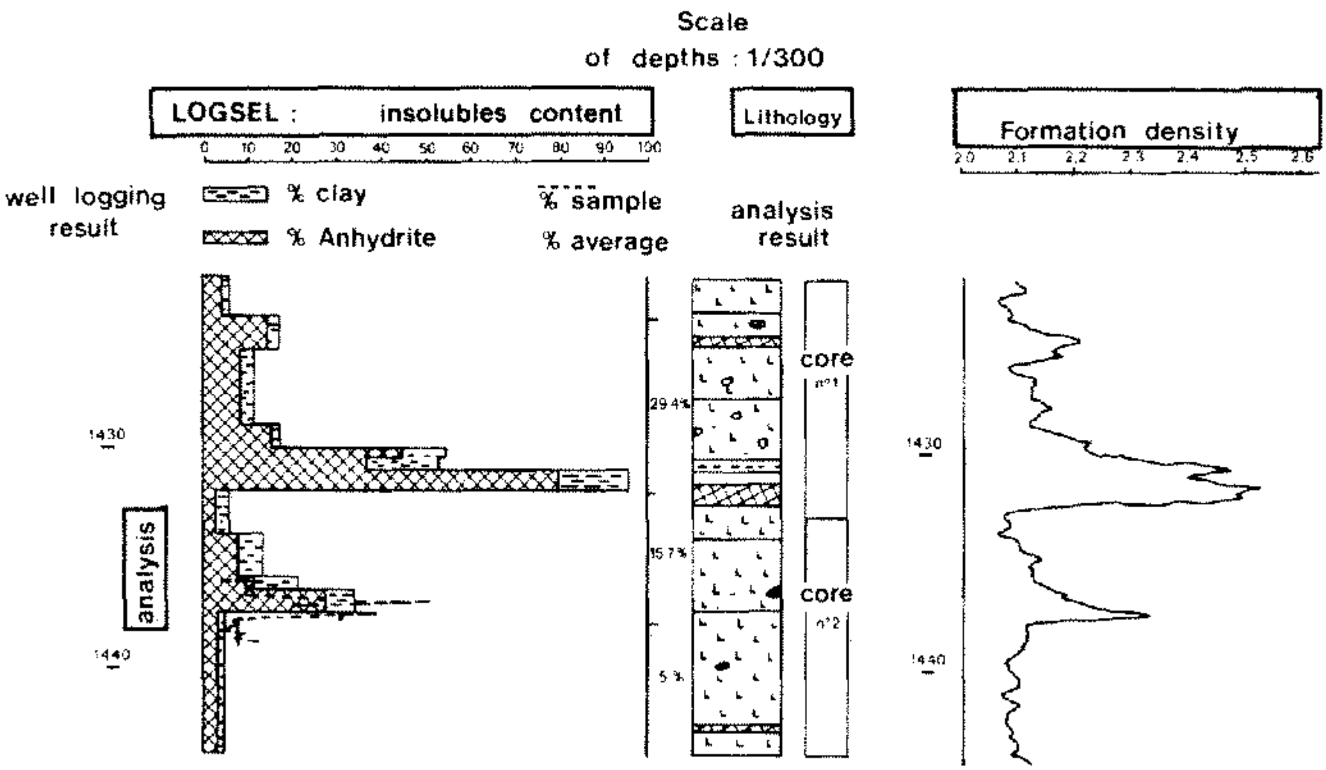


**Figure 3.**

mass flow transfers within the cavity enables simulation of the kinematic development of a cavity being leached.

Based upon the record of fresh water flows injected, the computer programme calculates the development over time of the cavity shape and volume and of the brine contents and flows. This computer programme is used to determine the duration of leaching periods and forecast the amount of brine produced by each cavity.

### Computer Programme for the Simultaneous Leaching of Several Cavities

When carrying out a project of simultaneous leaching of several cavities, there are a number of restrictions, possibly incompatible with one another, which limit the field of possibilities. Among these restrictions are the fresh water and seawater total flow rate that can be used for leaching and the brine total flow rate that can be evacuated.

Within the field of these restrictions, it is essential to have available given volumes, at a given time, in each such cavity.

Gaz de France and Sofregaz have a computer programme that helps in the management of such a project.

### Computer Programme for Leaching Control at Cavity Roof

Gaz de France has developed a technique and a computer programme permitting development of truncated cone-shaped cavity roofs. This technique and the associated computer programme enable control of the salt dissolution at the roof of cavities being leached while avoiding, in particular, an anarchic dissolution toward the top. In addition, it enables the shaping of the cavities in the ogival shape desired. This dissolution control at the cavity roof is based on the principle of using an inert fluid (diesel fuel is used by Gaz de France at Tersanne and Etrez, but other fluids can be used; this fluid must be inert in relation to salt and lighter than brine).

