Underground Storage of Hydrocarbons at Manosque, France

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ABSTRACT

Underground storage of hydrocarbons allows for storage of great capacity in economic conditions. The article describes the Manosque Storage, 70 km from Marseille (France). Thirty-four solution-mined cavities in salt deposits will have a capacity of 10 million m³ (60 million barrels) in 1976, possibly 14 million m³ (84 million barrels) later on. Brine from solution mining is stored in 2 lakes where it is dispatched by a pipeline system. Automatic control systems supervise the whole installation.

The behaviour of the salt is disconcerting. Salt formations exhibit considerable discontinuities inasmuch as they include anhydrite layers. In these conditions, theorical rock mechanics gives only approximate results, and it is necessary to study in situ the mechanical behavior of the cavities. Behavior was found to be elastic (±100 m³) over one year in the case of a 280,000 m³ excavation, between the depths 980–554 m, the inside pressure being the pressure of a saturated brine column up to the surface.

INTRODUCTION

Following progress made in the United States, the underground storage of gaseous and liquid hydrocarbons has developed considerably in Europe during the last five years. Many factors have contributed to this development: increased energy requirements, the cyclic nature of consumption necessitating substantial investment in refinery capacity, and economic solutions to the problem of storage in densely populated areas. Moreover, French law now compels refiners to store the equivalent of three months of consumption. After a few projects in aquifers by Société Nationale des Pétroles d'Aquitaine (SNPA) and Gaz de France, Geostock was set up as a subsidiary of four French oil groups (Shell Berre, B. P., Elf Union and Compagnie Française de Raffinage), to design and build large underground storage facilities for hydrocarbons and any other products suitable for this technique.

The geology of the French subsurface is extremely varied from volcanic massifs to vast sedimentary basins. Although salt is found to a lesser extent than in other countries such as Germany, there is still substantial potential in France for underground storage in salt.

The question of underground storage is dominated by problems of safety and economics, and concerns not only disused mines and quarries but also new cavities, especially in salt, where it is necessary to make best use of the salt deposit chosen. Schematically, the overland pipeline systems in France comprise the Seine Valley system, the Pipe Line Sud Européen (PLSE) system linked to the European network which starts in the Marseille area, follows the Rhone Valley northward, runs parallel the Saone Valley and then to the Rhine from Mulhouse to Karlsruhe and the Société du Pipeline Méditerranée Rhône (SPMR) system which reaches Dijon and brances off to Geneva and St Etienne. The PLSE system runs beside several salt-bearing zones, keeps connection costs between storage facilities and the pipelines to a minimum. As may be seen in Figure 1, there are six of these principal zones; two in Alsace near Strasbourg and Colmar-Mulhouse, two others in Bresse near Poligny and Bourg, one large zone near Valence and one in Provence near Manosque.

Apart from geological and geophysical aspects, there were several factors which simplified the choice between these sites. Alsace had to be eliminated for large storage projects because of the impossibility of discharging the brine, because the Rhine already has a Cl^- ion concentration of 250 mg/l, and there are no suitable deep geological formations. The same applies to Bresse, where the salinity of the neighboring Saone is 200 mg/l Cl^- and hence excluded brine discharge.

The Valentinois appeared the most promising area,

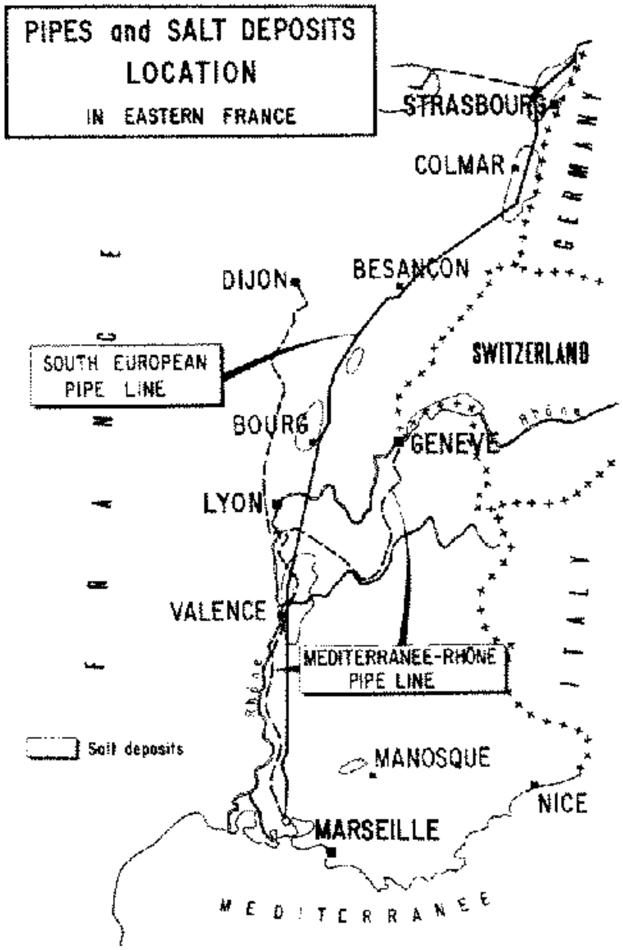

Figure 1. Pipelines and salt deposits in eastern France.

with two suitable salt-bearing horizons, one deep (Sannoisien) from 1200 m to 1800 m, the other (Chattien) from about 500 m to 600 m which would only have been suitable for small cavities. The Cl^- concentrations in the two large waterways, the Isere and the Rhone, were low, of the order of 50 mg/l, with high flow rates of 400 m^3/s and 1500 m^3/s; many underground and discharge possibilities were considered, but the refusal of the French Ministry of Agriculture to authorize discharge into the Rhone led to the investigation and completion of the Manosque project. In parallel with this research, a great deal of geological, geophysical, seismic, electrical and even gravimetric work was carried out to provide the maximum amount of information about all these structures so that the economic evaluations could be done on the soundest possible technical basis. Finally for Manosque, additional research was carried out in order to specify the geological formations, structures and geotechnical data.

