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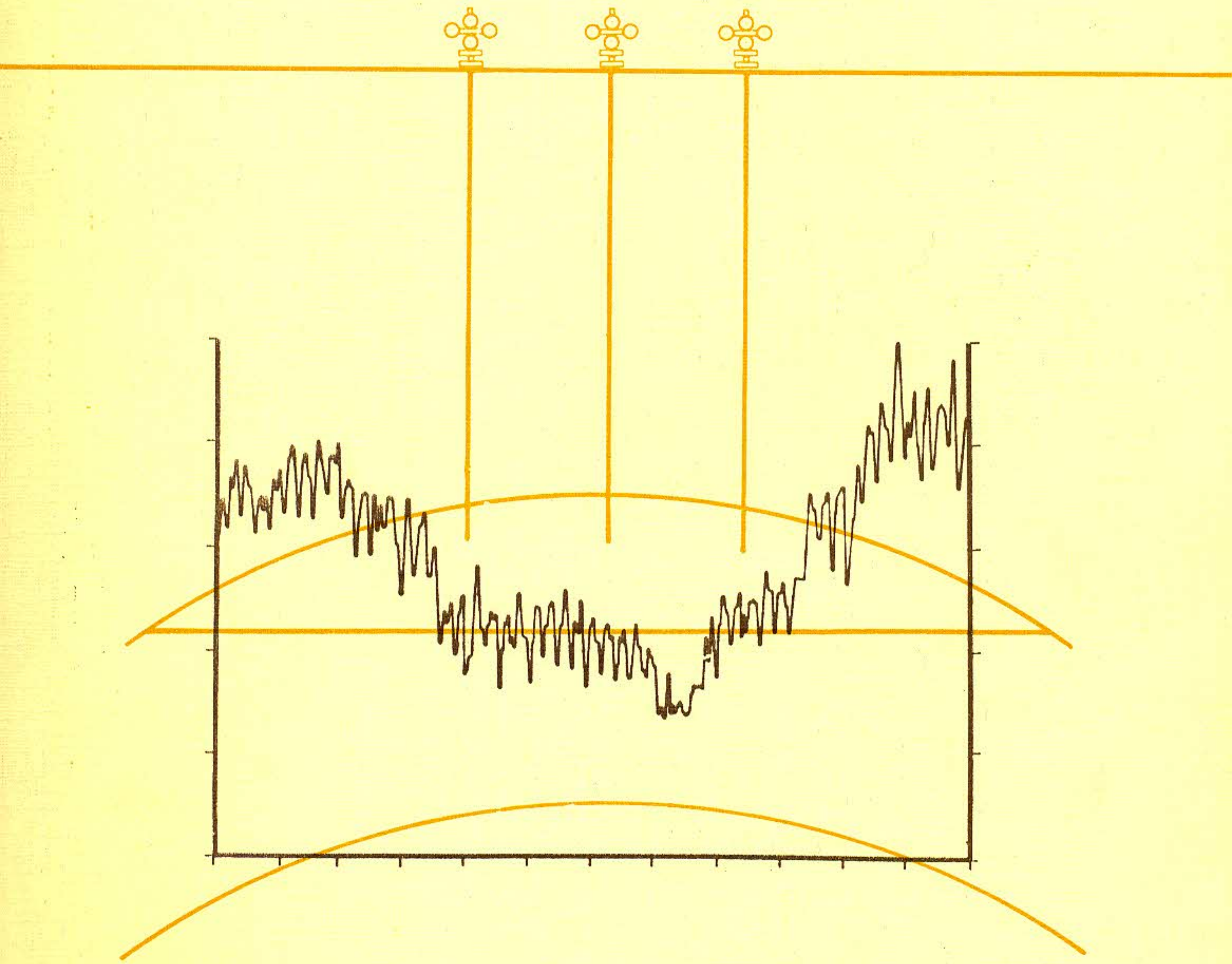

UNDERGROUND STORAGE OF NATURAL GAS IN ITALY

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UNDERGROUND STORAGE OF NATURAL GAS IN ITALY

by

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1. Introduction

In recent years natrural gas has become an alternative to other forms of energy, in particular, petroleum. Increased consumption in areas which are far from production areas and the ever increasing use of gas by low load factor users are the main reasons why storage of natural gas in geological formations has been created.

Before going into a detailed description of gas storage in Italy, there is now presented a brief outline of the development of gas storage, its basic characteristics and the various types of storage which can be made in the subsurface.

2. Origins and development

The technical possibilities and economic importance of storing natural gas in natural underground reservoirs, with the goal of saving the gas for a certain period of time and simplifying distribution, have been recognized and applied in many countries: the first were Canada in 1915 and the United States in 1916.

The first storage of natural gas in Italy, in operation since April 1964, was carried out in one of the gas pools in the Cortemaggiore Field.

The first storages in geological formations were carried out in depleted gas reservoirs; only after many years were storages made in aquifers (USA - 1931), in oil reservoirs with gas cap (USA - 1941), eventually arriving at storage in depleted oil reservoirs, in salt cavities, in worked-out mines and even storages in caverns induced by underground nuclear explosions.

From the one storage reservoir existing in 1915, we have come up to the present day with about 500 storage reservoirs located in 11 countries. 85% of these reservoirs are in the United States, 6% are in countries belonging to the European Economic Community, 5% in Russia and other Eastern European countries, and 4% in Canada.
In addition to Italy, the countries where there are underground storages of gas in geological formations are: Austria, Canada, Czechoslovakia, France, East and West Germany, Rumania, England, Russia and the United States.
The total storage capacity exceeds 200 billion cubic meters of gas, there are currently more than 18,000 storage wells and the total power of the installed gas compressors is in the range of 1,500,000 HP.

3. General Information

The main reason underlying the development of gas storage is that this technique enables oil companies to fulfill demand for maximum delivery rates on hourly and daily bases during the coldest periods of the year and at the lowest possible cost.

Figures 1 and 2 show two examples of peak send out: one daily, the other hourly.
It is clear from the two diagrams that, in addition to having the maximum peak demand during the winter period and the minimum in summer, there are also fluctuations in daily send out.

The first storage system consisted of underground tanks, in which there was stored mainly manufactured gas: the peak rates which could be obtained from such a system were clearly not very great. As the market evolved and the peak demand became higher, it was necessary to devise something different from tanks; this system, in fact, would have required thousands of tanks over very widespread areas and the expense would have been exorbitant.
Thus two possible alternatives were considered:the first was to use natural tanks in place of underground ones; that is, natural gas reservoirs which had already been depleted or which were becoming depleted, and were located near the zones of highest consumption.The second alternative was to connect, with large diameter gas pipelines, the areas of greatest consumption with those of greatest concentration of reserves, and therefore of production, in order to enable the transport of the necessary peak quantities to fulfill the market demand.
It is clear that in this way, the pipeline load factors, that is, the ratio between the average transported rate and the maximum transportable rate, would be very low and this would have a negative influence on the unit costs.
The first alternative is more advantageous, both from a technical and an economic point of view. In fact, underground gas storages are usually located as close as possible to the areas of greatest consumption; this permits two things: the transportation system works at a high load factor since even in the summer, when there is less demand, the gas is transported at high rates to be injected into the storage reservoirs and the reservoirs farther away from consumption zones can be produced continuously and without excessive fluctuations.
This second factor is particularly important in the case of offshore fields where a regular, continuous production not only guarantees proper exploitation, but also means savings in the investments made for the wells and sealines.

Therefore gas storage in geological formations represented mainly an alternative to the use of large diameter pipelines in order to fulfill the high peak demands in the winter period.

Another aspect of this complex problem of having to arrange a service which is economically acceptable to the natural gas market, lies in the so called "take or pay" clause which is incorporated in many contracts for the purchase and sale of gas. This clause sets up penalties for the producer if he cannot provide a minimum volume of gas and determined hourly and daily peaks as specified in the contract. These contracts must be adhered to, and therefore the market is assured of receiving gas from one or more storage fields when the regular pipeline transport system cannot supply it.

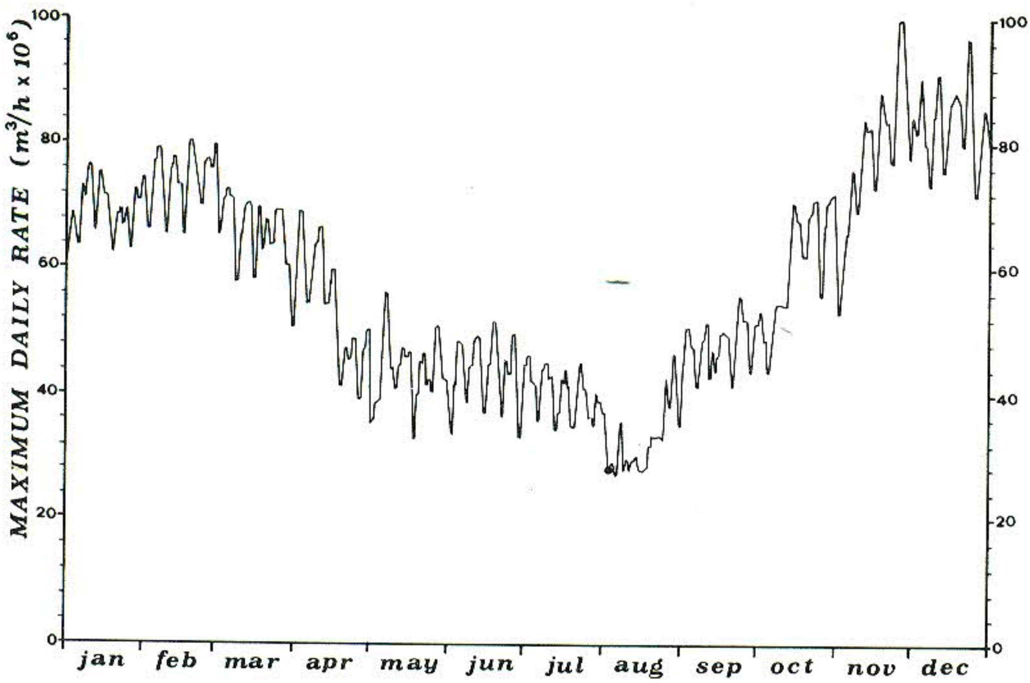


Fig. 1 – daily sendout for typical year

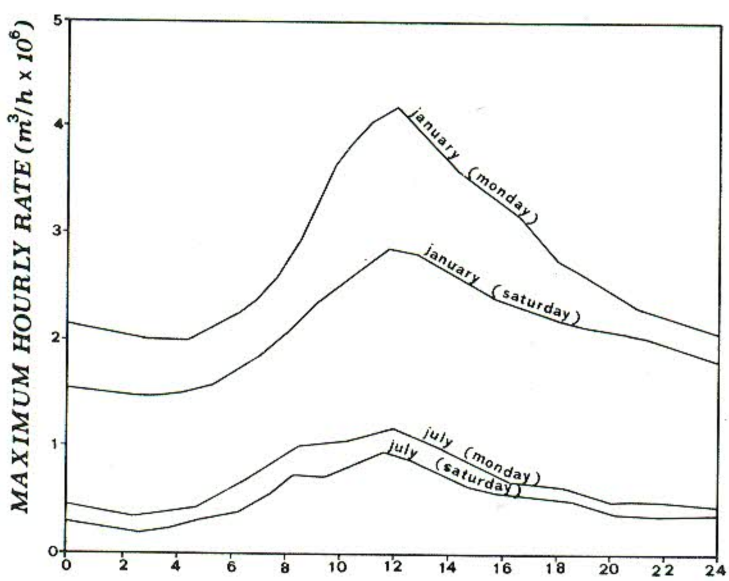


Fig. 2 – hourly sendout for typical winter and summer days

Gas storage therefore guarantees the transportation system a greater working security; in fact, even in an unforeseen emergency, a considerable volume of gas, situated close the area of consumption, can be made instantly available in order to guarantee flow in the pipelines. In some countries, especially where the greatest supplies of gas come from imports or production from distant reservoirs or offshore fields, there is the tendency to plan strategic underground storages; that is, the storages are principally planned to replace at least a part of these supplies if they should suddenly decrease or stop completely due to technical or political reasons. It is evident that storages may represent an alternative to these supplies only for rather limited periods of time.

Another case necessitating gas storage occurs when natural gas must be treated in very expensive plants before being transported by the pipeline system. These are the cases of the gas sweetening in the Lacq field in France, and the Ferrandina field in Italy.
In these cases, in order to avoid the interruption of gas supply in the event of a partial or total shut down of the treatment plants, it is useful to have one or more underground storage fields near the above-mentioned plants.

To summarize, underground gas storages enable us to:

— meet the fluctuations in peak demand, especially that exceeding the maximum capacity of the transport system;

— replace, for the longest possible periods, those volumes which may be lacking due to interruption or reduction in imports or production coming from reservoirs located in zones far from consumption areas.

— maximize the load factor of the transportation system.

— optimize the production of reservoirs located far from consumption areas, and in particular, of those located in offshore zones or of fields where the gas must undergoes expensive treatment in plants before being transported via pipeline.

4. Market study

To project an underground gas storage and evaluate its economic profitability as an alternative to strengthening the transport system the first approach is to do some market research, studying the characteristics as far as the distribution of the various users and the relative load factors are concerned. All uses (chemical, industrial, thermoelectric, civil) have a different load factor. It is obvious that the most critical load factor which determines a lowering of the weighted average of the various load factors is that of the civil demand for heating.

As an example table 1 shows the load factors of the main types of users.

Table 1

Types of users	*Load factor (%)*
Civil	30 - 35
Industrial	70 - 80
Chemical	90
Thermoelectric and discontinuous	?

Projecting and planning the size of the equipment for storage are usually based on the conditions which could occur on the worst winter day. Equipment sized in this way enables storage of those volumes of gas which become available during the summer.

5. Geological and physical characteristics

The technical problems which involve underground gas storage are similar to those pertaining to gas production. Therefore the knowledge of geological data and physical parameters enables better preparation of a storage project.
It is thus important for the formation, which will be used for storage, to have geological and physical characteristics which will easily permit the accumulation and flow of gas.

5.1 Geological characteristics

The geological factors of greatest interest are: the shape and size of the reservoir, the extension and characteristics of the aquifer, the gas-water contact and the characteristics of the hydrocarbon bearing and cap rock.

As a general rule, the structures most suitable for storage are anticlines and stratigraphic traps; however, it also possible to store gas in subhorizontal reservoirs. In the sections shown in figure 3 there are indicated the three main elements which can close a possible storage reservoir: cap rock, water-gas contact and spill-point.
The cap rock, which is generally composed of 100% water saturated shales should have those characteristics which prevent gas from dispersing in a vertical direction for the whole period during which the structure is used for storage. Laboratory tests made on samples taken in the lower part of the cap rock are necessary in order to evaluate the maximum pressure (threshold pressure) that the cap can withstand without the water contained therein becoming displaced by the stored gas.
During the storage phase it is necessary to check that the gas-water contact does not drop down below the spill-point: in that case the gas would migrate laterally.

5.2 Physical Characteristics

The following paragraphs present a brief description of the physical characteristics of reservoir rock and the fluids contained therein.

Porosity

As is well known, porosity varies according to the type of rock. When dealing with storage problems it is better to use high porosity rock, especially in the case of small structures.

Interstitial water saturation

Water is always present in the rock to be used for gas storage; this water is of two types, irreducible and movable. Under specific dynamic conditions the movable water may start moving and influence production. When selecting a reservoir for gas storage, it is important for the interstitial water saturation to be as low as possible. Determination of this value is based on the capillary-saturation pressure curves provided by laboratory analyses. Irreducible minimum water saturation is that value of water saturation which remains constant as capillary pressure varies.
Movable water is the difference between the total amount of interstitial water and the irreducible water saturation.