The principle of the original method designed by Gaz de France is as follows:

Given volumes of inert fluid are injected until the inert fluid/brine interface reaches the level of the withdrawal shoe. The inert fluid then overflows and rises with the brine into the intermediate annulus. After each overflow, the inert fluid is withdrawn and a new series of injections are started in order to create a succession of truncated cones whose summit angles are increasing (Figure 5).

To implement this technique, it was necessary to set up a computer programme to calculate the quantities of inert fluid to be injected and withdrawn. This programme has the following two functions:

- First, to calculate *a posteriori* the roof development in relation to the brine contents measured and the vol-

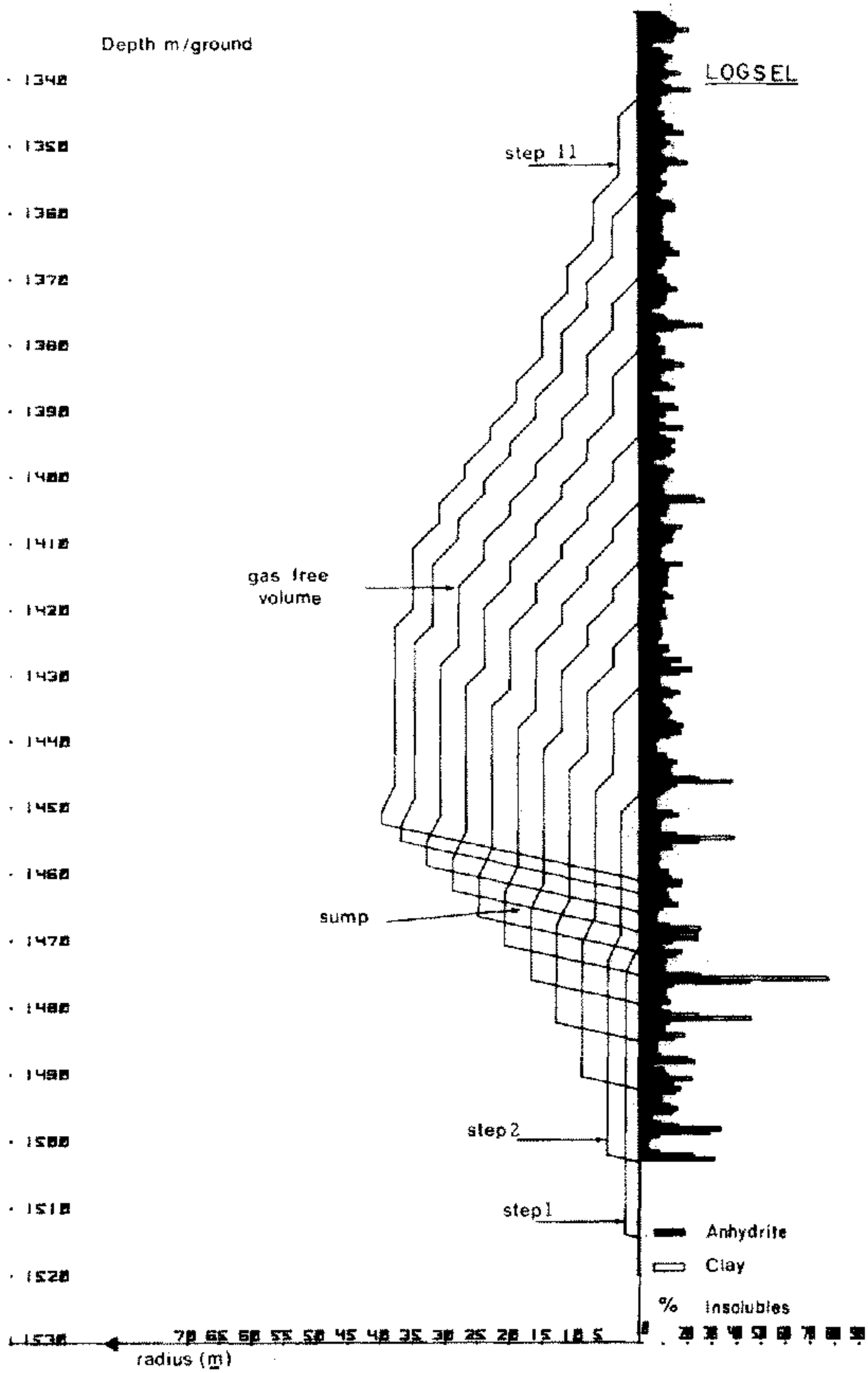


**Figure 4.** Theoretical Growth of Cavity E22.

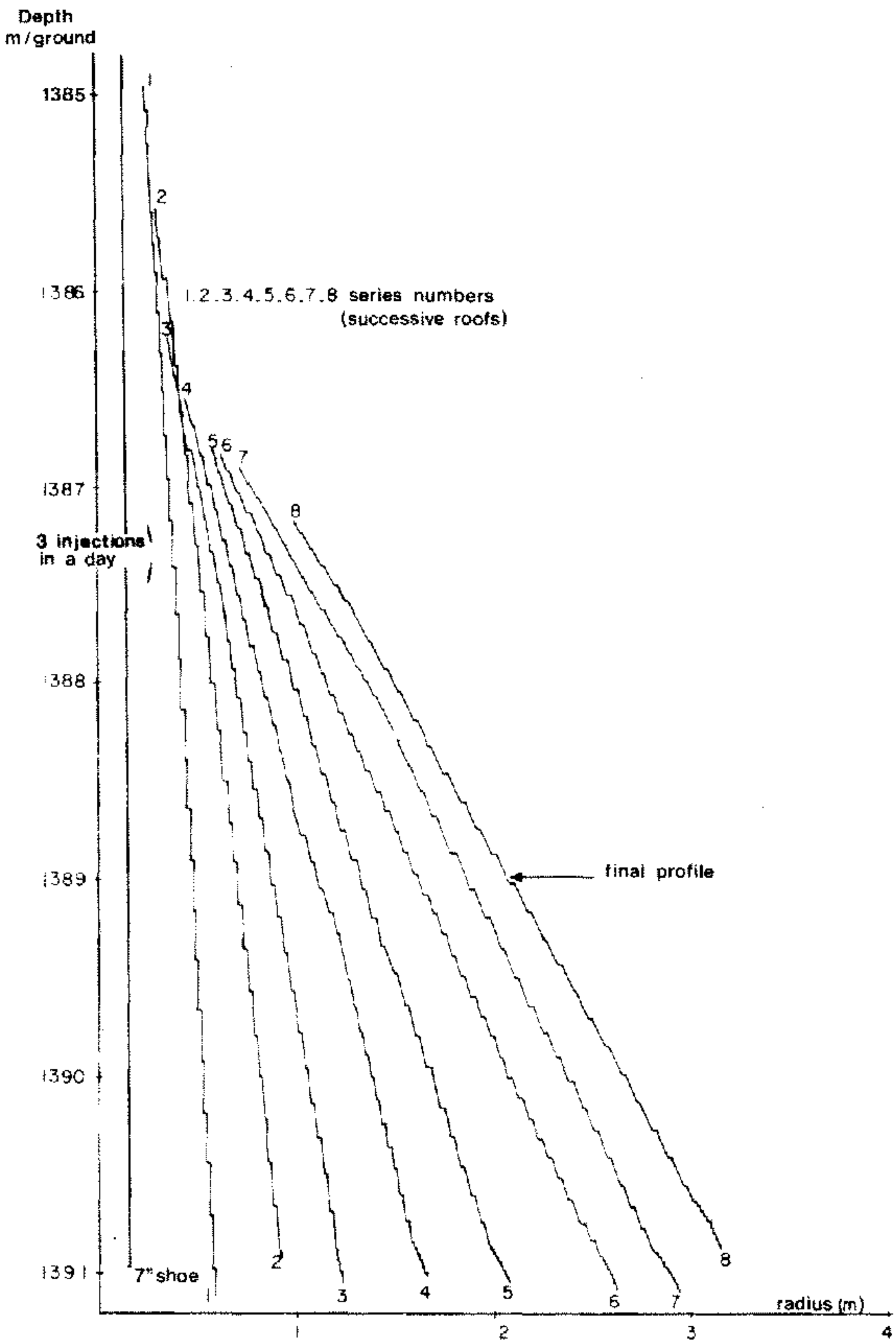


**Figure 5.** Formation of a Cavity Roof Cavity E24 Step 8.

umes of fuel injected and withdrawn. This part of the computer programme also includes a resetting routine which enables, on the basis of the data gathered during overflow of the inert fluid, recalculation of the past history. It is thus possible to maintain high reliability at the level of roof control over very long periods of time (more than 6 months).

- Second, to calculate the volumes of inert fluid to be injected in relation to the contents forecast for the brine produced and to the roof shape. This part of the computer programme also enables the calculation of the volume of inert fluid to be withdrawn after each overflow.

### Computer Programme Relating to the Operation of Cavities Filled with Gas

In order to have better control of the operation of cavities filled with gas and, more particularly, to make sure that the operating data are coherent, a simulation model of the thermodynamic behaviour of gas in a cavity was developed by Gaz de France. The corresponding computer programme numerically solves the differential equation giving an account of the balance of heat quantities exchanged by gas with the ground surrounding the cavity during injection, stop or withdrawal phases. This computer programme allows the numerical simulation of the gas pressure and temperature in the cavity with an accuracy of less than 1%.