Before describing the storage project itself, it is perhaps worthwhile to review the geographical situation, which gave rise to substantial economic problems.

THE MANOSQUE STORAGE PROJECT

Geographical situation

The geological and geotechnical advantages of the Manosque site (Fig. 2) were substantially counterbalanced by geographical aspects. This site is 80 km to the Northeast of Marseille and some 70 to 80 km from the Berre (Shell) and La Méde (BP) refineries and from the Lavera refinery and oil terminal. Moreover, some 95 km of connections were necessary to the pipeline system and the brine discharge point, and 17 km to the freshwater supply point. The cost of these connections had a significant effect on the project despite the possibility of creating enormous cavities (200,000 to 600,000 m^3) at depths between 600 and 1,000 m. After considering the capacities required, it was decided to create a volume of 5 million cubic meters (30 million barrels) for 1973, and then to double this capacity. Since by law, it had to be possible to empty the reservoir in less than three months, the pipeline diameter was fixed at 20". It was decided that fresh water supplies would be obtained from the Forcalquier dam and the Electricité de France (E.D.F.) canal (Brillanne Canal).

Brine discharge was impossible in the Durance or the E.D.F. canal and could take place only in the Berre lake. An agreement was also reached with the Compagnie des Salins du Midi et des Salines de l'Est (CSME) for using the lake at Lavalduc and Engrenier to store 20 to 25 million cubic meters of brine while awaiting a customer. Ultimate discharge into the Berré lake was finally accepted: investigations showed in fact that the Geostock discharges would not change its salinity by more than 0.5 mg/l.

Geological situation

Salt originates from the Oligocene strata (Figs. 3 and 4). It was deposited after the orogenic phase of the Pyrenees-Provence region in the basin of Apt-Forcalquier where considerable subsidence took place which gave great thickness to the sediments. The Alpine orogenic phase at the end of the Miocene epoch includes this level in a very marked anticline structure, orientated southwest-northeast (Fig. 3) and highly tectonic. In the Manosque anticlinal zone, the salt-bearing formation therefore appears as a formation of variable thickness (800 m and more) known to cover about 8 km^2 (approximately 2 X 4), in which the insoluble matter (anhydrite and other) which had been stratified, is now completely broken down into pieces ranging between 1 meter and 10 centimeters, distributed through the salt mass. However, the overlying anhydrite formation appears to have remained coherent, and the series, wherever it has been traversed, is well bounded by the lower Eocene and the intermediate Oligocene. Thus, there are no diapir domes, although the salt mass has clearly undergone plastic deformation. The great thickness of the formation and the dispersion of insoluble materials into small fragments made it possible to envisage

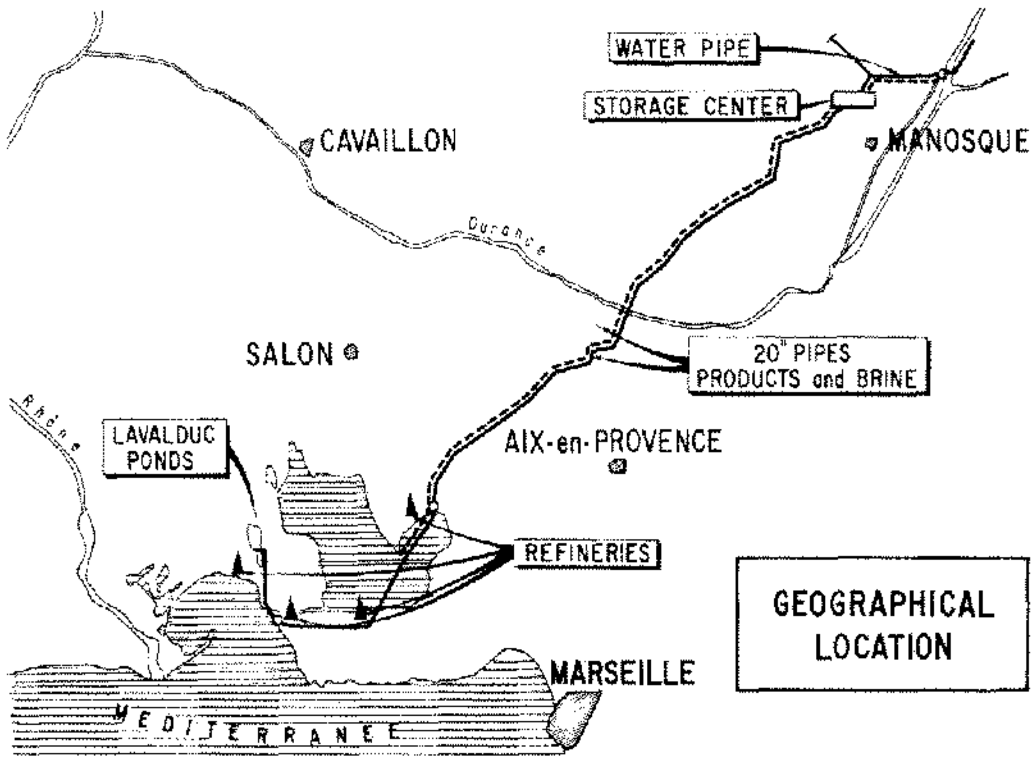

Figure 2. Location of installations in the Marseille-Manosque area.