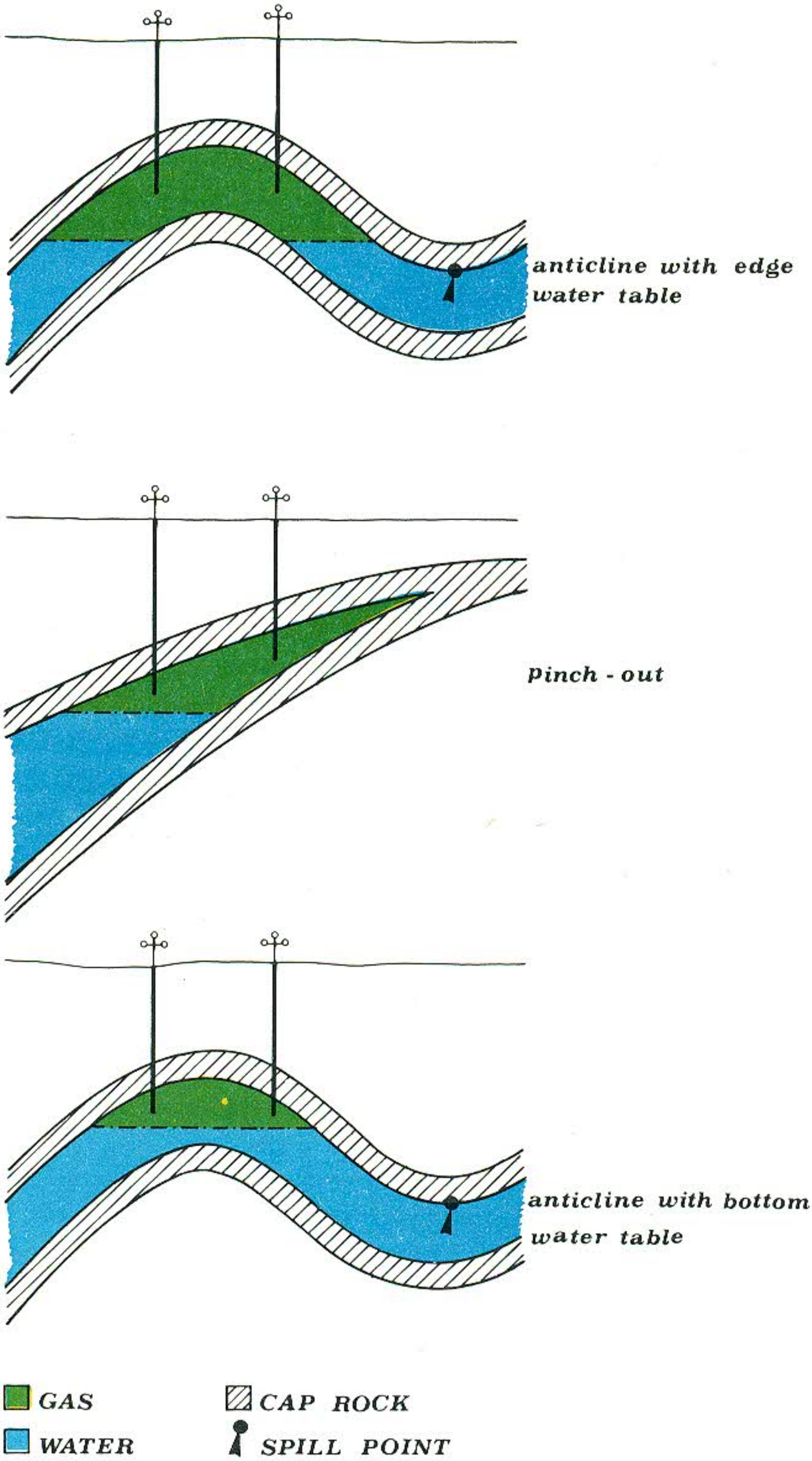


Fig. 3 – structures most suitable for gas storage

Permeability

Permeability is a parameter which influences both the injection and production phases. The greater the permeability of the reservoir rock, the more suitable it is for gas storage.

Reservoir pressure and threshold pressure

The initial pressure of a hydrocarbon reservoir ranges between the pressure deriving from the hydrostatic one and that deriving from the overburden pressure.
Any overpressures in reservoirs are generally caused by the compaction of marine sediments; however, sometimes they may be attributed to variations in the density of salt water and the geothermic gradients.
Pressures which are lower than those pertaining to the hydraulic gradient may be caused by movements of underground water, or they may be due to communications with other upper hydrocarbon bearing zones.
If, during storage, the reservoir pressure should exceed the geostatic gradient, the cap rock would crack and there would be a loss of gas in a vertical direction. The gas, would escape along preferential paths and could even arrive at the surface, causing risks and damage which cannot be estimated when planning a storage system. Therefore, during storage the maximum pressure gradient, which should not be exceeded, should be included between the hydraulic gradient and the geostatic gradient. Locating this maximum pressure value is done in the laboratory, using core samples taken in the lower part of the cap rock.
The laboratory analysis evaluates the maximum pressure value which starts off displacement of the water with which the sample is saturated. This pressure (threshold pressure) is the maximum value allowed during storage.

Relative permeability

Relative permeability regards the storage process, especially in the case of aquifers. During injection the gas (non wetting phase) displaces the water (wetting phase) and during production the water displaces the gas.
In gas injection problems it can be noted that the residual water saturation is higher in the consolidated formations than in non-consolidated ones; but in turn, with equal water saturation, non-consolidated formations have a considerably greater permeability.

Indirect Measurements

Using indirect measurements obtained from electric logs it is possible to complete the set of information regarding physical characteristics of the reservoirs. The values obtained from logs are then compared with the parameters which result from laboratory data.

6. Guidelines for selecting a storage system

When selecting a storage system it is necessary to make a careful technical and economic analysis in order to choose the best alternative to an oversized pipeline.
The basic criterion consistes of the maximum daily rate that the storage system should produce during a certain winter period.
Normally when projecting a storage it is assumed that the maximum daily rate should be produced at the end of the winter. In this manner there are the safest conditions from the standpoint of running the storage, but on the other hand there is the risk of having useless increase in investments if this event does not occur.
The characteristics which have the greatest influence on flow rate, and consequently on the costs of a storage system are described as follows:

6.1 Storage capacity

This means the volume of gas which can be contained in the reservoir in a situation of maximum and minimum ''gas in place''. Generally this volume is lower than the original gas in place calculated before the start of primary production. The ''cushion gas'' is the volume of gas which must stay permanently in the reservoir during the entire storage period. ''Working gas'' is that volume of gas which is produced and injected during storage cycles. In a situation of maximum ''gas in place'', the storage capacity consists of the cushion gas plus the working gas.
Statistical data show that on the average only 50% of the total gas present during maximum ''gas in place'' can be utilized as working gas in injection and production cycles. Consequently the amounts of cushion gas are always quite high and therefore have great significance in the general economy of the storage system.

6.2 Maximum and minimum reservoir pressure corresponding to situation of maximum and minimum ''gas in place''

These pressures and the relative storage capacities are interdependent, since they are connected through the equation of volumetric balance.
The maximum pressure is limited by the hazard of fracturing the cap rock, and in addition, should not exceed the threshold pressure. The maximum pressure may be established on the basis of technical - economic criteria when the safety standard pressure is very high (for example, in the case of very deep depleted reservoirs).
On the other hand, the minimum pressure is determined exclusively on the basis of economic criteria, i.e. it depends generally on the characteristics of the treatment and compressor-station plants.

6.3 Productivity of the wells

This is a function of the formation permeability, the completion characteristics, and the location of the wells themselves. These parameters being equal, productivity increases with the pressure and capacity of the storage.

6.4 Dimensions and characteristics of the aquifer

These are very important factors, in water drive reservoirs and when dealing with storage in aquifers. The movement of water in the formation influences the pressure trend in relation to the amount of stored gas.

6.5 Geometric characteristics of the structure

These are normally distinguished through the relationship height - hydrocarbon pore volume. The height is generally measured by the original water table depth. This relationship (fig. 4), which in fact characterizes the shape of the structure, is very important in studying the storage (especially in the case of aquifers), because it determines the function ''well flow rate - amount of gas in the reservoir''. For example, in a flat structure (curve ''a'' of fig. 4) the well flow rate, stored volume and pressure being equal, will be lower than in an arched structure. In fact, in the first case the water table will be closer to the wells, and therefore the production rate will be more greatly restricted due to the problem of water coning; on the other hand, in the second case the water coning will be of lesser influence on the well flow rate.

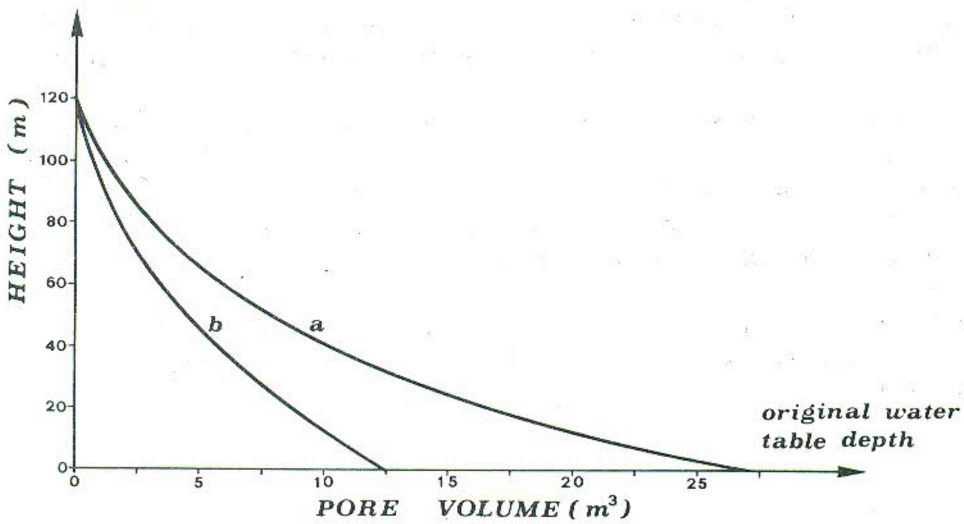


Fig.4 – hydrocarbon pore volume versus height

Both the aquifer characteristics as well as the geometric features of the structure are factors of the trap and must be assumed as basic data for a storage study; the other factors, especially pressures and storage capacities, are to be considered as alternative parameters of the problem on the basis of which the most economical solution is chosen.

7. Types of underground gas storage

Underground gas storages are generally divided into 3 categories:

a) conventional storages

b) semi-conventional storages

c) special storages

Storages made in depleted or nearly depleted gas reservoirs belong to the first category; those carried out in depleted oil reservoirs and aquifers fall into the second type, whereas the third category comprises those gas storages in salt cavities, worked-out mines or in traps formed by nuclear explosions.

7.1 Storage in depleted gas reservoirs

If partially or totally depleted gas reservoirs are located at a reasonable distance from consumption areas then they are the safest and most economic solution to the problem of underground storage.

The production of a gas reservoir utilized as a storage is different from primary production because of the flow rates. In fact attempts are made to obtain much higher production rates from storages than those resulting from primary recovery. For this reason the technical problems related to well completion, and location, as well as compression-station plants have to be resolved in such a way as to guarantee high flow rates during both injection and production.

When studying a storage in partially or totally depleted gas fields the basic data qualifying the reservoir, determining its storage capacity and relative pressures, is the production mechanism governing the reservoir during its productive life.

Production of a gas reservoir can result from depletion and from partial or strong water drive.
Figure 5 shows a sketch of the average pressure of reservoirs which, with gas originally in place being equal, have produced by means of the three above mentioned types of drive mechanism during primary production.

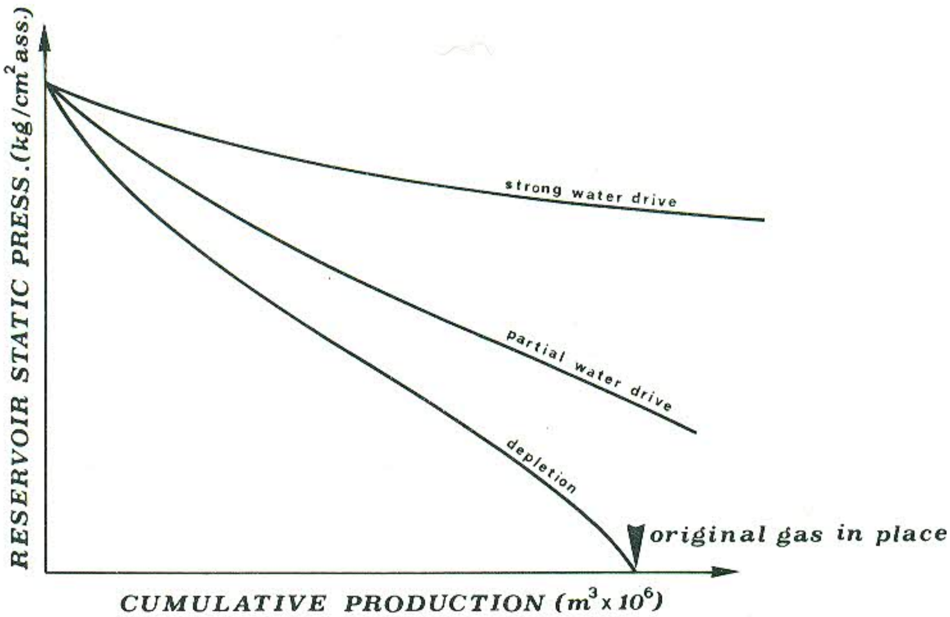


Fig. 5 – average reservoir static pressure versus cumulative production for different drive mechanisms

A production mechanism due to depletion occurs when dealing with a very limited aquifer (the volume of the aquifer is in the same range as the gas volume): in this case the average reservoir pressure reflects only the expansion of the aquifer underlying the gas zone; in practice, the pressure drop can be considered to be directly proportional to the amounts of gas produced.
If the volume of the aquifer gradually become larger and larger in comparison to the volume of the gas bearing zone, rock permeability being equal, the production mechanism changes from simple depletion to a partial water drive until reaching drive levels so high that the reservoir pressure is kept very close to the original pressure for the entire producing life.

Conventional underground storages are usually carried out in reservoirs which have produced due to expansion or partial water drive during primary production. Storages which are made in reservoirs having a strong water drive can be compared to those carried out in aquifers, and will be dealt with later on.

In reservoirs having a production mechanism due to depletion or partial water drive the storage capacity and the pressure limits (upper and lower) generally depend on economic criteria deriving mainly from the number of wells and the power of the compression-station plant.

For gas reservoirs the "material balance" equation indicates the relationship between the static reservoir pressure and the corresponding volumes of reservoir gas; it is written as follows:

$$G\,B\,g_i = (G - Gp)\,Bg + W \qquad (1)$$

where:

G = gas originally in place at the start of primary production at standard conditions (15,5°C and 760 mmHg)

G - Gp = amounts of gas in the reservoir after a cumulative production Gp, at standard conditions

Bgi and Bg = gas volume factors corresponding to the original pressure p_i and the generic pressure p; these factors enable the gas volumes to be transformed from standard conditions to reservoir conditions

W = water which has entered the volume initially occupied by the gas due to the effect of movement of the aquifer

If W = Gp Bg the aquifer efficiency is so high that the reservoir pressure is always equal to the original value. In conventional storages W is much lower than Gp Bg.

Equation (1) enables evaluation of the corresponding value of reservoir pressure for every value of cumulative production.

Another very important factor in a storage study is the trend of the productivity of wells existing during primary production as a function of the reservoir pressure, and thus the trend of the amount of gas left in the reservoir after a certain production.
Knowing the relationship "pressure - gas in place - productivity of the wells" permits determination of the best storage solution from a technical and economic standpoint.

Other factors to be considered when selecting the pressure limits of a reservoir to be used for underground storage are:

a) the pressure taken from the reservoir being studied for storage and the amount of gas still remaining in the reservoir

b) the production behavior of the wells at the pressure cited in (a); in other words, if the productivity of the wells at this pressure reflected any deterioration due to water coning, sand entry or other factors, and if this is the case, at what field pressure such deterioration started

c) the number of marginal wells that had been abandoned during primary production, and those pressure values at which abandonment occurred.

It is clear that in order to evaluate both the relationship "pressure-gas in place-well productivity" and the other above mentioned factors, a thorough history of the primary production of the reservoir must be available.

Evaluating all the above factors results in an initial approach to the minimum pressure value of the storage field. The selection of this pressure enables the minimum value of "cushion gas" to be established, that is, that volume of gas which must remain in the reservoir in order to guarantee the minimum performance of the storage.
If there is not enough "cushion gas" at the beginning of storage operations, it is necessary to inject a certain amount of gas so as to reach this minimum value.

When there is more than one storage field, one important decision involves the preferential choice of running these fields. That is, it is necessary to choose, from among all the available fields, those which are to be produced first and for longer periods of time, and those which have to be set aside exclusively for meeting peak market demand.
All other conditions being equal, this choice may be based on the relationship between the initial productivity and the quantity of reserves in the reservoir. Assuming that this relationship represents the reservoir potential, it is evident that the reservoirs having a lower potential should be produced first.

The graph shown in figure 6 clearly demonstrates that reservoir "a" will be the first to produce and more continuously, whereas "b" will be put into production only to fulfill peak market demand.