### Computer Programme Relating to the Mechanical Behaviour of Salt Cavities

Gaz de France has monitored cavities filled with gas for the last ten years and carried out, more recently, *in situ* testing permitting adjustment of two models describing the mechanical behaviour of salt.

These models are used in computer programmes implementing the method of finite elements and allowing solution of the following problems: spacing between cavities, shape and size of cavities and study of stresses at certain critical points of the cavities, such as the well casing shoe.

Besides these solutions Gaz de France was able to find analytic equations that account for the mechanical behaviour of a spherical cavity isolated in an infinite massif from the Bingham model.

The Bingham model is representative and is quite satisfactory with regard to the real behaviour of salt cavities. It enabled the construction of two charts which allow answering two types of concern:

- One chart enables the calculation of the instantaneous creep rate corresponding to a given stress (short-term cavity management).
- One chart enables the calculation of the cumulate creep rate corresponding to a succession of pressure reports over several years (long-term cavity management); the second chart is based upon the concept of threshold pressure.

## ORGANIZATION OF THE IMPLEMENTATION AND CONTROL OF SALT CAVITY LEACHING

### Local Follow-up

The computer programme which controls leaching at the cavity roof is used every day on each site and for each cavity. It is implemented on a mini-computer. This programme enables calculation of the movements (injections and/or withdrawals) of inert fluid to be carried out during the day. The corresponding volumes are then fed into a second computer which manages the injection and withdrawal operations themselves. It is the programme which, from the control room, controls the operations carried out on each platform of well being leached by means of the equipment described in the section on "fuel skids."

At Etrez, the same computer is responsible for the automatic acquisition of all measurements carried out on site. An auxiliary calculation programme constantly monitors the consistency of the measurements carried out and thus detects possible failures or deviations of measurement equipment or possible incidents occurring on leaching equipment (leak on a line, deterioration of a pump's characteristics).

The computer programme controlling the leaching at cavity roofs also follows up the shapes of cavities being leached. Every day, this programme enables calculation of the vertical wall progression, the free volume of the cavity (mined volume less the volume of insolubles deposited and swelled). It also indicates the actual shape of the roof of each cavity.

### Centralized Follow-up in Paris

In the particular case of the projects presently being carried out by Gaz de France at Tersanne and Etrez, Gaz de France follows up these two projects from its head office in Paris.

All the operational data used by the computer programme which controls the leaching at cavity roofs are teletransmitted every day to Paris, where they are reprocessed in order to be controlled and then filed on a magnetic file. It is therefore possible to restore the history of flows, contents and volumes, the water and brine balances, the data used for short and medium terms forecasts. Once a week the shape of each cavity is calculated by two independent methods:

- Calculating the development of the cavity shapes on the basis of the contents measured and according to the laws of dissolution (from this calculation a first estimate of the free volume called "Durie" volume can be made)
- Calculating a "mass balance" volume on the basis of the contents and flows measured and then determin-