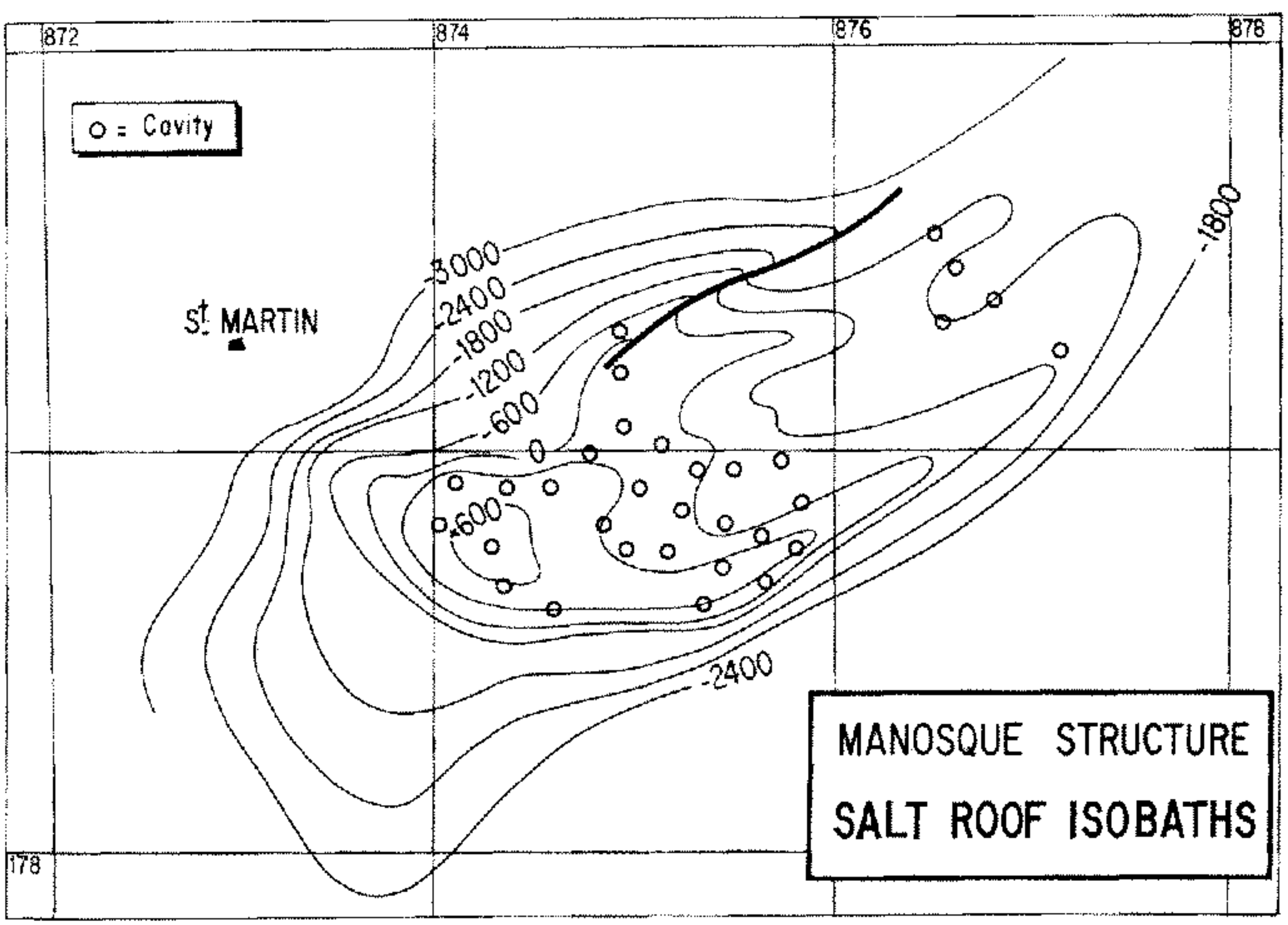

Figure 3. Structure map on top of the salt at Manosque. Isobaths contour (interval: 600 meters).