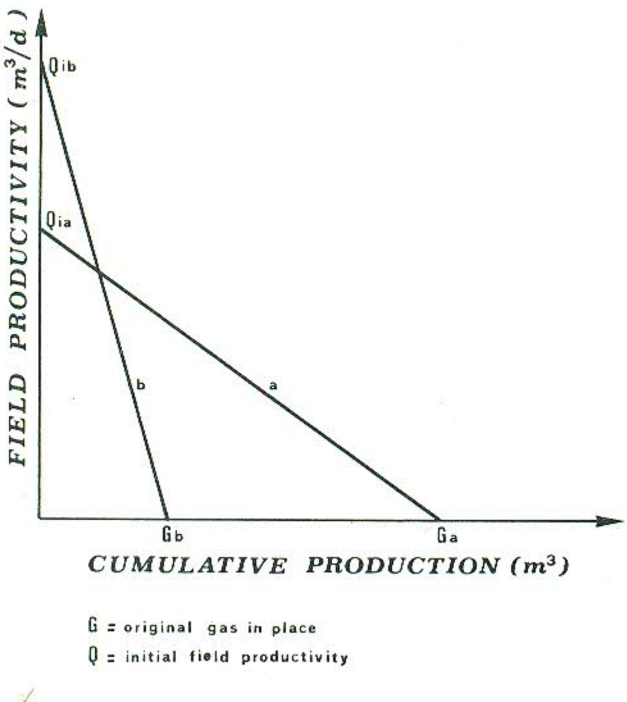


Fig. 6 – field productivity versus cumulative production

Pressure measurements and production history

Observation wells play an important role in storage operations; in fact, a certain number of wells is generally used to make periodic measurements of reservoir pressure. Generally these wells are not even used during injection or production.
The pressures measured are correlated with the cumulative volumes of gas in place in order to establish certain curves; these curves indicate the average pressure trend of the reservoir as a function of the "working gas", or those amounts of gas which are stored or produced during storage operations.
An example is figure 7 which shows the following trends for a typical underground storage:

figure 7a: average static pressure as a function of the amount of gas in the reservoir, or the gas originally in place minus that produced. The moment when the reservoir has started to be used for storage is clearly shown.

figure 7b: trend of the gas in the reservoir and of the corresponding value of formation pressure versus time.

figure 7c: injection and production forecasts (pressure versus gas in place).

Storage and production cycles are studied so that the formation pressure never goes over the original pressure for safety reasons. However, in some cases it may be desirable to keep the field pressure above the original pressure on purpose; this is in order to increase the volume of the gas bearing zone, and thus the storage capacity.

In these cases it is necessary to use the laboratory method already mentioned to calculate the threshold pressure; during storage operations it will be necessary to keep a strict structural control over the reservoir in order to prevent gas from escaping vertically or horizontally.

Limits in well flow rates

Well flow rates of any reservoir, not only storage ones, may be limited by:

a) water coning

b) sand dragging

c) dynamic well head pressure

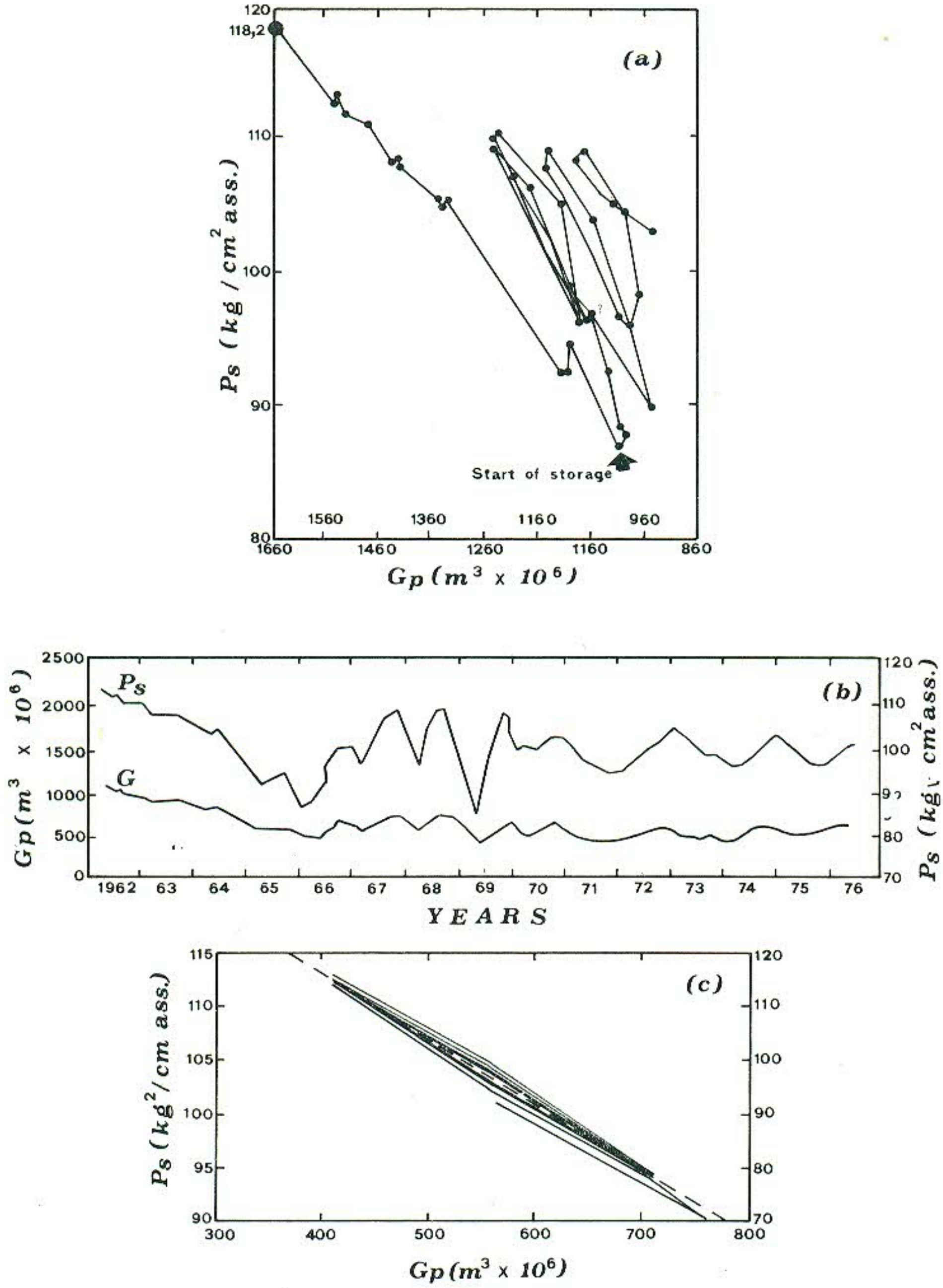
To maximize the flow rates of wells in storage fields it is necessary to study as throughly as possible the completions of the individual wells, that is:

a) perforate the intervals which are farthest from the aquifer in order to minimize the possibility of water coning

b) complete the wells, if necessary, with "gravel packing" that is, a special filter so as to prevent any possible sand dragging

c) complete the wells with "tubings" having the largest possible diameter in order to minimize friction losses increasing the flowing well head pressure.

To evaluate flow rate limits it is important to carry out periodic production tests during the productive life of the wells.



G. gas in place – Gp. cumulative production – P. static pressure

Fig.7 – gas reservoir turned into storage after primary production

7.2 Storage in depleted oil reservoirs

Partially or totally depleted oil reservoirs have many characteristics similar to gas reservoirs in the same condition; therefore, some of the operational and development methods commonly used for gas fields can be applied also to oil reservoirs.
On the other hand, certain other characteristics are not the same in the two cases and therefore require an explanation.

Injecting gas in an oil reservoir, for example, may be part of a program for secondary recovery of oil.

The productive history is the most important requirement of a storage study, and thus of the secondary recovery in a depleted oil field. It is extremely important to know the production mechanism of oil, specifically if it is water drive, solution-gas drive or gas-cap drive, and to what degree by gravity drainage.
As in the case of gas reservoirs, a knowledge of past history provides the data regarding the productive capacity of oil wells; the analysis of these data enable the injection and production capacity of the gas to be determined.
The cumulative production of oil and gas will permit computation of the porous space available for the gas storage.
The history of the static reservoir pressure, which is a function of the drive mechanism and the past production rate, provides the pressure limits which are the most important elements in determining the size of the storage plants.

Generally in cases of oil reservoirs which have been transformed into storages in addition to the advantages deriving from the storage operation, there have been considerable technical-economic benefits resulting from the secondary recovery of oil.

Storage Capacity

Storage capacity, that is the free or utilizable volume in a depleted oil reservoir which can be used for gas storage, can be expressed by a volumetric balance equation:

$$V = NpBo/Bg \qquad (2)$$

where:

V = volume of gas in substitution of produced oil, m^3 at standard conditions

Np = produced oil, m^3 at standard conditions

Bo, Bg = oil and gas volume factors.

In addition to this free volume there should be added that volume which is available due to the effect of producing solution gas deriving from the oil remaining in the reservoir; this amount is known when the oil recovery factor is learned at the time of making the calculation.
In oil fields where production occurred due to water drive, the storage capacity of gas does not directly depend only on the free space remaining after production of oil, but also on the volume of reservoir invaded by the aquifer and the possibility of driving this aquifer back to the starting positions.
A gas storage pressure higher than the reservoir pressure should enable the original reservoir volume to be gradually restored.
It has been proved that a few years of gas storage at pressures close to original reservoir pressures are enough to make the water, which had invaded the reservoir during primary production, return to its original position.

7.3 Storage in aquifers

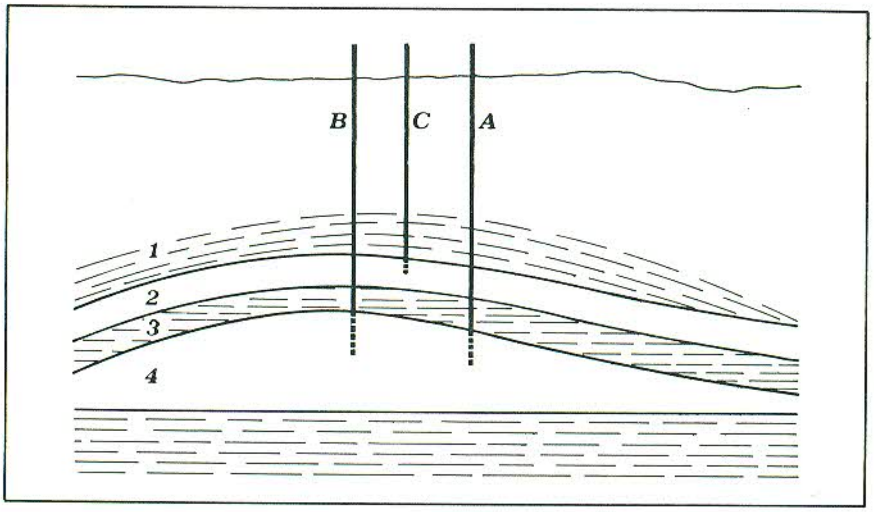
Storage of gas in an aquifer means creating an artificial gas reservoir in a porous formation which has varying depth and is originally filled with salt water. There are no substantial differences in the operations regarding discovery and development of both this type of reservoir and a natural gas reservoir.

When preparing an underground storage in an aquifer three basic phases can be distinguished: exploration and discovery of structures having suitable characteristics for storing gas under pressure; injecting gas to displace water from the reservoir; development and operating the storage.

Determination of the structure

When exploring for an aquifer to carry out the storage it is first of all necessary to find a structure which possibly is anticlinal. Geological and geophysical surveys may show the structure, but confirmation of the presence of such a structure is to be had only by drilling wildcat wells.
These wells should be cored in order to carry out measurements of porosity and permeability of the aquifer formations, and to determine the existence of an impermeable cap rock.

Once the formation has been chosen, other wells must be drilled in order to define the shape of the structure and possible variations in the petrophysical characteristics of the rock. In any case, the most important requirement for a storage in an aquifer is to have a continuous, impermeable cap.
Figure 8 shows how communication through the cap rock is effectuated by means of pumping tests. Water is pumped into well A and the two observation wells B and C respectively act to control the permeability of the reservoir rock and the sealing capacity of the cap rock.



1 — shale
2 — sand (first permeable layer above the cap rock)
3 — cap rock
4 — aquifer (to be studied or as storage)
A — pumping well
B-C — observation wells

Fig. 8 — control of the permeability of the aquifer and the sealing capacity of the cap rock

In general cap rocks have very low permeability, from 10^{-4} up to 10^{-6} mD. However, if this rock were not water saturated this permeability would be sufficient to permit vertical movement of gas through the rock itself. The presence of water eliminates this danger as long as the reservoir pressure remains below the threshold value.

In gas storages in aquifers, the hydrostatic pressure is always exceeded in order to inject gas, but it is necessary to be very careful not to exceed the threshold pressure.

Gas injection and behavior of the aquifer

When gas storage is begun in an aquifer, the gas displaces the water, advancing more quickly where greater permeability is encountered. Figure 9 shows a schematic representation of how the gas-water contact develops until formation of a bubble occurs as in stage c. After a rather long period of time (several years) the water in the high zone of the reservoir, apart from a certain residual saturation, will be completely displaced and the gas zone will take on the shape shown in figure 10.

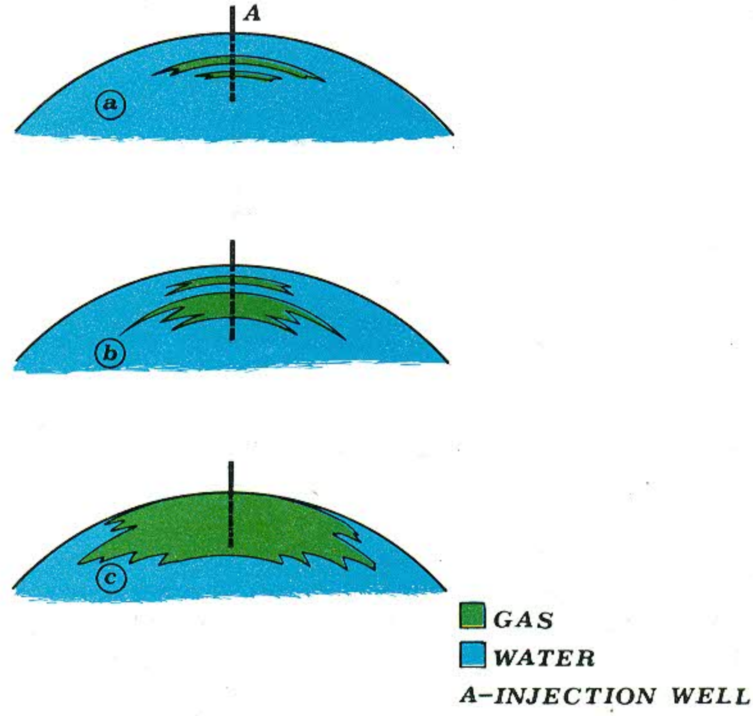


Fig. 9 – formation of a gas bubble in an aquifer

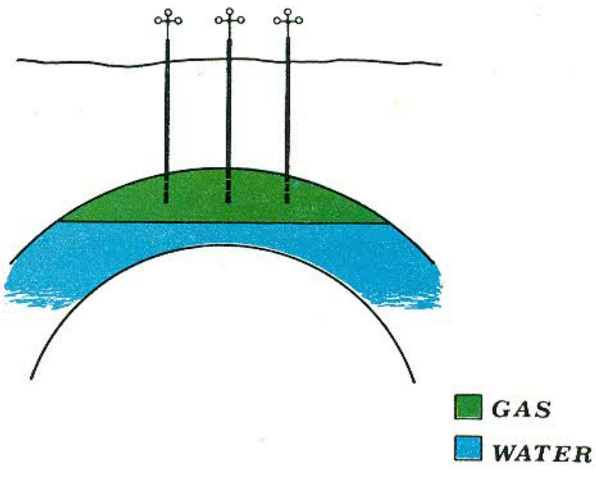


Fig. 10 – gas storage in an aquifer

The aim of the calculations is to evaluate the effect of the water movement on the dimensions and pressure of the gas bubble in any injection and production program. The dimensions and petrophysical characteristics of the aquifer are the essential data for studying the movement of water which is subject to the conditions of unsteady-state flow and the laws of physics governing the dynamics of fluids in porous media.

A study of a storage in an aquifer is based on a few simplifications; therefore, the preliminary forecast of the behavior of the pressures and flow rates is rather risky and uncertain since it is not possible to have, as in the case of depleted gas or oil reservoirs, the real behavioral situation of the field on the basis of which the geometrical and physical characteristics are determined.

When calculating the storage behavior the basic data are the amounts of gas which should be injected and produced.

The combination of the volumetric balance equation of the gas bubble and the equation of the movement of water enable, by knowing the amounts of gas which are injected and produced, the pressure trend of the gas bubble to be forecasted.

The maximum capacity of the reservoir is a function of the utilizable cubic volume of the structure (pore volume above the spill point), the maximum pressure allowed and the water saturation behind the advancing front of the gas bubble. If a certain volume of gas is injected the water level lowers in relation to the shape of the reservoir and the water saturation behind the gas front.

The injection flow rate is principally connected to the behavior of the aquifer which depends on its dimensions and permeability and the maximum pressure allowed.
The injection pressure must be sufficient to overcome the friction losses and balance the pressure of the reservoir. The evolution of the pressures during injection leads to complex phenomena which are linked to the movement of water in the formation.
In storage operations the injection rate, that is the speed at which gas can be injected to create a certain volume of gas, can be predicted if the law governing the movement of the water is known.