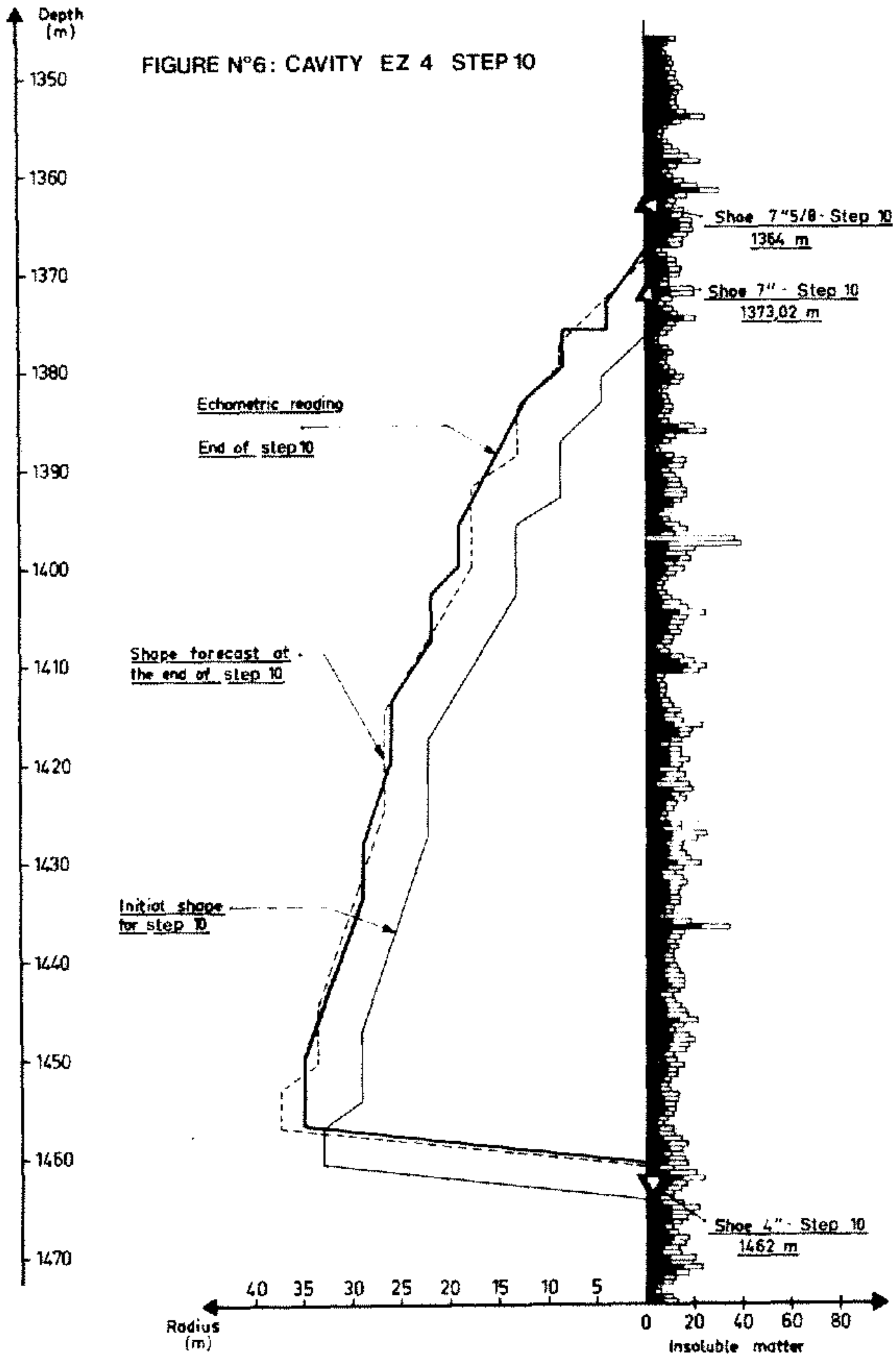


Figure 6. Cavity EZ 4 Step 10.

ing the development of the cavity shapes from this volume.

### In Situ Measurements of the Cavity Shapes by Sonar Caliper Survey

*In situ* measurements of the cavity shapes are carried out by sonar caliper survey on average every three steps in order to check that there is a good agreement between the development forecast and the real development of the shapes, taking into account, in particular, the presence of insoluble layers.

These measurements are carried out by means of Sofregaz's sonar caliper survey unit (Figure 6). An example of these measurement results is given in Figure 7.

### Special Follow-up of First Step

The insoluble materials, mainly clay and anhydrite, released by leaching, deposit at the cavity bottom. The effect of this process is to stop the dissolution of the salt layer at the cavity bottom. The height of salt massif thus neutralized increases all the faster as the sedimentation surface remains small in relation to the lateral surface being dissolved. This shows how important it is to control the first step, when the risk of bottom rise is the highest, and the success of which governs the rest of the leaching.

The development of the content of brine produced during the first step is simulated by the computer programme which calculates the kinematic development of cavities being leached. The high sensitivity of this calculation to the parameters involved in the dissolution process enables determination of the exact dissolution conditions by adjusting the measured and calculated contents of the brine produced.

In fact, during the first step, two phenomena become very important. In one, the small cavity volume enables the presence of turbulence that keeps in suspension the insoluble particles, which only deposit after a certain thresh-