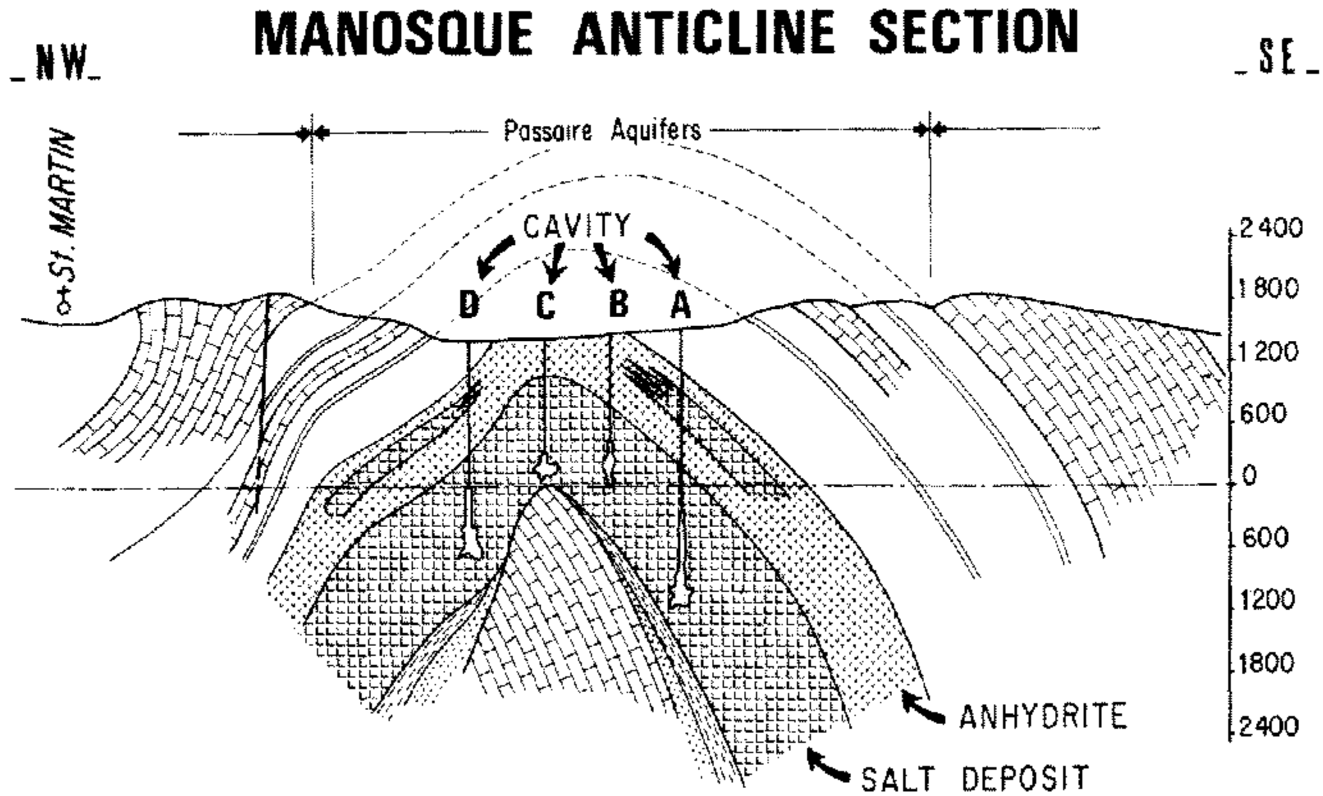

Figure 4. Geological cross section of the Manosque anticline showing the location of 2 cavities A-D.

cavities of great height and substantial volume. Certain cavities now exceed 500,000 m^3.

Design and installation of surface facilities

The project has a double objective of 1) the storage of crude and diesel oil from the petroleum complex at Berre lake, and "strategic" return of these same products to Berre, Lavera or La Mede in times of economic need and 2) the seasonal storage, particularly for stocking surplus diesel oil in summer for use in winter.

The principal operations therefore were the creation of cavities at Passaire (Manosque), the construction of a Passaire-Lavera pipeline (filling with hydrocarbons in one direction and emptying in the other) and the provision of fresh water supplies from the Passaire center for creating cavities in the first and second phases and releasing hydrocarbons in the third phase. In fact the planned storage project comprised three main stages: Stage one, launched in 1968, was for the creation of 18 cavities by 1973, totalling 5 million cubic meters (30 million barrels). Stage two, now underway, is to double this capacity with 16 additional cavities by 1976. Stage three, is when seasonal emptying operations will be carried out using freshwater, enlarging the cavities to a total volume of 14 million cubic meters (84 million barrels). The timing of this third phase depends on future seasonal needs or shortages.

The following surface installations were therefore established (Fig. 4):

1. A freshwater pumping station at La Brillanne, on the E.D.F. canal.
2. A pipeline linking La Brillanne to Passaire (1,800 m^3/h).
3. A pipeline bringing another freshwater supply from the La Laye dam near Forcalquier.
4. At the Passaire site:
   a. Pumping stations to send brine or hydrocarbons to Berre.
   b. Pumping stations to be used for solution mining of cavities.
   c. Two brine storage basins (capacity: 200,000 m^3) to hold excess flow at the start of solution mining, to allow uninterrupted constant flow in the Passaire-Lavera pipeline, and to collect brine displaced as the hydrocarbons are pumped in.
5. A pipeline linking Passaire and Lavera, operating in both directions (1,500 m^3/h in the direction Passaire-Lavera and 1,000 m^3/h in the direction Lavera-Passaire).
6. A pumping station at Lavera to send the hydrocarbons to Passaire.
7. A relay station at Berre, and a brine discharge station with a line running to the Vaine lake.

8. Hydrocarbon delivery stations at Lavera and La Mede, together with brine discharge plant and a brine transmission system to the Lavalduc lake and seawater flush to Passaire.

All these plants were installed according to a very carefully planned economic program. For example, to reduce interest during construction, a first 20" pipeline was put into service in 1968 and a second in 1972. Similarly, the cavities have been created one after the other so that some of them could be put into service each year.

Cavity mining system

Each cavity in the first phase is obtained by solution mining of the salt over a thickness of up to 400 m, between depths of 600 and 1000 m.

Briefly this well-known mining technique involves:

1. Starting from a well drilling operation of the oil-rig type, freshwater is circulated in the salt-bearing formation;
2. The shape of the cavity is controlled by regulating the jet tubes and the brine discharge. From time to time, a sonar check is made to confirm that the required shape is being obtained;
3. The roof is prevented from developing upwards by protecting it with a substance inert to salt; for this purpose, diesel oil was injected into the outer annulus. At Manosque, the oil was kept at constant level, giving a plane horizontal cavity roof. This has no disadvantages from the stability point of view up to about 700 m, as shown by calculation and confirmed by experiments on existing cavities. The cavities are basically pearshaped, the bottom of the cavity being filled with insoluble matter which sometimes becomes detached from the walls, and gives rise to eddies which can damage the tubes inside.
4. At each well-head, there are isolating valves, turbine gauges to record the input and the output water, brine or hydrocarbons, manometers, thermometers and over-pressure safety systems linked to the pumping stations.

Each cavity is built to deliver 1,500 m^3/h by drilling operations of the oil type in which an 18 5/8" casing is positioned (down to 520 m for example in A 4) and cemented back to the surface, and by solution mining with freshwater, pumped through a 7" pipe (down to 960 m in the same cavity), and returned through the annulus between the 7" and another 11 3/4" casing (extending down to about 560 m).

In the first phase, cavities were created at a rate of 5,300 m^3/day, the resulting brine being discharged either to the Berre lake, or, for further use, to the Lavalduc lake or the Salines de Berre, the 18 5/8" casing were run down to depths of 600 m and strict control was required to keep the holes to within 2° maximum of vertical. Changes of direction must not exceed 1/4° per 30 m hole length. The steep dip of the superjacent strata (40° to 60°) made supervision critical to meet these criteria.

Various drilling programs were tried in order to obtain an acceptable cost.