The production flow rate of a well is limited by the same factors indicated in paragraph 7.1 and therefore the well completion must be carefully evaluated.

The problems existing during the phases of injection and production in these storages are similar to those occurring in storages in depleted or semi-depleted gas reservoirs which have produced by strong water drive.

7.4 Storage in non-porous media

There are several storage systems for natural gas in non-porous media; however, these systems are still in the experimental stage.
The most interesting forms of storage which will be briefly described are: storage in salt cavities, in worked-out mines and in caverns induced by nuclear explosions.

7.4.1 Storage in salt cavities

The first examples date back to 1951; in these cavities, however, only propane and butane were stored.
Generally in these types of storages only one wells is used both for injection and production of gas (fig. 11). Once the well has been drilled in the salt stratum, fresh water is pumped into the well in order to dissolve the salt and create the cavity.
The brine which is produced is generally injected in another formation.
The final shape of the cavern depends largely on the position of the tubing through which water is pumped, and the pumping pressure.

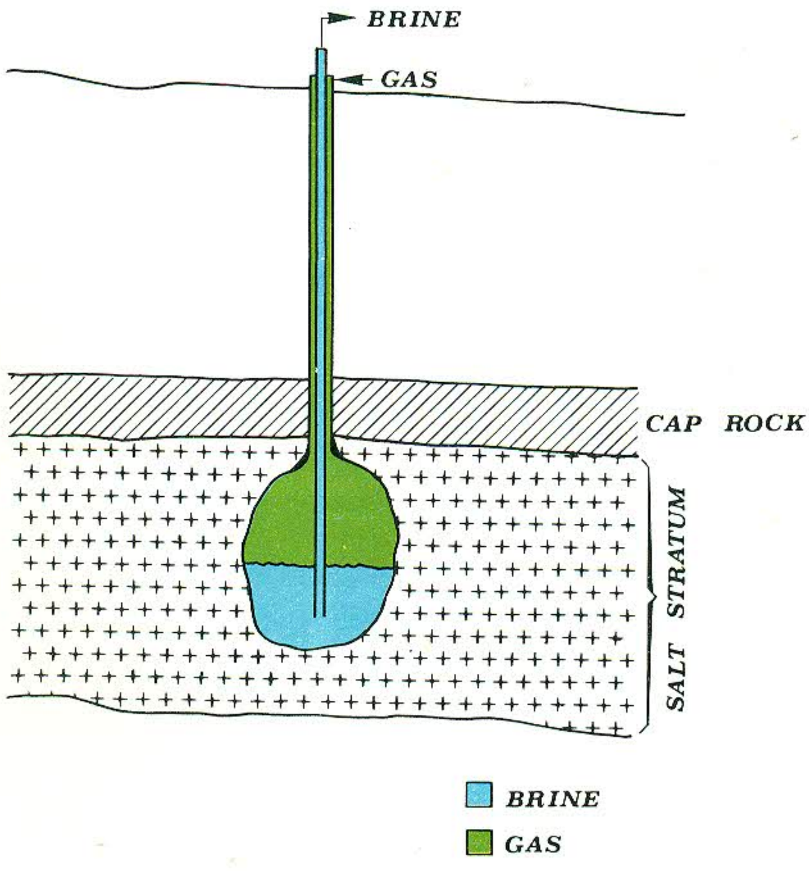


Fig. 11 – gas storage in salt cavity.

Special tests are carried out to make sure that the artificially created cave does not leak.

During the period of injecting gas the brine is expelled to leave place for the hydrocarbons. During the production, the volume of gas is replaced by an equal volume of brine so asto keep the pressure in the cavity constant.

It is clear that in the case of peak requests for gas, it is necessary to have high flow rates of pumped water. However, if it is possible to let the pressure drop without danger, the problem is much less significant.

Knowledge of the shape of the cavity and the type of material which surrounds the cave, are two very important elements for determining the values of the minimum pressure. Generally, these types of storage do not permit high production flow rates.

7.4.2 Storage in abandoned mines

This is still in the experimental stage.
The developmental phases are:

1) obtain geological information by means of core samples

2) carry out production of the mine

3) equip the mine for storage.

Given the high costs, such types of storages should be carried out at low depths. The possibility of storing natural gas in mines basically depends on the maximum pressure that it is possible to have without going over the safety limits and the permeability condition of the walls of the mine. In the case of mines which have been abandoned for some time, special attention must be paid to inspections. In fact, during the period when the mine is completely abandoned, it may be possible to observe phenomena which discourage its use as storage.

7.4.3 Storage in cavities induced by nuclear explosions

Like the preceding type, this kind of storage is still in an experimental phase. The high cost of explosives is the main reason why nuclear devices have not been used on a large scale for forming storage cavities.

The idea of using this system for creating such cavities came about in the United States, by analyzing, from an engineering standpoint, the results of underground nuclear explosions made after 1957.
In fact, in 1957, the Atomic Energy Commission of the United States established an experimental program to develope and demonstrate peaceful uses of nuclear explosives. (Project Plowshare). The first experiment of this kind, called "Rainier" took place on September 19, 1957.
Many other experiments of this type were carried out at different depths. Those at greater depths have involved various types of formations such as tufa, salt domes, granites, etc.

A nuclear explosion may or maynot be controlled. Controlled explosions are those which do not cause surface damage and do not emanate radio-activity on the surface. Uncontrolled explosions are characterized by the eruption of explosive material on the surface.
Among the experiments carried out under Project Plowshare, the "Gnome" was the most interesting from the standpoint of storages. In fact, it was the first controlled subsurfaces nuclear explosion which induced an underground cavity which did not cave in.

The shape and size of the cavity resulting from a controlled nuclear explosion depend on the characteristics of the subsurface area near the explosion zone, the depth at which the explosive was placed, and the energy of the explosion.
The shape of the cavity is generally spherical, but at times it may be "chimney" shaped.

The economy of a storage of natural gas in a cave induced by nuclear explosion is also based on the following elements:

— nature of the internal surface and impermeability of the cavity;
— threshold pressure;
— possibility of causing fractures during drilling injection wells and production or due to the effect of overpressures;
— absence of radioactivity.

At the present date, the cost of a storage of natural gas in cavities produced by nuclear explosions results to be very high. However, improvements in the design of nuclear explosives, perfected technologies, production on a widescale commercial basis all lead to a forecast of a rapid lowering of costs, and therefore, in the near future it will be possible to make this type of storage economically feasible.

8. Italian energy consumption and the role of natural gas

In the last 20 years the Italian consumption of primary energy has increased about 5 times (from around 30 million TOE in 1955 to 140 million TOE in 1977).
Figure 12 shows the trend of Italian energy consumption in TOE, from 1955 to 1977, subdivided according to primary sources (crude oil, natural gas and other sources such as coal, hydroelectric energy, etc.).
The graph clearly shows that, as in other industrialized countries, natural gas has assumed more and more importance as an alternative to other forms of energy, especially crude oil. In fact, today natural gas accounts for about 16% of national energy consumption whereas 5 years ago it covered only 10% of the total energy consumption. In the same period oil consumption fell from 76% to about 67%.

Figure 13 shows the trend of natural gas consumption (expressed in cubic meters at standard conditions) in Italy from 1955 to 1977.
It can be seen that after 1971 Italy had to import gas to fulfill the market demand. In fact, in spite of rather large discoveries in the Adriatic offshore, the domestic production alone could not cover all the demand of a market which was undergoing considerable expansion.

Imported gas, which today accounts for 50% of domestic gas consumption, will reach 65% in the next few years. In fact in addition to present imports (Libya, Holland, Russia) in 1981-82 there is expected to start importation from Algeria (around 11 billion cu m per year): the total gas imported in Italy will thus rise to about 27 billion cu m per year.

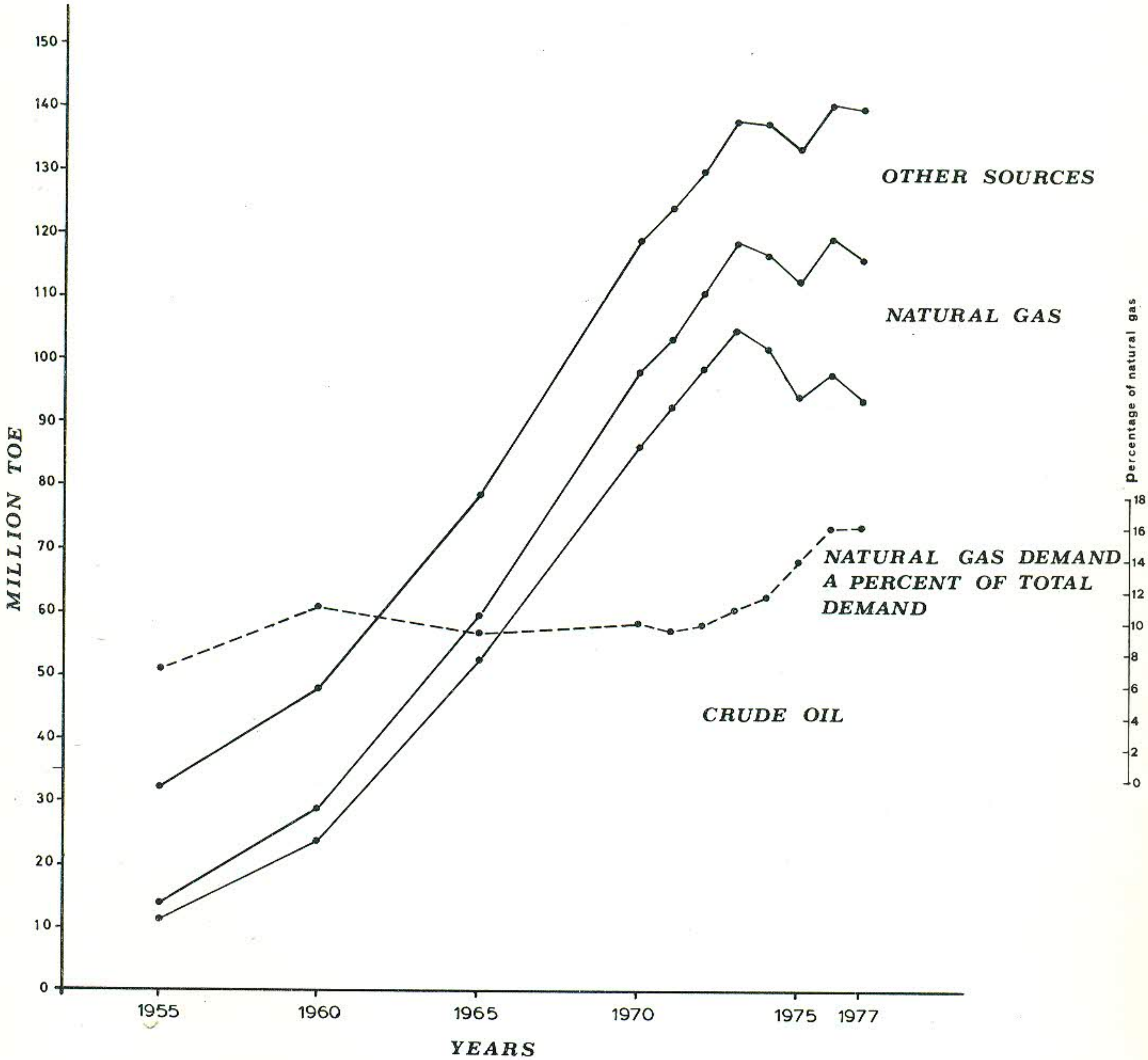


Fig. 12 – ITALY – energy consumption and primary sources (1955 - 1977)

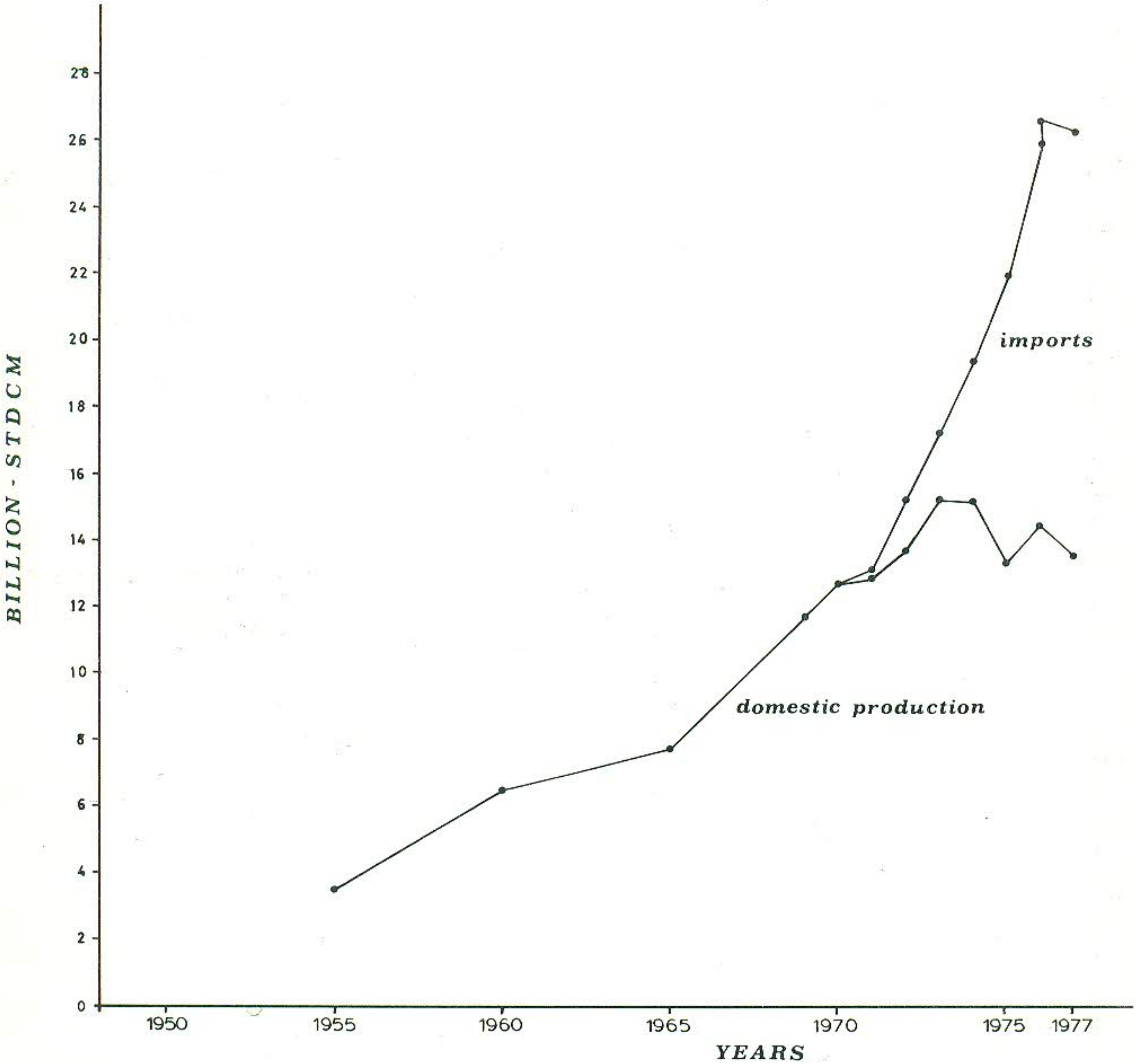


Fig 13 – ITALY – consumption, domestic production and imports of natural gas (1955 - 1977)

9. Origins and development of natural gas storage in Italy

The ever growing importance of imported gas on Italian consumption is the main reason why underground storages of natural gas have been reinforced, and new ones have been created.

The first storage which started up operations in Italy dates back to 1964 (Cortemaggiore); in fact, at the beginning of the 1960's the necessity of having storage reservoirs was already apparent.
In fact, during this period there was a considerable increase in the peak demand in the North-West zone of the country; in the same period there was a decrease in reserves in the same zone and a great increase in the productive capacity from the fields located in the eastern part of the Po Valley, due mainly to important discoveries in the Adriatic offshore.
Thus also in Italy it was necessary to compare the alternatives of constructing large diameter pipelines from East to West or finding depleted or about to be depleted reservoirs in the West which could be used for storage.

The first Italian storage to start up operations was at Cortemaggiore (April 1964), followed rapidly by Sergnano (April 1965), Brugherio (June 1966) and Ripalta (April 1967). These fields are all located near Milan (fig. 14).
When imports began (1971) and there were successive increases in imported quantities, (bearing in mind the fact that the load factor of imports is very close to the unit, whereas the average load factor, of the users is in the range of 0,5 - 0,6) it became necessary to reinforce existing storages and create new ones.