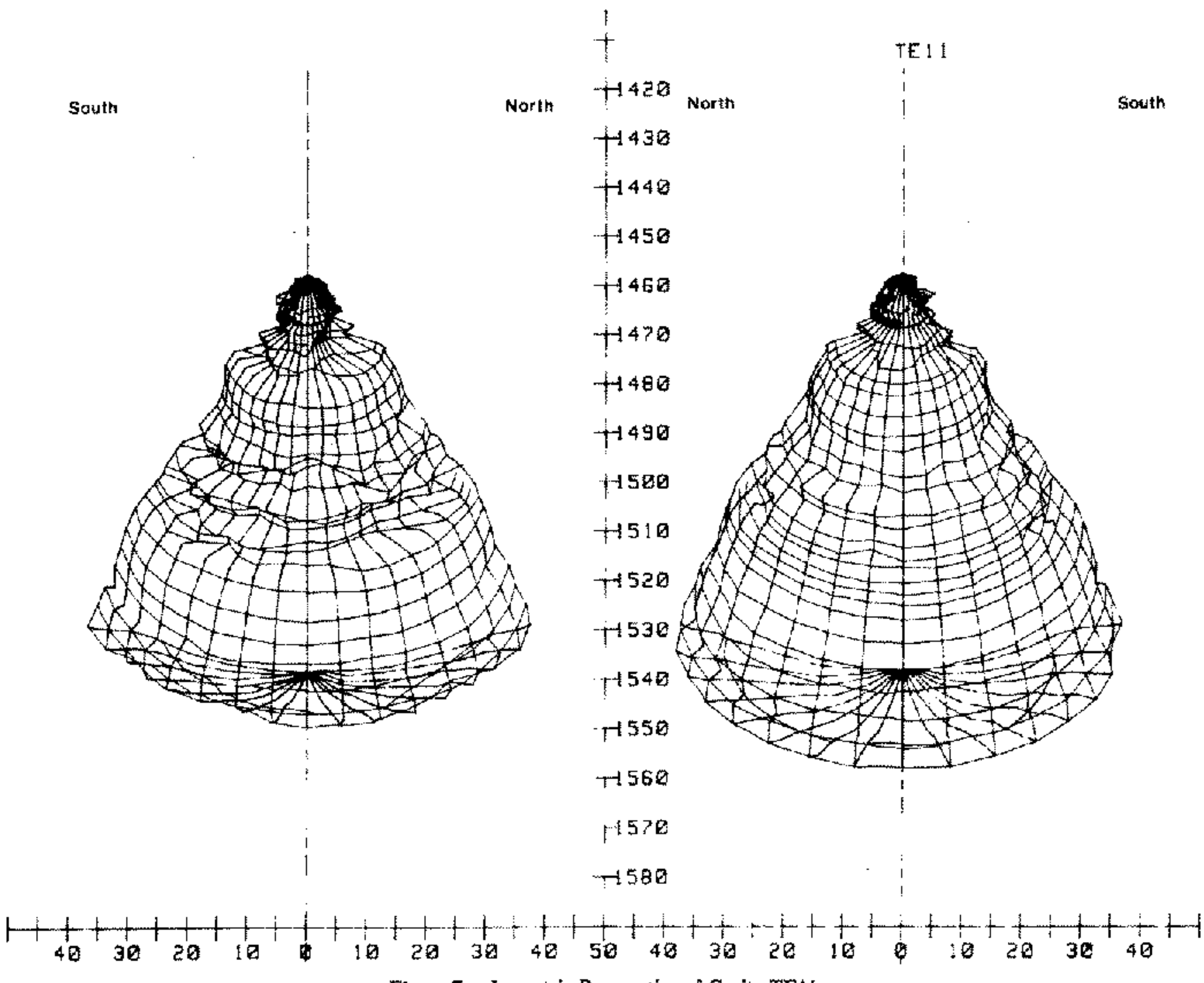


**Figure 7.** Isometric Perspective of Cavity TE11.

oid or, last of all when leaching stops at the end of a step. Thanks to the computer programme mentioned above, it is possible to predict this sedimentation threshold. In the other phenomenon, the presence of insoluble layers sometimes causes, particularly during the first step, the formation of superposed cavities. With this simulation programme, it is possible to show this phenomenon.

It is thus possible to forecast with accuracy the cavity shapes at the end of the first step, which enables one to omit at that stage in situ measurements of shape by means of sonar caliper survey.

## MEANS IMPLEMENTED TO ENSURE THE SAFETY OF SALT CAVITIES STORAGE

The means implemented by Gaz de France and Sofregaz to ensure the safety of salt cavities storage are very great.

They are mainly of two kinds: one, the development, in close cooperation with the Mining Administration, of tightness testing procedures carried out before and after leaching of the salt cavities, and two, the use of very reliable equipment and safety material for the completion of operating wells of cavities filled with gas.

### Tightness Test After Drilling

The major risk in an underground storage a possible leak of the stored product along the well casing cementation; such a leak may emerge at the surface and may cause damage. Therefore, the greatest care must be given to tight cementation and casing control.

To this end, Gaz de France has developed a tightness testing procedure carried out under pressure at least one month after the casing cementation. This test is conducted with a special completion enabling the testing, separately, of the casing tightness and of the tightness of the unit, including the casing shoe and the drilling hole (Figure 8). The test principle consists of applying various pressure levels to the two columns and of measuring the liquid readjustment levels necessary to keep these pressures (the test fluid is saturated brine).

For the casing test, a pressure corresponding to a gradient of 1.46 (ratio of the relative pressure applied to the pressure that a water column with a density of 1 would exert at the same depth) is applied to the two columns at the packer level of the test completion (the highest pressure that may be applied during leaching). The two pressures on both sides of the packer being equal, the risk of leak through the packer is nul, and the readjustment flow rate measured at the annulus head corresponds to the apparent flow of any possible casing leak.