The values adopted now are that the height of the cavity, if possible, is 400 m and the rate of mining water flow is 250 m^3/h.

Operating technique

As currently operated, the stored oil is displaced by freshwater for emptying purposes. The cavities as mined are undersize to allow for further solution of the salt during this process. Other techniques will be employed once the cavities have become so enlarged that they can only be emptied twice more by the fresh water displacement method, so that seasonal drawdown and refilling can continue without further enlarging the storage chambers. Before dwelling on a few specific problems, there follows a brief description of some of the automatic systems installed.

Automatic control systems

The whole installation (storage cavities, pumping stations, pipe systems, pipelines) is controlled and supervised from a central post at Passaire.

The remote supervision system includes local automatic controls at Berre, La Mede, Lavera and La Brillane (water supply), transmission equipment, a small computer, a control panel.

With this system, three eight-hour shifts of two operators can carry out all normal operations. Orders originating from the control panel are transmitted to the local automatic controls.

Local automatic controls prepare stations for filling and emptying, actuate and put cleaning slugs into sidings after use. They switch standard meters on and off, signal any operating fault (overpressure, no flow, electrical faults) and shut down the plant in the event of a serious fault. The local automatic systems are built with miniaturised solid state relays.

Transmission equipment ensures despatch of all signals and figures from station to central control, and orders and corrections from control to station. Information is sent serially in cycles. Orders take priority and interrupt the cycle. Priority signals necessary for line operation (pressures, flow rates) are transmitted continuously. Signals are transmitted on special telephone lines rented permanently from the French Postal Authorities. Checking devices prevent any chance of transmission errors (parity control, double send and return).

Computer. PD 8.8 data logger, with print-out and adjusts measured volumes to volumes at 15° C.

Control panel. The control panel shows all controls, slaves, measuring instruments, pressures, flow rates and

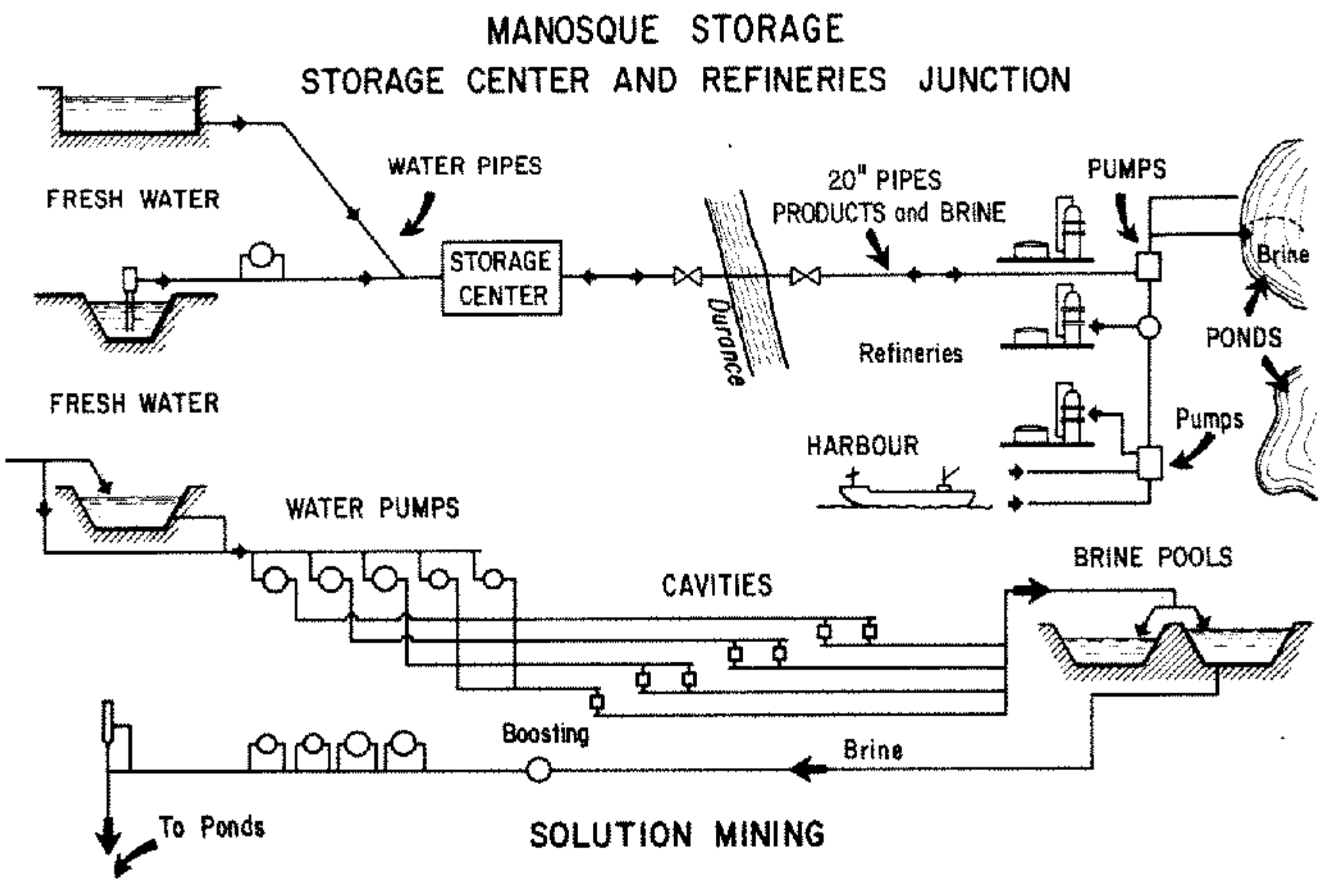

Figure 5. Manosque storage center and refineries junction.

cumulative volumes on a flow chart display so that operators are fully informed of conditions at all times. Order preparation and transmission sequences are kept separate for a final check before transmission to eliminate operator error.