In April 1975 the Minerbio storage in the province of Bologna was put into operation, and in September 1977 and February 1978 storages at Ferrandina and Pisticci in the province of Matera started up; the latter two which are located in southern Italy will be of greater interest when imports from Algeria will be underway.

As mentioned before, in Italy storages have been made in partially depleted gas reservoirs where, except for Brugherio and Pisticci, production took place due to partial water drive. With the exception of these two cases, for the moment serious consideration has not been given to the possibility of creating a storage in semi-depleted reservoirs which have produced due to strong water drive, or in aquifers.
This limitation is due to the fact that the law governing storages in Italy (Law N° 170 of 26.4.74) not only indicates the conditions necessary for obtaining storage concessions and the obligations to be respected by the concessionaires, but also states that the original static reservoir pressure must never be exceeded.

In the winter 1977/78 the maximum available daily peak (47 million cu m/day) from underground storages accounted for 45% of the total available peak from Italian fields, and 31% of the maximum peak that could be delivered to the consumer on the day when demand was greatest.
Within 5 - 6 years it is expected that the maximum peak of the storages will increase to around 100 million cu m/day, by reinforcing the storage reservoirs which are presently in operation. Therefore, in 1982 the maximum daily peaks produced by storage reservoirs will account for about 69% of the total peaks produced by national fields and 50% of the maximum peak delivered to the consumer.
Figure 15 shows the trend of the maximum available daily peaks for the period 1971 - 1977, including both domestic production and imports. As indication, the forecast for 1982 is shown.

1 -	CORTEMAGGIORE	APRIL	1964
2 -	SERGNANO	"	1965
3 -	BRUGHERIO	"	1966
4 -	RIPALTA	"	1967
5 -	MINERBIO	"	1975
6 -	PISTICCI	FEBR.	1978
7 -	FERRANDINA	SEPT.	1977

Fig. 14 – ITALY - location of storage fields

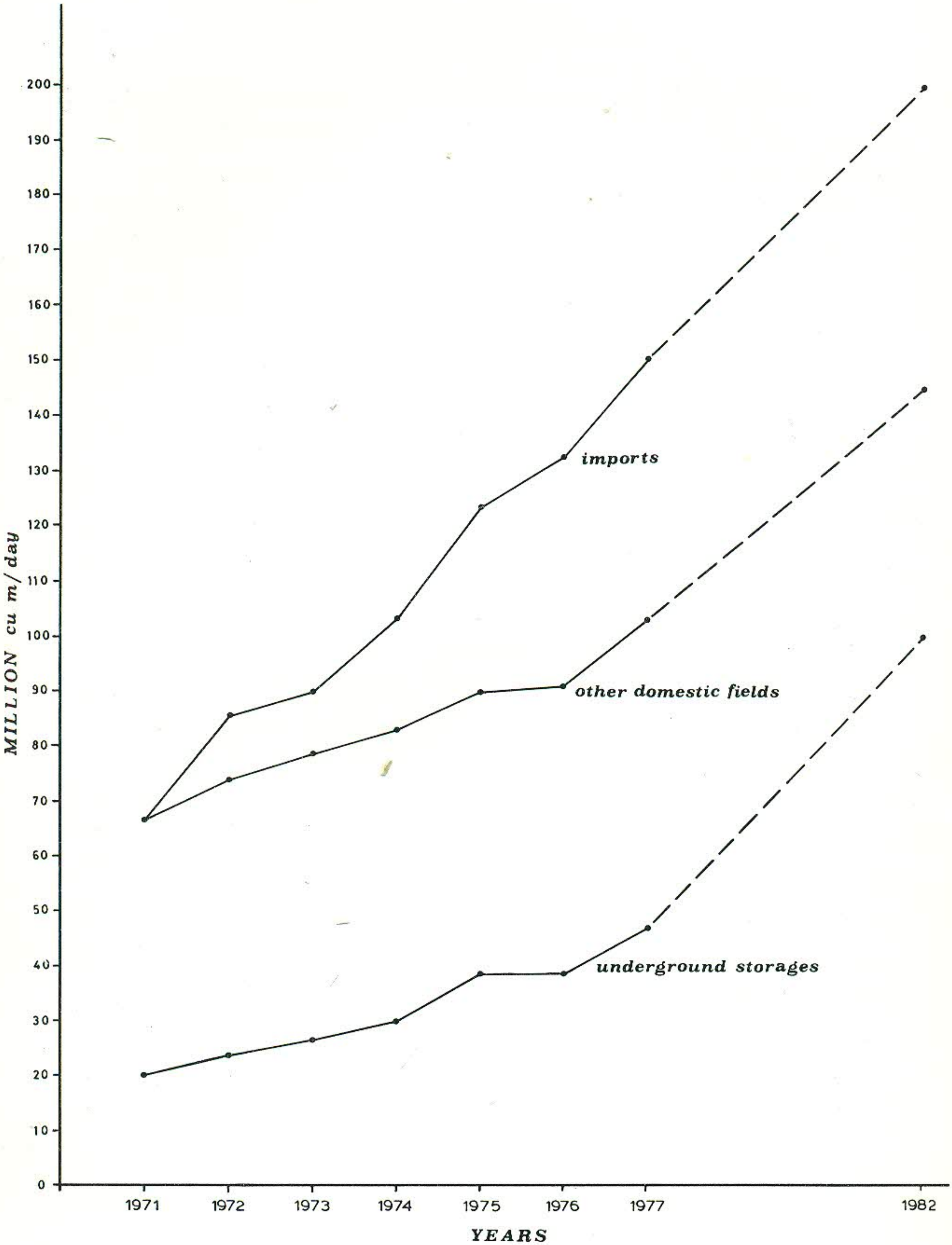


Fig. **15** – ***ITALY*** – ***available peaks***

Another problem which arose as the amount of imported gas increased, is to have a certain number of reservoirs which are able to quickly produce great quantities of gas that can at least partially substitute an interruption in the supply of imports. The main objective of developing the Minerbio storage is to store the gas so as to have a supply on hand to be used for emergencies.

To summarize, in Italy there are presently 7 underground storages of natural gas; the main characteristics of these reservoirs are shown in Table 2.

Table 2

		Corte-maggiore	Sergnano	Brugherio	Ripalta	Minerbio	Ferrandina	Pisticci
Depth	(m)	1500	1300	1100	1500	1300	1000	900
Original gas in place	($m^3 \times 10^6$)	2690	4286	2064	4080	14233	2500	1038
Original gas water contact	(m s.s.l.)	1545	1300	945	1518	1368	650	772
Maximum thickness of the hydrocarbon zone	(m)	25	100	80	80	180	60	35
Thickness of the cap rock	(m)	60	200	260	300	100	50	500
Average porosity	(%)	30	24	20	28	30	25	22
Average water saturation	(%)	30	20	20	20	20	27	25
Range of permeability	(mD)	10-150	100-500	100-500	20-60	60-300	100-300	400-500
Production starting	(year)	1950	1954	1961	1949	1959	1963	1964
Storage starting	(year)	1964	1965	1966	1967	1975	1977	1978
Cumulative production before storage	($m^3 \times 10^6$)	1732	3027	672	3477	12826	721	446
Original average reservoir pressure	(Kg/cm^2)	181.2	157.4	118.3	184.9	153.0	72.2	82.2
Final average reservoir pressure before storage	(Kg/cm^2)	80	70	90	70	30	57	70
Maximum storage pressure	(Kg/cm^2)	156	140	107	156	120	66	81
Maximum storage capacity	($m^3 \times 10^6$)	1700	3000	1600	2000	5500	1900	700
Working gas	($m^3 \times 10^6$)	300-350	600-1200	200	400-450	1000-3000	100	60-100
Maximum available peak	($m^3/dx10^6$)	3	50	11	4.5	30	1	1
Maximum number of wells		23	36	17	23	40	15	7

During primary production these fields had produced a total of about 13 million cu m/day. When development is completed (1981-82), the 7 fields will be able to provide daily peaks of around 100 million cu m/day.

To conclude this general part concerning Italian storages, it is to be remembered that studies are being made on the possibility of transforming reservoirs (in the depletion phase) into storages, both for peaks and emergencies, not only in the Po Valley and South of Italy, but also in Sicily.

In the following paragraphs a brief description of the seven underground storages, in Italy, will be given.

9.1 Cortemaggiore Storage

The Cortemaggiore field, discovered in July 1949, lies under the village of Cortemaggiore, in the province of Piacenza, around 75 Km from Milan (fig. 14).

The hydrocarbon bearing zone (seven pools) was discovered in the Lower Pliocene at a depth of around 1500 meters (gas pools) and Miocene at a depth of around 2000 meters (oil pools).
The pool which, after primary production, was used for storage, is conventionally called "C". This reservoir (fig. 16) is an anticline of clean sands and the cap rock consists of a shaly bank, more than 60 mt thick. The area of the reservoir is 4 Km x 1 Km; the main axis is located in an East-West direction.
The reservoir has an edge aquifer; the original gas-water contact was at 1545 meters below sea level. The porosity and water saturation are both 30%; permeability is in the range of 10 ÷ 150 mD and the average value is about 50 mD.
The production of pool "C" started in January 1950, and continued until April 1964, the period when storage operations began.
In this production period around 1,7 billion cubic meters were produced, equal to 64% of the original gas in place. The static pressure of pool "C" declined from the original 181.2 Kg/cmq to 80 Kg/cmq. The water table rose up to 1519 meters.
A total of 87 wells were drilled in the Cortemaggiore field but only 14 wells produced from the pool "C" reaching a maximum daily rate of around 0,8 million cubic meters.
The production history (fig. 17) indicated a mechanism due to partial water drive.
During the production period there were water coning as well as sand problems especially in the wells close to the gas-water contact. Other limits were exclusively to the flowing tubing head pressure and the capacity of the surface facilities.
Due to the fact that reservoir hydrocarbon was a condensate gas, preliminary studies of gas cycling were carried out to increase the liquid hydrocarbon recovery. The low liquids recovery foreseen discouraged the cycling and the pool was chosen as gas storage principally due to the important location in the pipeline network.
The gas injection was done for six years using only the eight wells which were in production at the end of the preliminary production period.
In 1970-71 nine new wells were drilled and the treatment plant was enlarged.
Threshold pressure was not analyzed during this period because the maximum pressure reached is about 66% of original static pressure.

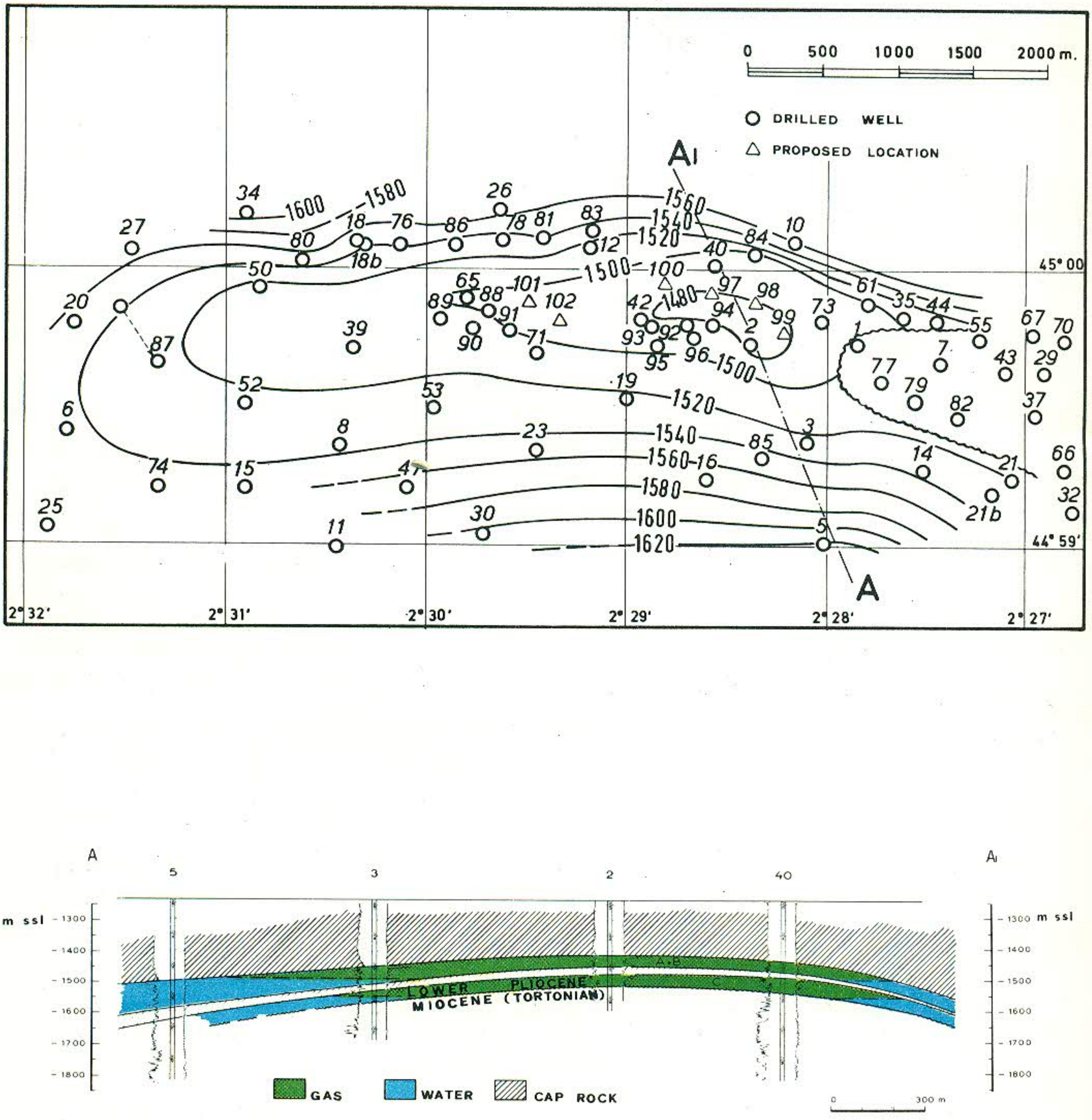


Fig. **16** **CORTEMAGGIORE** *Field*

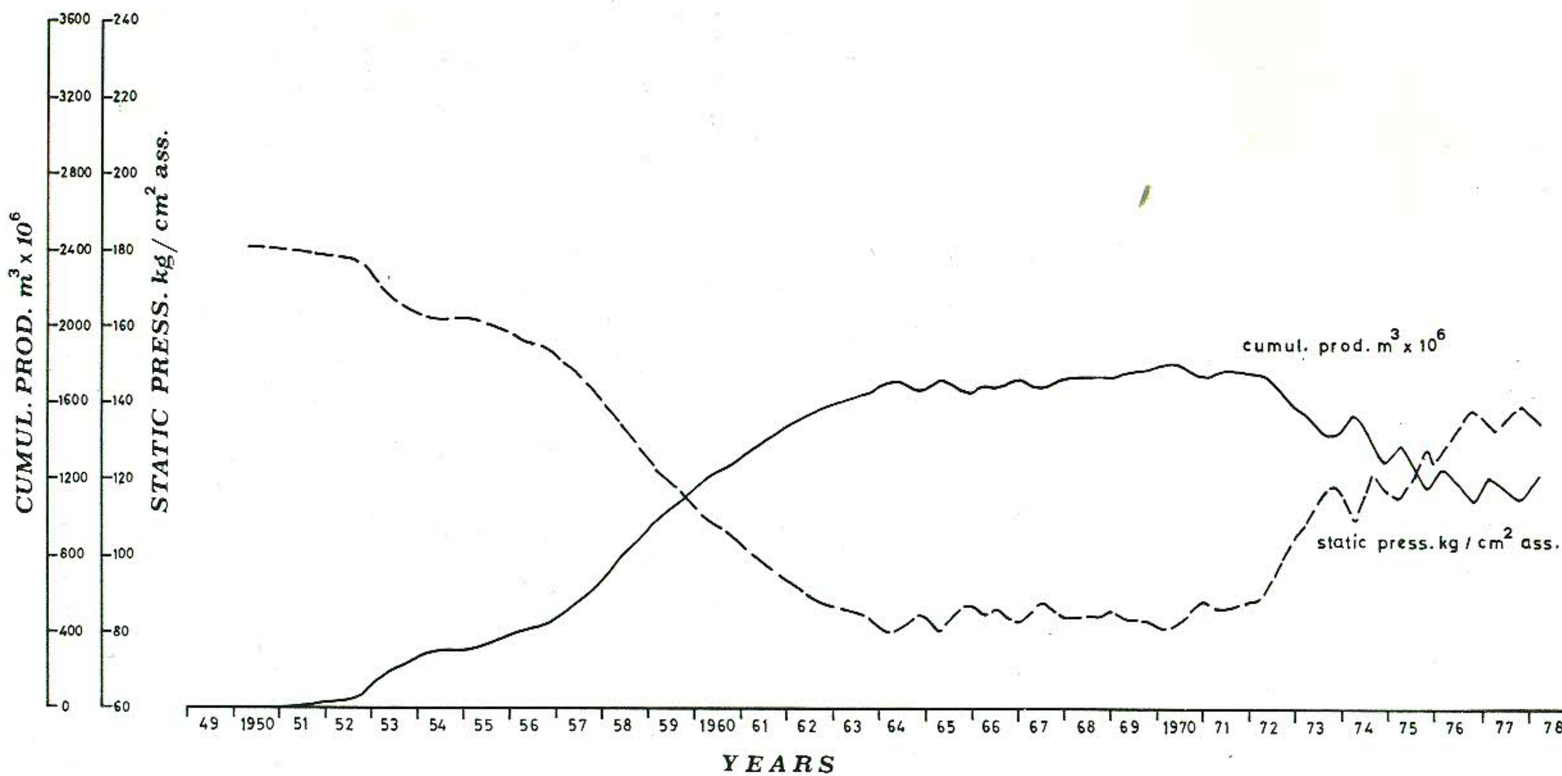


Fig. **17** – *CORTEMAGGIORE storage – reservoir average static pressure and cumulative production*

During this period the gas in place (950 million cubic meters at the beginning of storage) was increased up to around 1300 million cubic meters and the working gas (50 ÷ 100 millions of cubic meters at the beginning of storage) was increased up to 200 ÷ 250 million of cubic meters. The maximum available peak is now around 1.5 million cu meters.
For the final development, now in progress, six wells will be drilled.
It is expected that the rate of 3 million cu m/d will be available. The working gas is expected to be in the range of 300-350 million cubic meters.