For the casing shoe test, the pressure applied on the annulus is maintained and the pressure levels corresponding to gradients between 1.8 and 2 are applied to the casing shoe. The estimate of the apparent leak flow rate at the casing shoe is given by the sum of the readjustment flows carried out to keep the pressures constant at the head of

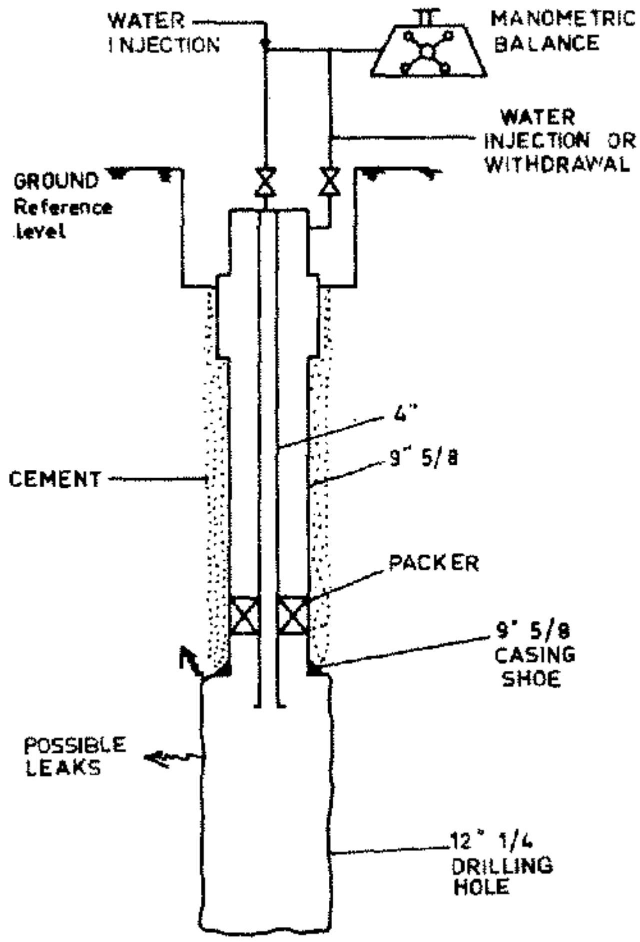


**Figure 8.** Diagram of Device for Tightness Test Before Leaching.

the two columns. The sum from which the apparent flow rate of the casing leak was measured during the previous test is deduced. This test is declared to be satisfactory as soon as the apparent flow rate of the leak remains below a few liters a day.

### Tightness Test After Leaching

After leaching, the well completion for the operation of the cavity to be filled with gas is installed. Generally the maximum operating pressure in the cavity at the level of the casing shoe is taken as equal to 0.9 times the test pressure before leaching. The tightness of this cemented shoe is tested again before filling the cavity with the fluid to be stored.

The principle of this new test consists of applying a pressure equal to the test pressure before leaching at the casing shoe level, using a test fluid inert in relation to salt, lighter than brine and easy for accurate volume measurements. Diesel fuel is used by Gaz de France at Tersanne and Etrez. Using a mass-balance method appropriate to this test fluid, before and after the test is carried out, enables determination of the apparent flow rate of any leaks