RESEARCH, TESTS AND SPECIAL PROBLEMS

For several reasons, very special attention has been devoted to protecting the environment. In fact, this project had to prove that the system of stocking, then being installed for the first time in France, added a remarkable degree of safety and a highly attractive quality of environmental invisibility to its economic advantages. On photograph N°5, showing the whole of the surface installation, it can be seen how little it encroaches on nature and the way it fits into the background. Proof of the technique's environmental advantages is the fact that the Manosque site has recently been authorized as a hunting reserve and stocked with wild boar and other game. It might also be mentioned that the May-Sur-Orne site in Normandy is now a sport fishing reserve. In addition, more than 20,000 trees were planted to efface the scars caused by construction work for drilling platforms.

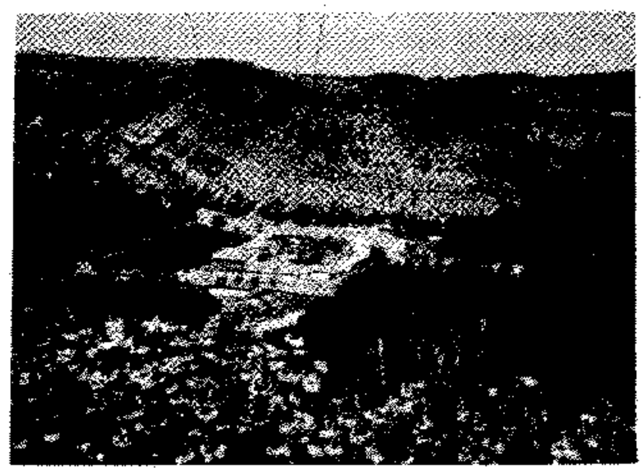

Figure 6. General view of the Manosque surface installations.

Superintendance of pipe-lines

The pipe-lines obviously need very careful watching so as to eliminate any risk of pollution by hydrocarbons or brines. Corrosion of the Passaire-Lavera pipe raised a new problem. Its length, working pressure, alternating liquids did in fact make it a rather special case. After research and synthesis of known processes, it was decided to add extra thickness for corrosion and a corrosion control system. It became evident corrosion would be affected largely by brines (source water, composition flow velocity), but also by the type of metal, the oxygen dissolved in the brine, differential air contact, and finally galvanic and bacterial effects.

Several known systems can reduce or detect corrosion:

1. Inhibition by polyphosphates, de-aerator plant.
2. Vents for controlling air entrainment.
3. Drains for controlling entrainment of brines and insoluble material.
4. Oxygen detectors at both ends for checking the amount of oxygen absorbed by the steel.
5. Corrosionmeters measuring corrosion level by correlating the variation in resistance of a standard specimen made of the same metal as the pipe and immersed in the same fluid.
6. Measurement of the iron content of the fluid at both ends of the line.
7. X-ray checks of the pipe at certain points on the line.

Tests and supervision of cavities

Tests primarily concern cavity wall impermeabilities. The cavities are pressure chambers, and must be tested as such. They are tested in two stages by testing the well suitability before solution mining, and by an acceptance test on the cavity before filling it with hydrocarbons. It is obviously very difficult to establish a pressure test value of such cavities, as it will vary with cavity height. Geostock has therefore agreed with French government authorities that the weakest point is the shoe of the deepest cemented casing. At this depth, operating pressure in the least favorable working conditions can be estimated. The suitability test is at present carried out so as to obtain 20% higher pressure at this level than is required for operational pressure.

Fluid loss criteria

There is no absolutely reliable criterion and we have chosen the limit reached in the Manosque wells of 2 to 3 liters leakage per day for a shaft kept under constant pressure. It is hardly possible to check the degree to which the cavities are watertight to within less than several tens of liters per day and even this involves long, tricky, indirect means. In fact, it is assumed that permeability is no greater than at the time of the shaft test before mining the chamber.

Cavities—behavior & mechanical stability

The comparatively shallow depth of the cavities (less than 1,500 meters) indicated good stability, based on as calculations and also from the experience in many countries. Geostock nevertheless wanted to forecast how the cavities would behave and follow their behavior. To this

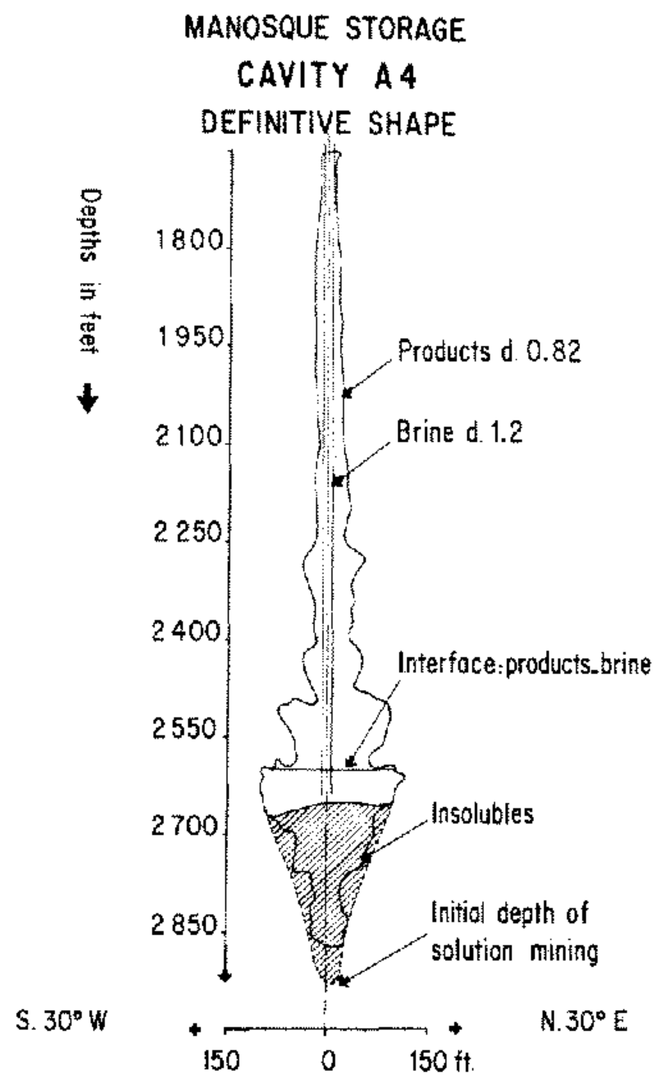

Figure 7. Manosque storage cavity A4 at the definitive shape.