Figure 17 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.

9.2 Sergnano Storage

This is the most important underground gas storage in Italy.

The Sergnano field, discovered in January 1954, lies under the village of Sergnano, in the province of Cremona, around 40 Km from Milan (fig. 14).

The hydrocarbon bearing zone (six pools) was discovered in the lower Pliocene at a depth of around 1300 meters.
The main pool which was conventionally called "F", afterwards used for storage, contained practically all the original reserves. The reservoir (fig. 18) is a stratigraphic trap determined by the deposit of coarse clastic rocks of the lower Pliocene (Sergnano gravels), overlying the Miocene marls folded in an anticline. The area of the reservoir is 4.2 Km x 1.6 Km; the main axis is located in an East-West direction. The aquifer is on the bottom, and the original gas-water contact was at 1,300 mt. below sea level. The maximum thickness of the hydrocarbon bearing reservoir was around 100 mt. The cap rock consists of a shaly bank, more than 200 meters thick.
The porosity and water saturation are 24% and 20% respectively; permeability is in the range of 100 - 500 mD.
The production started in October 1954, and continued until 1965, the period when storage operations began. In this production period around 3 billion cubic meters were produced, equal to 75% of the original gas in place. The static pressure declined from the original 157,4 Kg/cmq to 70 Kg/cmq. The water table rose up to 1286 meters.
Eight wells have been producing reaching a maximum daily rate of around 2 million cubic meters. The production history (fig. 19) indicated a mechanism due to partial water drive, and an absence of sand problems as well as water coning.
Production tests carried out during this period ascertained excellent productivity of the formation and the flow rate limits of the single wells; these limits were due exclusively to the flowing tubing head pressure and the capacities of the surface facilities.
These elements, together with the location of the field in a high consumption area, were critical for selecting the reservoir as a natural gas storage.

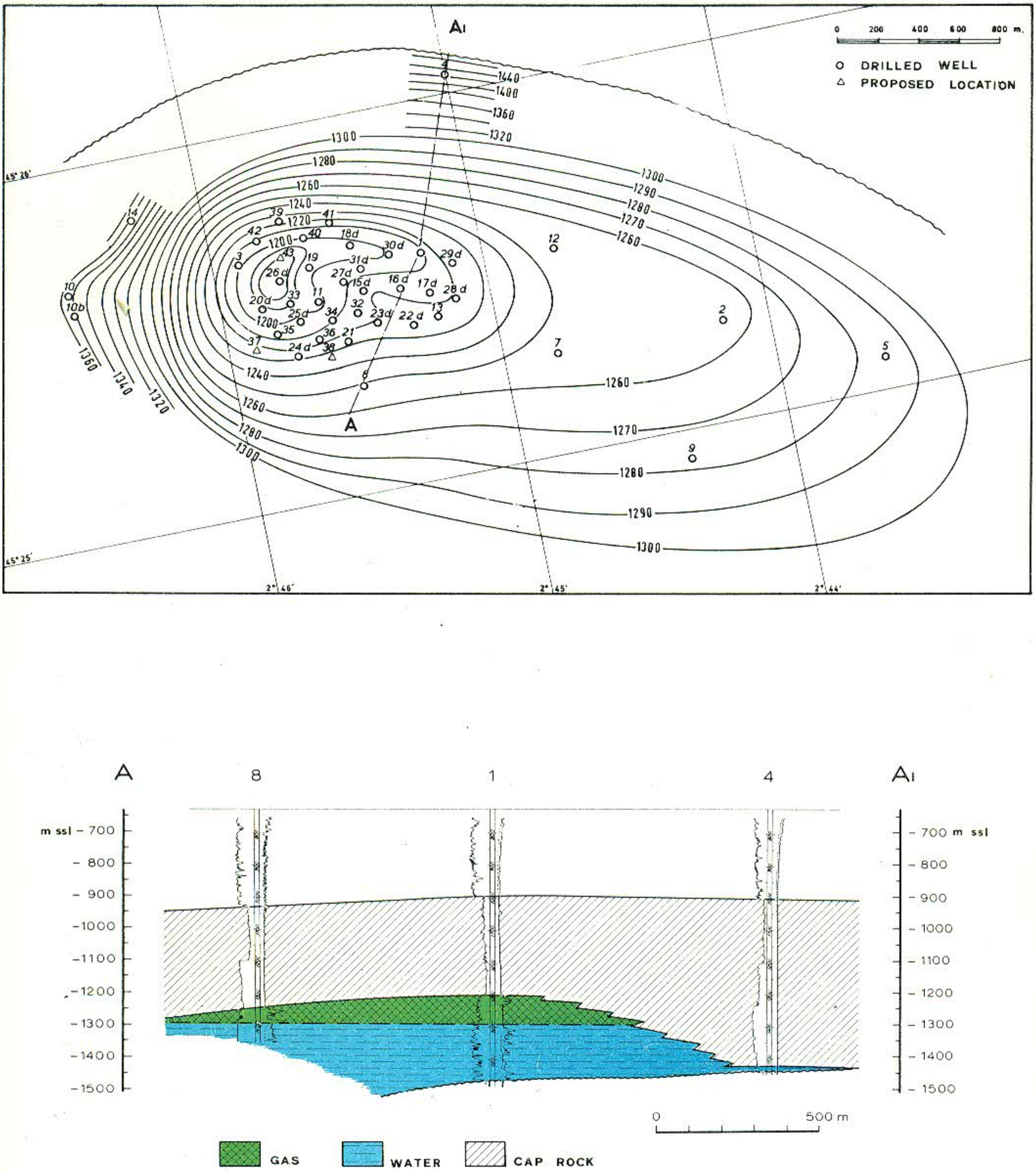


Fig. ***18*** ***SERGNANO*** ***Field***

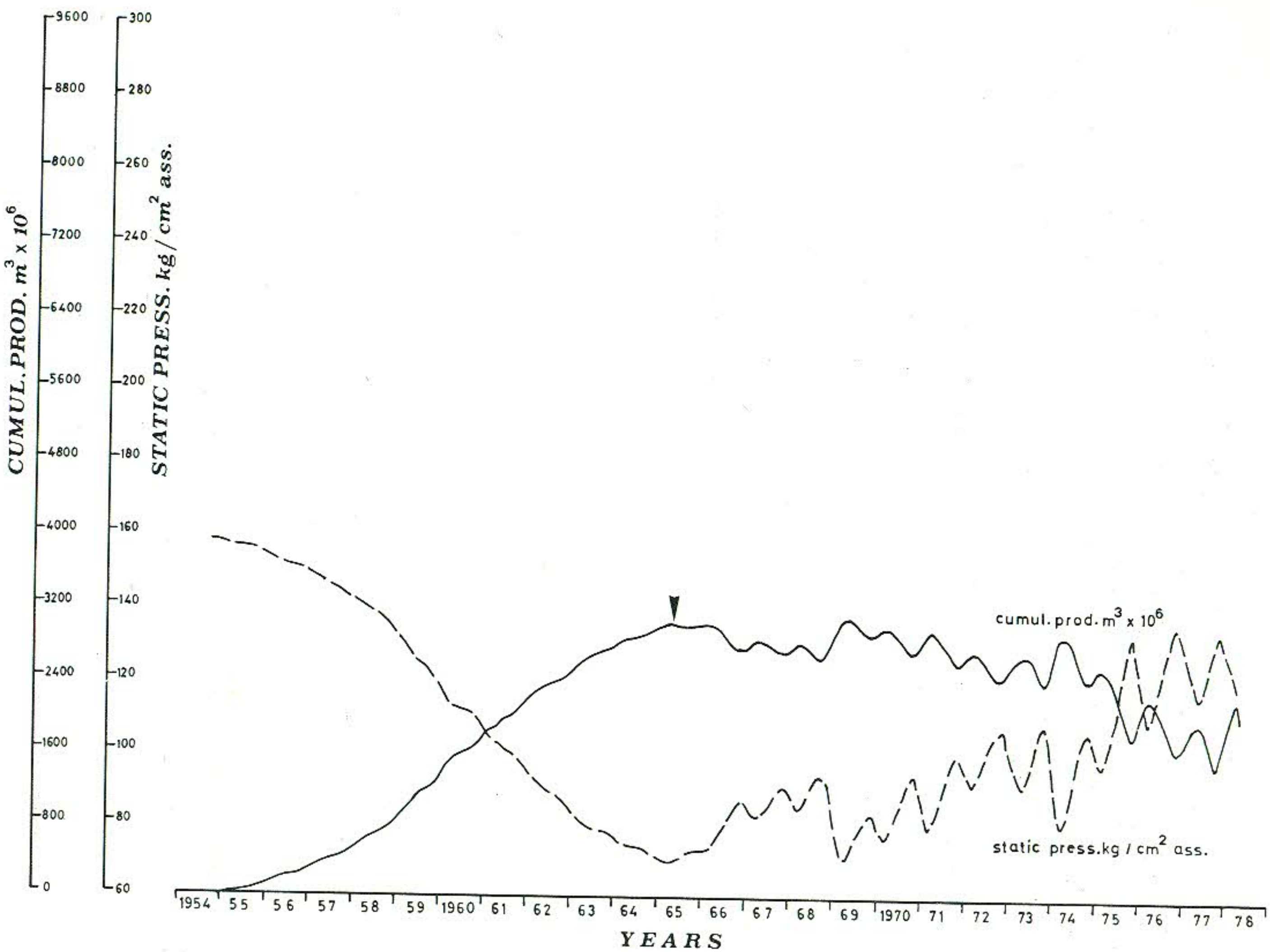


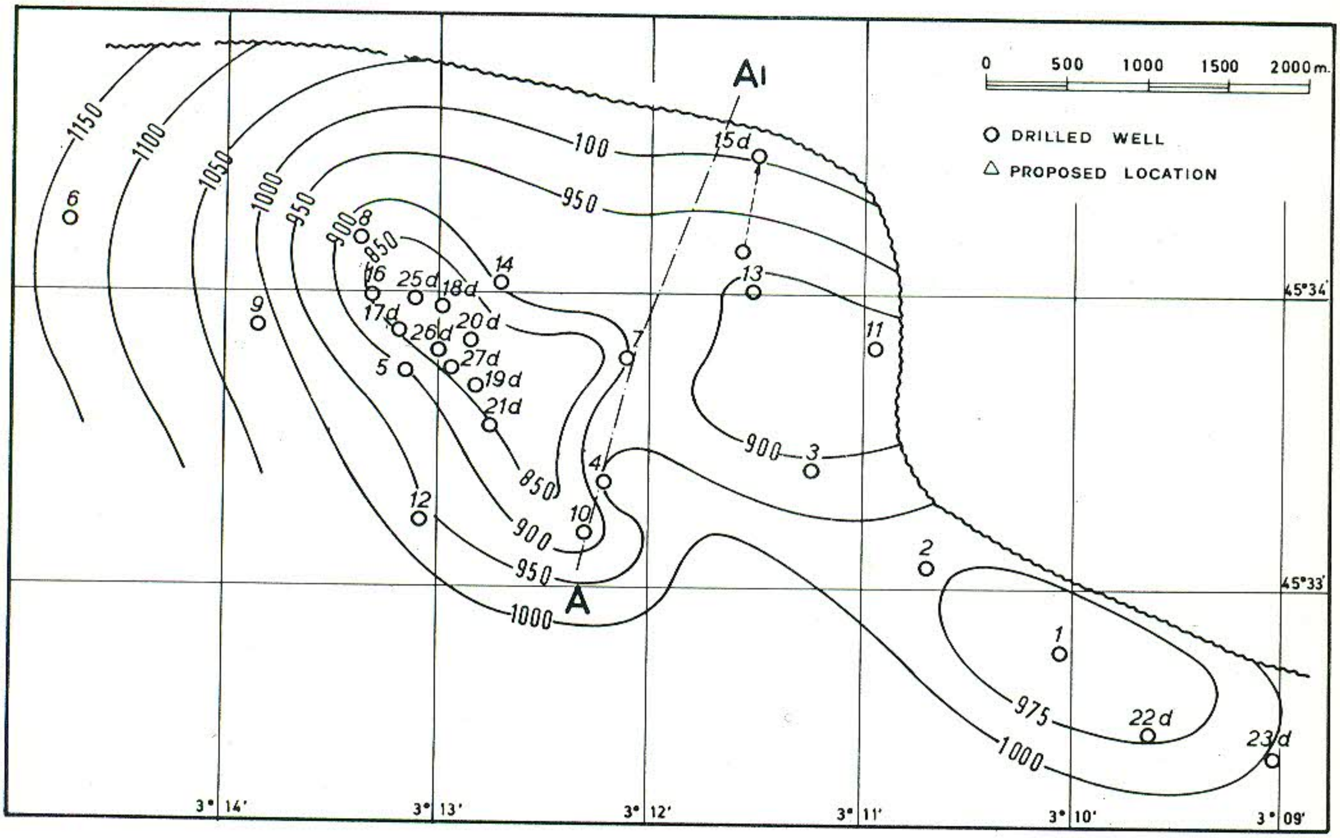
Fig. 19 – SERGNANO storage – reservoir average static pressure and cumulative production

After preliminary studies, gas injection started in April 1965; at the beginning only the seven existing wells were utilized (Nos. 1-2-3-7-8-11-13).
In order to get more information on the reservoir three new wells (Nos. 15-16-17) were drilled and cored. Threshold pressure was calculated after analyzing cores in AGIP laboratories: the maximum pressure allowed during the storage is the original static pressure. A safety coefficient of 10% was assumed so that the maximum pressure allowed in this field is 90% of original static pressure i.e. 142 Kg/cmq.
The acid jobs carried out in the new wells indicated that the maximum rate of each well could be in the range of 1 ÷ 1,5 million cubic meters per day at a pressure of approximately 140 Kg/cmq.
In 1967-68 No. 7 wells (Nos. 18 ÷ 24) were drilled, acidized and completed with 5'' tubings. In this period the gas in place (1,25 billion cubic meters at the beginning of storage) was increased up to around 1,6 billion cubic meters. The maximum available peak was 8 million cu m/day.
In 1971-74 a new drilling campaign was carried out. So No. 7 new wells, acidized and completed with 5'' tubings, were added to the 17 existing wells. The gas in place was increased up to 2,5 billion cubic meters.
In the winter 1974-75 the maximum available peak was around 20 million cu m/day.
Due to the ever increasing peak demand, a detailed study was carried out with a three-dimensional model to investigate whether a peak rate of 50 million cu m/day could be reached.
The study confirmed that the above mentioned peak could be reached with a value of gas in place of 3,0 billion cubic meters and a total of 36 wells.
Based on the results of the study, 12 wells (Nos. 32 ÷ 43) were drilled in 1976-77 and the gas in place was increased up to around 3 billion cubic meters.
Figure 19 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.
In the winter of 77/78 the maximum available peak was 35 million cu m/day.
All the necessary work to enlarge the treatment plants and the compressor-station plant (25000 HP) is now in progress. It is expected that the rate of 50 million cu m/day will be available next winter 78/79.
The working gas is expected to be in the range of 600 - 1200 million cubic meters.

9.3 Brugherio Storage

The Brugherio field, discovered in June 1958, lies under Cinisello Balsamo, around 6 Km from Milan (fig. 14).