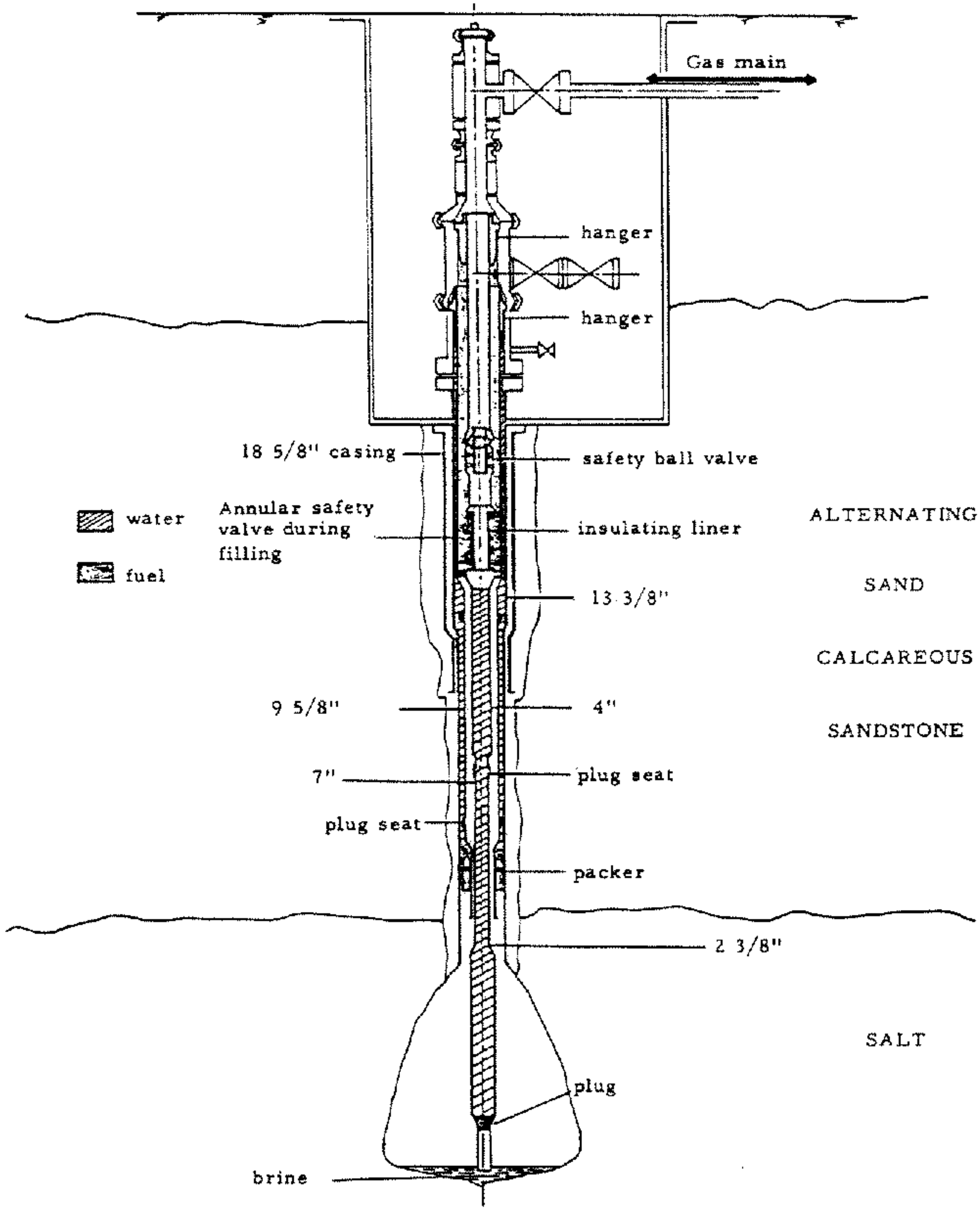


**Figure 9.** Salt Cavity Completion.

at the level of the cemented shoe. In the case of cavities intended to store natural gas, this test is confirmed by a second test with gas, based on the observation of the pressure developments at the head.

### Completion of Wells for the Operation of Cavities Filled with Gas

The gas completion is schematically made of two 7-inch and 4-inch concentric tubings hung at the well heads (Figure 9).

The bottom of the 7-inch column slides inside a packer anchored in the 9⅝-inch casing; the tightness of this unit is ensured by slip joints. The 9⅝×7-inch buffer annulus is filled with fresh water and is used to protect the casing cementation against the pressure and temperature variations occurring inside the production annulus. During filling of the cavity, the gas is injected through the 7×4-inch annular space and brine is sent back through the 4-inch column.

After filling, the cavity filled with gas is operated by the 7×4-inch annulus. In order to improve the well production, it is also possible to use, in addition, the 4-inch column to operate the stored gas. The search for the best possible tightness for the connections between the well completion tubings led us to choose VAM thread joints with double conic shoulder, metal against metal.

During filling of the cavity with gas, the gas injection and brine removal circuits each have underground safety valves located between 15 and 30 metres under the ground surface. For the gas circuit an annular safety valve is used (sliding side-door sleeve) and for the brine circuit, it is a ball valve. These valves are kept open by oil pressure. In case of an "incident," the oil circuit is opened and these valves close under the pressure of the fluid of the appropriate circuit. Any "incident" is defined as being

- for gas, the breakdown of the well head or of the surface circuit which would result in an abrupt pressure variation of the surface gas due to pressure drops,
- for brine, the breakdown of the 4-inch brine rising column that would result in an abrupt pressure rise, with risks of mechanical damage to the brine return line.

These safety valves are controlled by an automatic system that can be adjusted in relation to the pressure thresholds desired (low threshold for the gas circuit, high threshold for the brine circuit). This system includes a fuse plug intended to close the valves in case of fire at the surface.

These valves are also special because they are retrievable. At the end of the gas filling they are lifted up. Instead of the annular safety valve, a "ghost" system which transforms the gas production annulus into a tubing inside space is installed. The safety ball valve is put back in its place in its original seat; it ensures the safety of the gas circuit, after having done so on the brine circuit during the in-filling.

## CONCLUSION

Due to the experience they have acquired, Gaz de France and its subsidiary Sofregaz have now mastered the technique of solution mining of salt cavities intended for underground storage. Several examples of the fruit of their experience are illustrated mainly by the industrial installations of Tersanne and Etrez but also by projects carried out abroad, in Great Britain and Iraq. Means of calculation were developed in order to ensure the carrying out and control of the cavity mining process and operation. Finally, efforts were made to ensure the safety of these storage areas.