end, cavity A4 of 280,000 m^3 (Fig. 7) from 550 to 1000 m depth, was observed for more than a year, and was subjected to a pressure equal to that of the weight of the brine column rising to the shaft head. The comparisons between the volume withdrawn to keep a constant pressure at the head and the reduction of apparent volume, due to thermal causes, showed an equivalence to within 100 m^3—in other words the cavities were not subject to important or irrecoverable delayed deformation, through creep,* and their behavior was elastic.

The following method was used: The original tempera-

*In this context we define "creep" to mean such deformation as appears under constant pressure, of which only a part is recoverable. The critical pressure at which creep occurs will be revealed by larger, only partially recoverable delayed deformations; at the same time, there will be plastic deformation in some parts of the cavity.

ture before mining of the cavity was measured, then on completion of mining, and after filling with diesel oil, repeatedly for about one year, it was noted that the inside temperature of the cavity rose by less than 5°C (Fig. 8). Taking the vol/vol/°C as 0.4 10^{-3} for cubic expansion of brine and vol/vol/°C as 0.8 10^{-3} for diesel oil, the volume of liquid in the cavity has increased by approx. 800 m^3. After maximum temperature rise (36°C), this increase should be approx. 2,300 m^3. Thermal expansion of the walls (1.2 10^{-4} vol/vol/°C) and insolubles (0.3 10^{-4} vol/vol/°C) must not be ignored.

We measured expansion (which in this instance means an apparent volume decrease in the cavity) from the volume of fluid withdrawn from the cavity to keep it at constant pressure. The latter comes from reduction of the excavation volume by cavity walls expanding due to temperature rise and from mechanical deformation during the cavity's life. As the cavity is under constant pressure, this is a creep. If such deformation is slight, however, we can

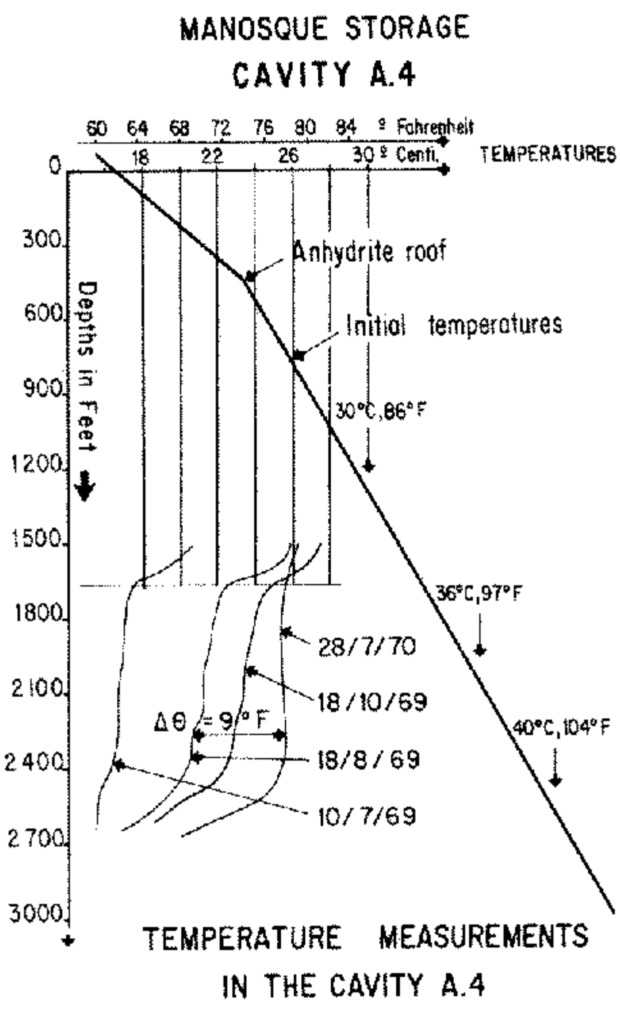

Figure 8. Temperature measurements in the Manosque storage cavity A4.

assume that most deformation took place a long time ago, and that new deformation is elastic. In addition, factors are estimated from the increase in volume, through expansion, of diesel oil, residual brines, and insolubles lying at the bottom.

Expansion cannot readily be measured at strictly constant pressure. This would entail having a large reservoir whose volume content could be easily measured. It is much simpler to close off the cavity and measure the increase of pressure at nearly constant volume; the volume decrease at constant pressure can be found by multiplying the variation of pressure at constant volume by the coefficient of global compressibility of the cavity. This coefficient can be broken down into the volume changes per unit pressure of the cavity (increase), the brines (decrease), diesel oil (decrease), and the insolubles at the bottom (decrease). The coefficient can be determined quickly experimentally by measuring the volume to be withdrawn so as to lower the pressure slightly by a set amount near the desired pressure. It can moreover be estimated from the brine, diesel oil and insolubles volumes, and the salt's mechanical properties. Four measurements of pressure increase at constant volume have been carried out, shown as chosen unit equal to one day. These measurements give an average global compressibility for the cavity in given conditions, of 14 m^3/bar. From this can be derived the expansion in m^3/day at constant pressure, and integrating over the period (Aug. 1969–July 1970) gives the global expansion for constant pressure conditions. In this case, we have 910 m^3/day, which correlates fairly well with the expression:

$$Y = -0.814 \log t + 6.645 \quad (y \text{ in } m^3/\text{days}) \quad (t \text{ in days})$$

ignoring the initial transition period.