The hydrocarbon bearing zone (four pools) was discovered in the lower Pliocene at a depth of around 1100 meters.
The main pool which was conventionally called ''A + B'', afterwards used for storage (fig. 20) is a stratigraphic trap determined by the deposit of coarse clastic rocks of the Lower Pliocene (Sergnano gravels). The area of the reservoir is 2,5 Km x 1,5 Km; the main axis is located in a NW-SE direction. The aquifer is on the bottom, and the original gas-water contact was at 945 meters below sea level. The maximum thickness of the hydrocarbon bearing reservoir was around 80 mt. The cap rock consists of a shaly bank, more than 260 meters thick.
The porosity and water saturation are 20% both; permeability is in the range of 100-500 mD.



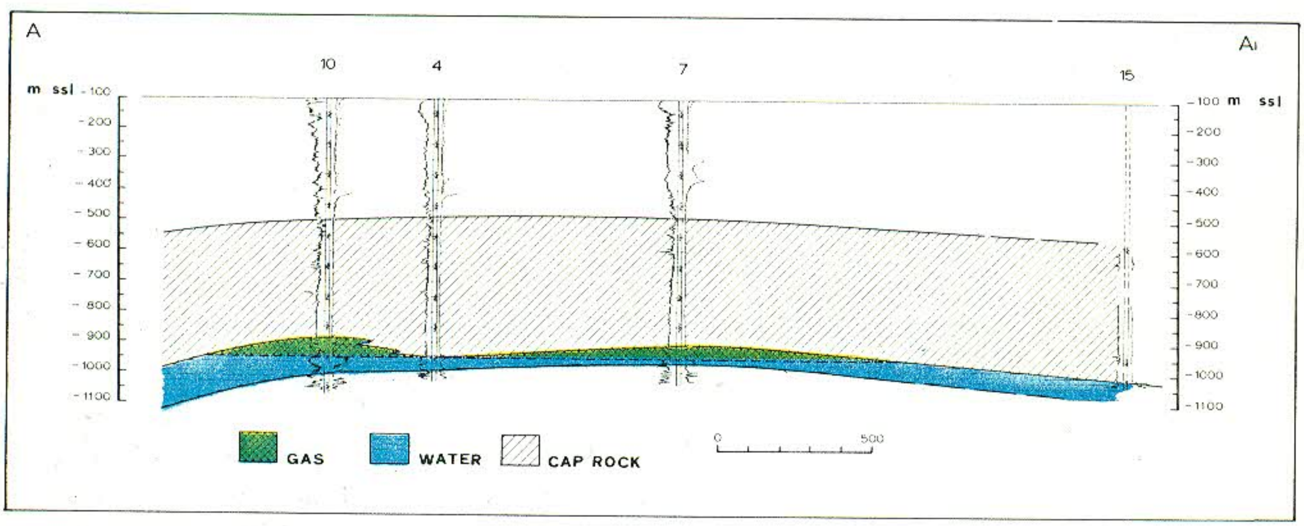


Fig. **20** **BRUGHERIO** ***Field***

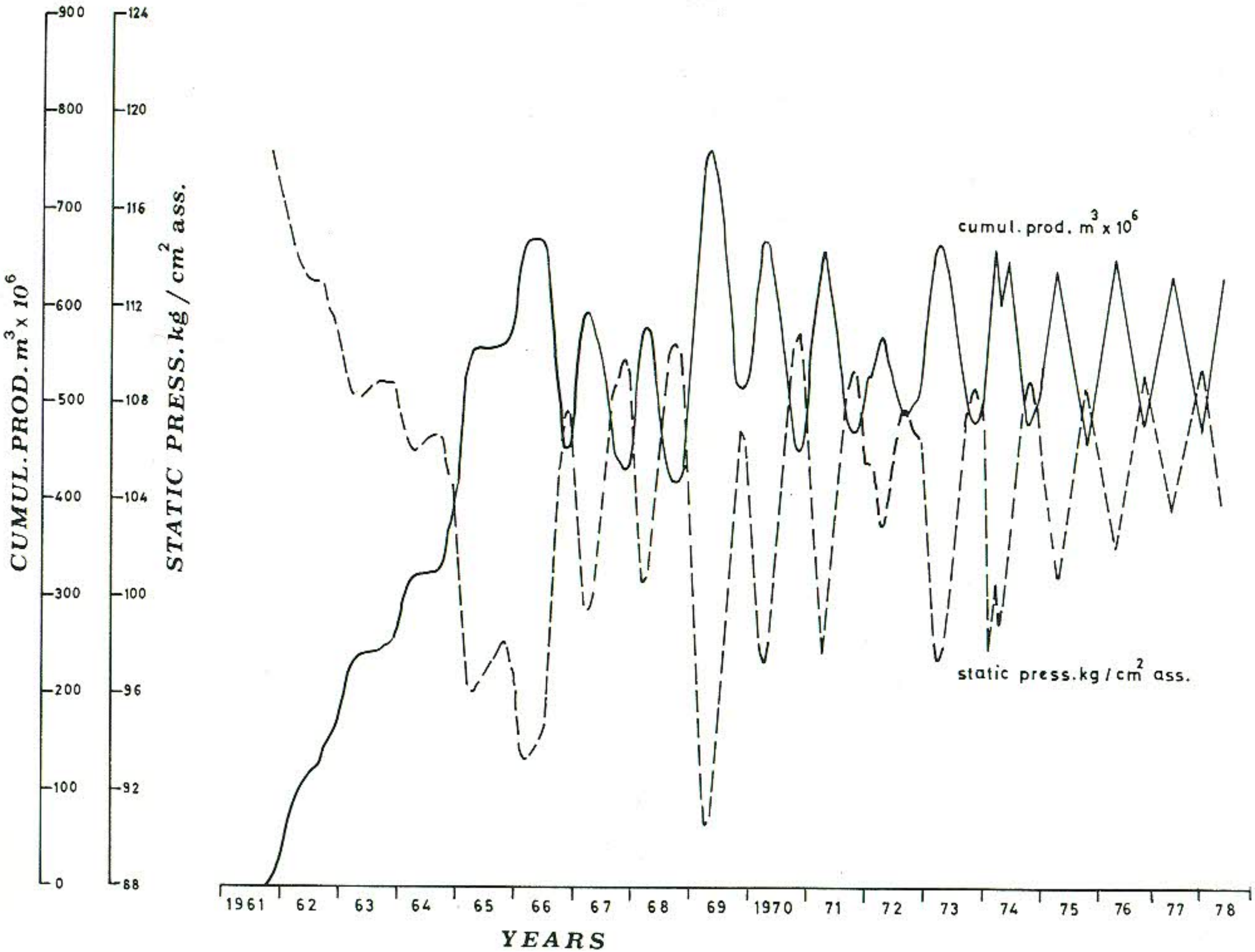


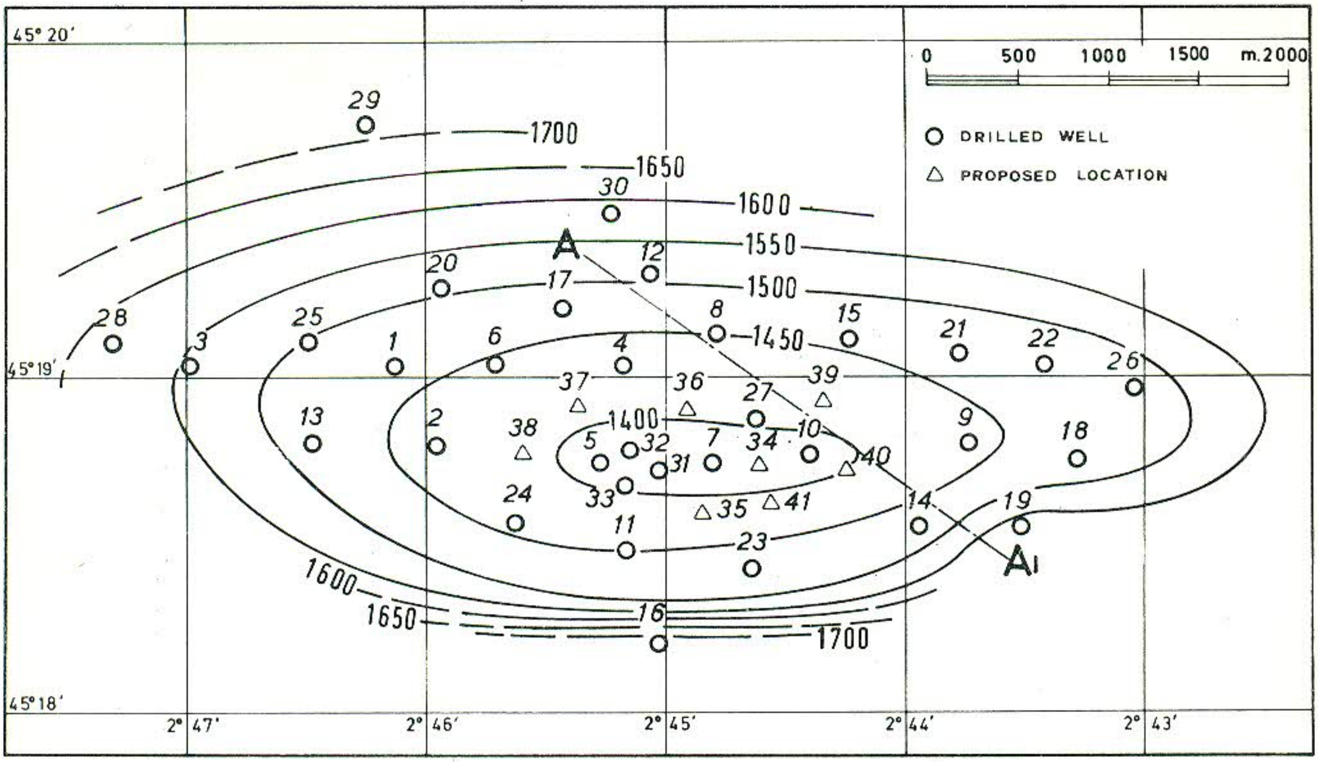
Fig. 21 – **BRUGHERIO storage – reservoir average static pressure and cumulative production**

The production started in October 1961, and continued until June 1966, the period when storage operation began. In this production period around 0,7 billion cubic meters were produced, equal to 35% of the original gas in place. The static pressure declined from the original 118.3 Kg/cmq to 90 Kg/cmq. The water table rose up to 935 meters. Fourteen wells have been producing reaching a maximum daily rate of around 2 million cubic meters. The production history (fig. 21) indicated a mechanism due to water drive, an absence of sand problems, but big water coning problems, especially for the wells close to the gas-water contact.
From production tests carried out during this period a poor productivity on the boundary but an excellent productivity on the top of the formation and the flow rate limits of these wells have been ascertained; these limits, about 1 million cu m/d x well, were due exlusively to the flowing tubing head pressure and the capacities of the surface facilities. These elements, together with the location of the field in a high consumption area, were critical for selecting the reservoir as a natural gas storage.
After preliminary studies, gas injection started in June 1966; at the beginning only the fourteen existing wells were utilized (Nos. 1-3-5-7-8-10-11-14-16-17-18-19-20-21).
In 1968 the reservoir was developed by drilling three new wells (Nos. 25-26-27). Threshold pressure was evaluated after analyzing cores of similar cap rock in AGIP laboratories: the maximum pressure allowed during the storage is the original static pressure.
A safety coefficient of 10% was assumed so that the maximum pressure allowed in this field is 90% of original static pressure i.e. 107 Kg/cmq.
In the same period all the wells on the top reservoir were acidized and completed with 5'' and 7'' tubings.
The gas in place (1,4 billion cubic meters at the beginning of storage) was increased up to only around 1,6 billion cubic meters, due to the static pressure limit. Working gas is about 200 million cu m.
The maximum available peak is 11 million cu m/day.
Figure 21 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.

9.4 Ripalta Storage

The Ripalta field, discovered in March 1949, is near the homonymous village, in the province of Cremona, around 40 Km from Milan (fig. 14).

The hydrocarbon bearing zone (seven pools) was discovered in the lower Pliocene at a depth of around 1500 meters.
The main pool which was conventionally called ''A'', now used for storage, contained practically all the original reserves. The reservoir (fig. 22) is determined by an anticline of coarse clastic rocks and sands, interbedded by shale. The area of the reservoir is 5 Km x 1.6 Km; the main axis is located in an East-West direction. The aquifer is on the bottom, and the original gas-water contact was at 1518 mt below sea level. The maximum thickness of the hydrocarbon bearing reservoir was around 80 mt.
The cap rock consists of a shaly bank, more than 300 meters thick.
The porosity and water saturation are 28% and 20% respectively; permeability is in the range of 20 - 60 mD.



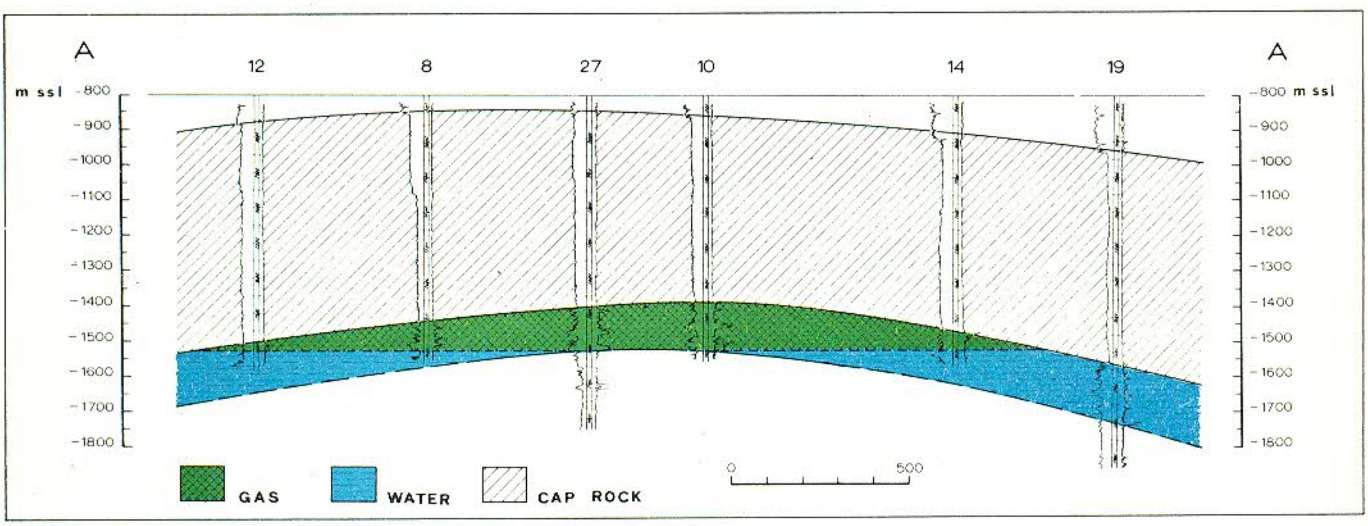


Fig. 22 ***RIPALTA Field***

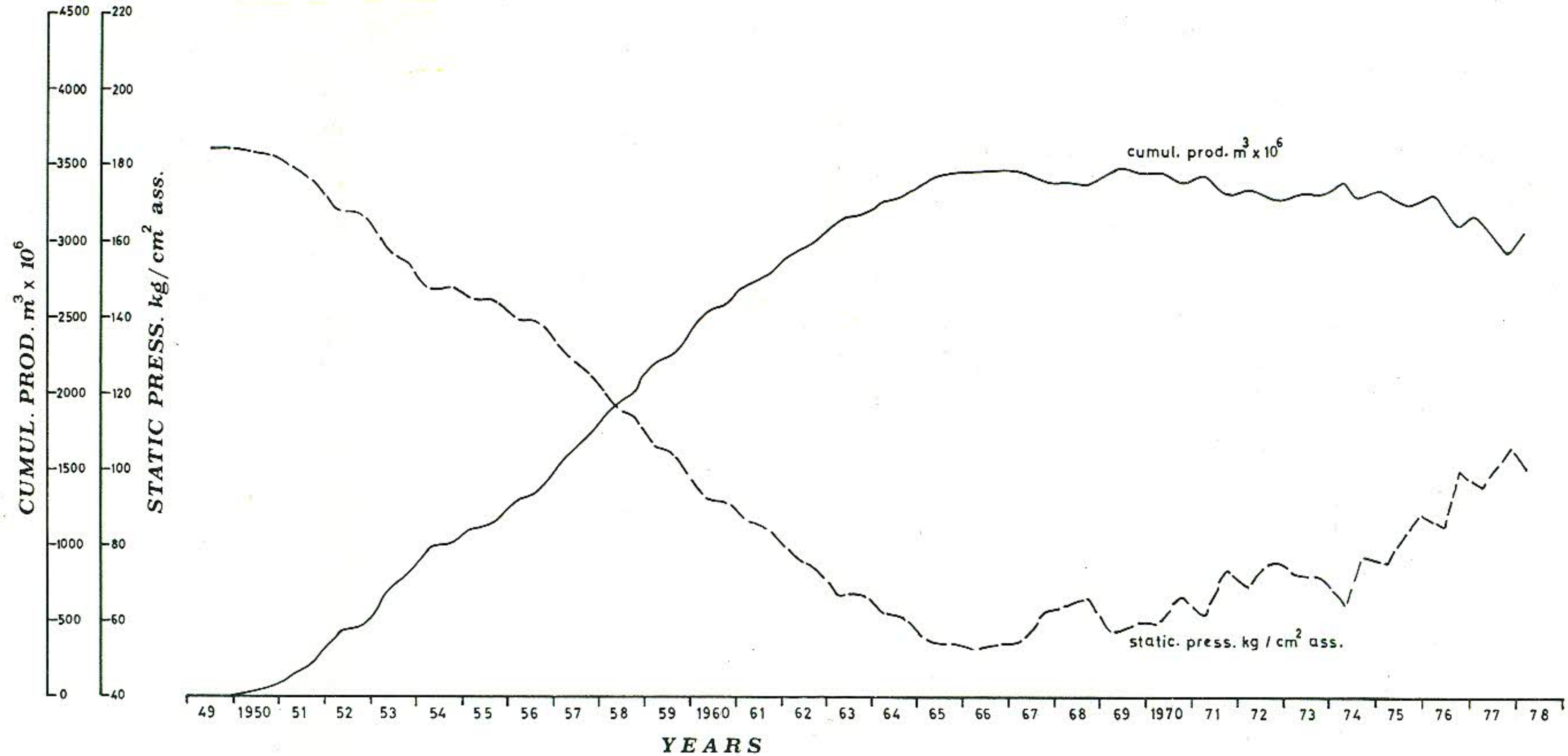


Fig. 23 – RIPALTA storage – reservoir average static pressure and cumula ıve production

Production started in August 1949, and continued until 1967, the period when storage operations began. In this production period around 3.5 billion cubic meters were produced, equal to 85% of the original gas in place. The static pressure declined from the original 184.9 Kg/cmq to 70 Kg/cmq. The water table rose up to 1472 meters. Thirteen wells have been producing reaching a maximum daily rate of around 1.4 million cubic meters.