So it can be seen that only 100 m^3 are left to cover cavity wall expansion, insolubles expansion and mechanical deformation of the walls under a near constant pressure (recoverable or irrecoverable creep). If expansion of insolubles can represent 5 to 10 m^3, there are errors in other directions e.g., mistakes in brine volume between 10,000 and 15,000 m^3. The value of 10 m^3 can go as far as 200 m^3. This small delayed deformation in a cavity of 240,000 m^3 can only suppose that there is almost no creep, which is typical of the elasticity of the cavity under the pressures to which it has been subjected.

If we extrapolate the approximate logarithmic temperature rise measured in the first year, total expansion by 1979 will be 2,600 m^3. Estimates based on the thermal expansion of the stored liquids as the final cavity temperature gives a figure of 2,300 m^3. This indicates that the full temperature rise will be completed in about ten years, if conditions remain constant. Other measurements are being made to try to define *in situ* salt behavior and correlate

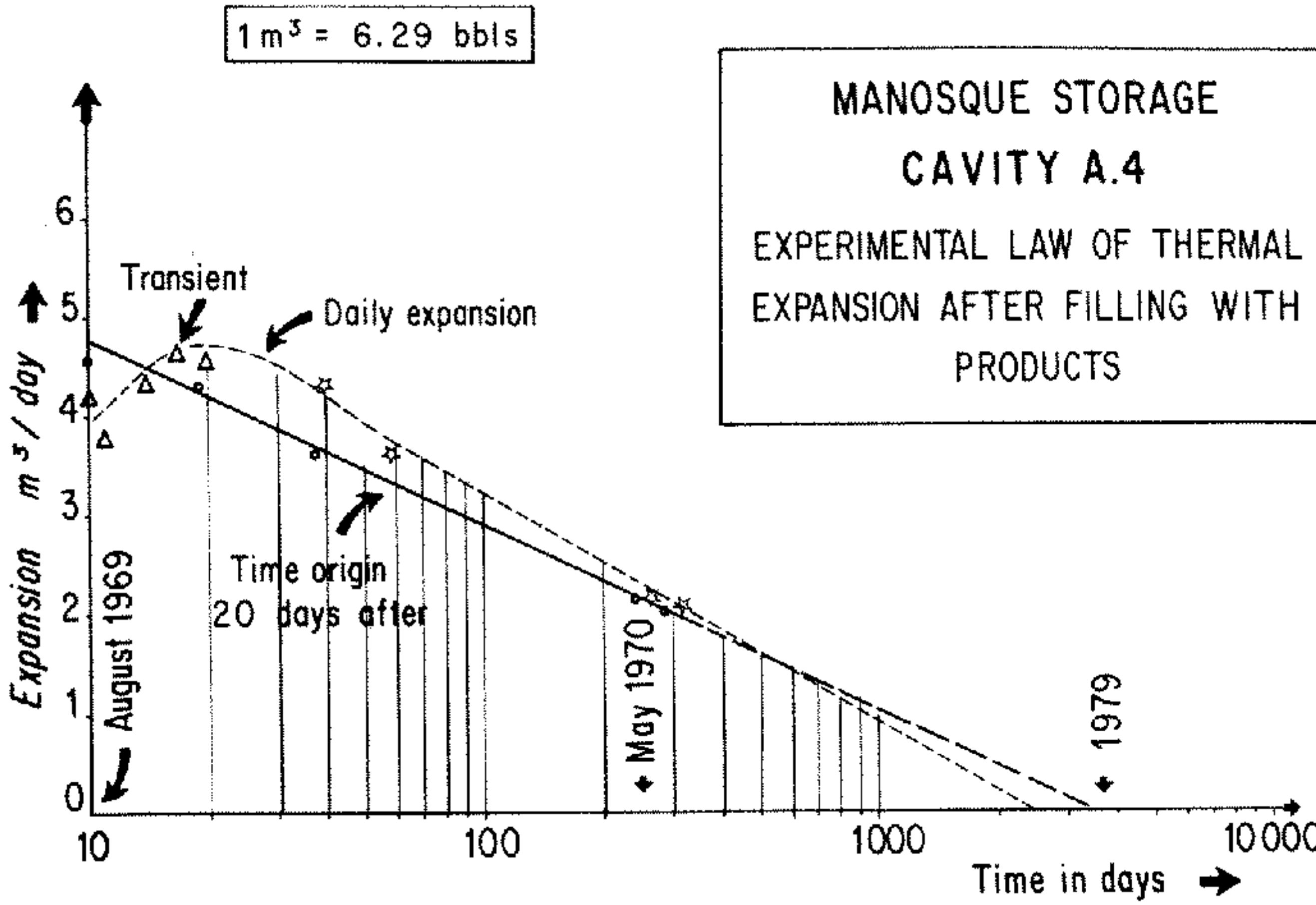

Figure 9. Experimental law of thermal expansion after filling with product Manosque storage cavity A4.

this with laboratory findings. Quite serious discrepancies have been found so far.

CONCLUSION

The rather peculiar conditions at the Manosque storage project have led Geostock to give close study to a certain number of problems such as: corrosion, permeability, cavity reactions etc. First results set out here seem to confirm certain theories, particularly those on corrosion. On the other hand, observation of some cavities has shown important gaps between forecasts based on laboratory calculations and the mechanical behavior of salts.

The differences seem important for economic development of this small salt basin and its surface installations. This type of research would seem to remain important for several reasons relating to long term cavity behavior, maximum cavity size, and use of cavities at greater depths and for storing other substances.

A sound theory should be capable of interpreting the actual mechanisms and Geostock shall continue to examine the actual behavior of these sites to see which theory represents them most satisfactorily.