The production history (fig. 23) indicated a mechanism due to partial water drive, an absence of sand problems, but water coning and high water-gas ratio problems especially at the end of production period.

The location of the field in a high consumption area and in the pipeline system were critical for selecting the reservoir as a natural gas storage.

After preliminary studies, gas injection, started in April 1967; at the beginning only the twelve existing wells were utilized (Nos. 2-4-5-7-8-9-10-11-18-22-24-27).

In 1967 three new wells (Nos. 31, 32, 33) were drilled.

Threshold pressure has been not analysed because the maximum pressure, already reached, is about 55% of original static pressure.

The gas in place (0.6 billion cubic meters at the beginning of storage) was increased up to around 1.1 billion cubic meters.

The maximum available peak is 1.5 million cu m/day.

For the final development, now in progress, eight wells will be drilled. It is expected that the rate of 4 ÷ 4.5 million cu m/d will be available. The working gas is expected to be in the range of 400 ÷ 450 million cubic meters.

Fig. 23 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.

9.5 Minerbio Storage

As far as the working gas is concerned, this will be the most important underground gas storage in Italy.

The Minerbio field, discovered in July 1959, lies under the Minerbio village, around 25 Km from Bologna (fig. 14).

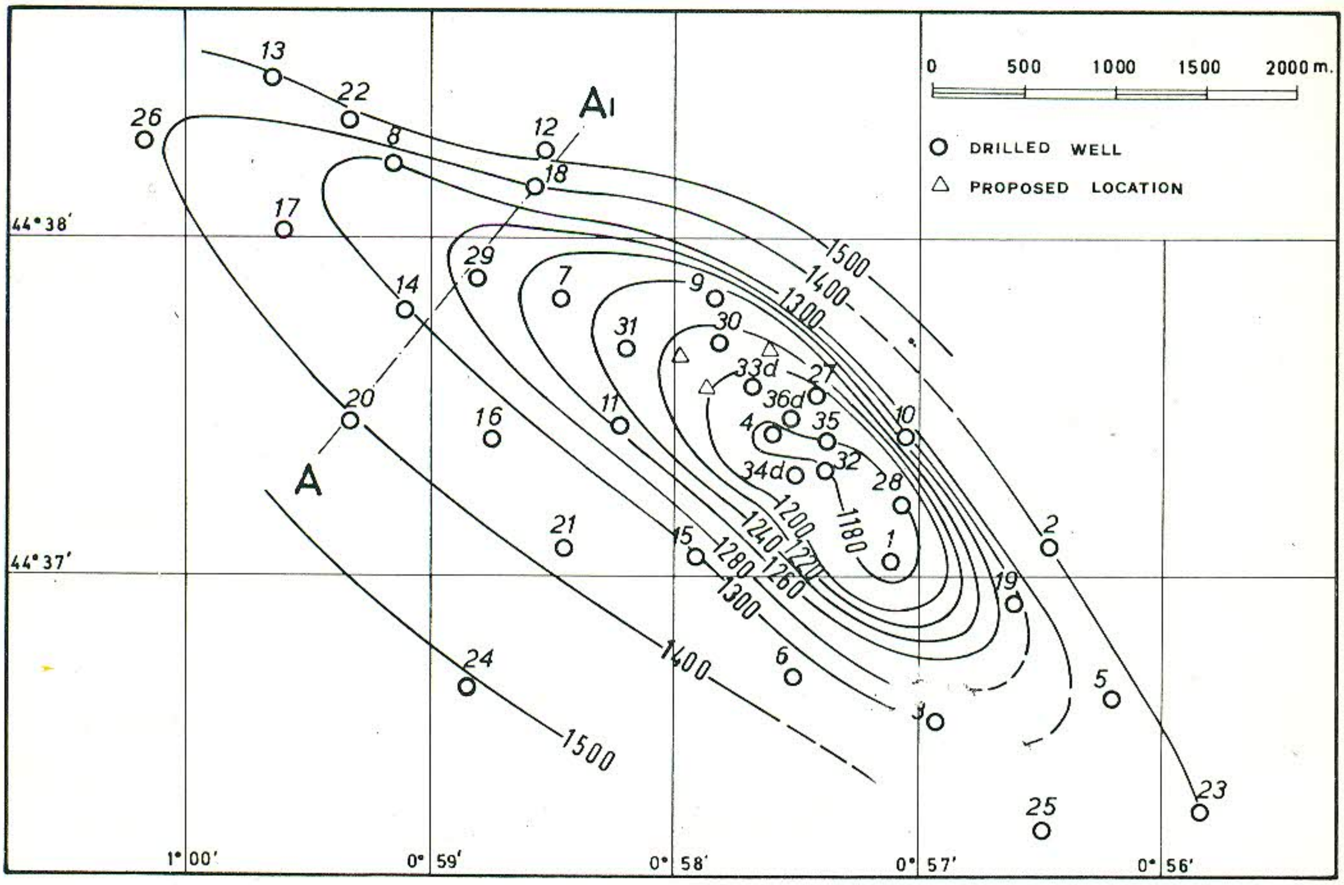
The hydrocarbon bearing zone (seven pools) was discovered in the middle-upper Pliocene at a depth of around 1300 meters.

The main pool, which was conventionally called "C", afterwards used for storage, contained practically all the original reserves. The reservoir (fig. 24) is an anticline of interbedded sand and shale. The area of the reservoir is 6 Km x 2 Km; the main axis is located in an NW - SE direction. The reservoir has an edge aquifer; the original gas-water contact was at 1368 mt below sea level. The maximum thickness of the hydrocarbon bearing reservoir was around 180 mt.

The cap rock consists of a shaly bank, more than 100 meters thick.

The porosity and water saturation are 30% and 20% respectively; permeability is in the range of 60 - 300 mD.

Production started in March 1959, and continued until 1972. The field was closed until April 1975 when storage operations began. In the production period around 12.8 billion



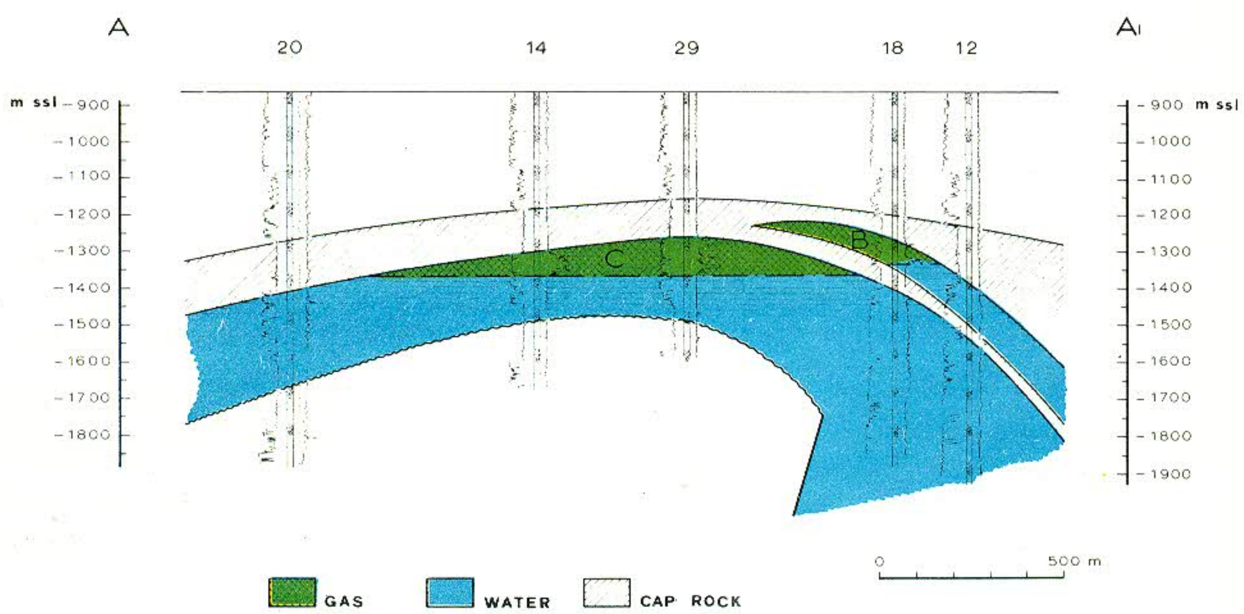


Fig. 24 MINERBIO Field

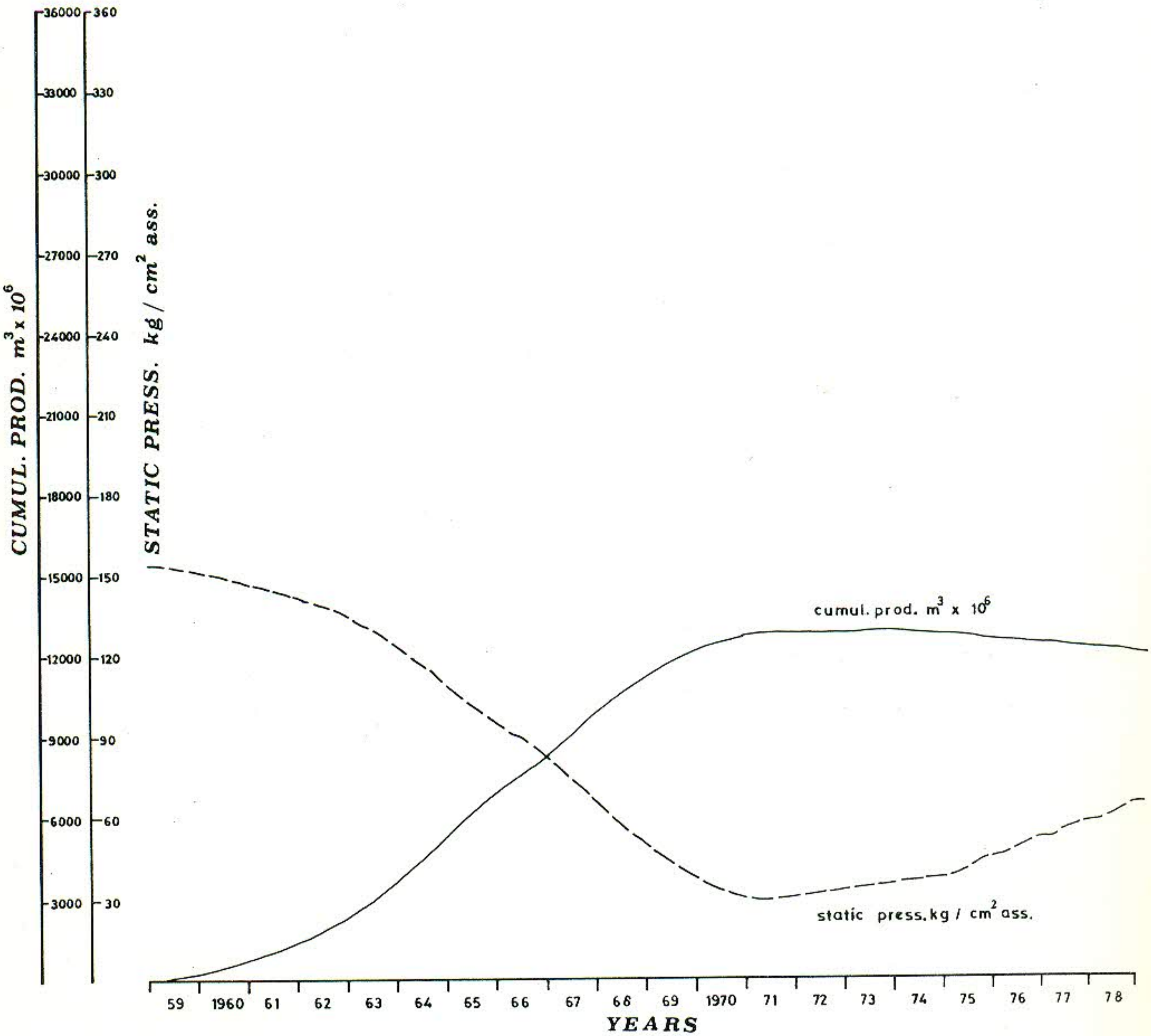


Fig. 25 — MINERBIO storage — reservoir average static pressure and cumul. production

cubic meters were produced, equal to 90% of the original gas in place. The static pressure declined from the original 153.0 Kg/cmq to 30 Kg/cmq. The water table rose up to 1260 meters. Twenty five wells have been producing reaching a maximum daily rate of around 5.6 million cubic meters. The production history (fig. 25) indicated a mechanism due to partial water drive. Sand and water problems have been very important in the last years of the primary production.
Production tests carried out during this period ascertained excellent productivity of the formation and the flow rate limits of the single wells; in general these limits were due exclusively to sand problems; these will be eliminated, in the future, by "gravel packing" completions. These elements, together with the good location of the field in the pipeline system, were critical for selecting the reservoir as a natural gas storage.
Gas injection started in April 1975; only three of sixteen existing wells were utilized (Nos. 30-31-33).
In order to get more information on the reservoir, two new pilot wells will be drilled and cored. Threshold pressure will be evaluated after analyzing cores in AGIP laboratories: the maximum pressure at the present is established at about 120 Kg/cmq.
The completion of the existing wells will be changed so that the maximum rate of each well could be in the range of 0,5 ÷ 1 million cu m/d at a pressure of 120 Kg/cmq.
In 1980 No. 15 wells will be drilled, and will be completed with 5" tubing and gravel packing.
In the future the gas in place (1.4 billion cubic meters at the beginning of storage) will be increased up to around 5.5 billion cubic meters.
The maximum available peak will be 19 million cu m/day in 1985.
A detailed study was carried out with a mathematical model to investigate whether a peak rate of 30 ÷ 33 million cu m/day could be reached.
The study confirmed that the above mentioned peak could be reached with a value of gas in place of about 6.0 billion cubic meters and a minimum of 40 wells. So that it is possible that after 1985 another 7-10 wells will be drilled to reach the above mentioned peak rate.
The working gas is expected to be in the range of 1000 million cubic meters. In emergency conditions the working gas could reach about 3 billion cubic meters.
Figure 25 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.

9.6 Ferrandina Storage

This is the most important underground gas storage in the southern part of Italy.

The Ferrandina field, discovered in January 1959, is near the villages of Ferrandina and Grottole, in the province of Matera (Fig. 14).

The hydrocarbon bearing zone (two pools) was discovered in the Quaternary sands and upper Cretaceous limestones at a depth of around 1000 meters.
The pool which, after primary production was used for storage, is conventionally called "sabbie". The reservoir (fig. 26) is a stratigraphic trap determined by the deposit of sand. The area is 9 Km x 5 Km; the main axis is located in an NE - SW direction. The aquifer is on the bottom, and the original gas-water contact at 650 mt below sea level. The

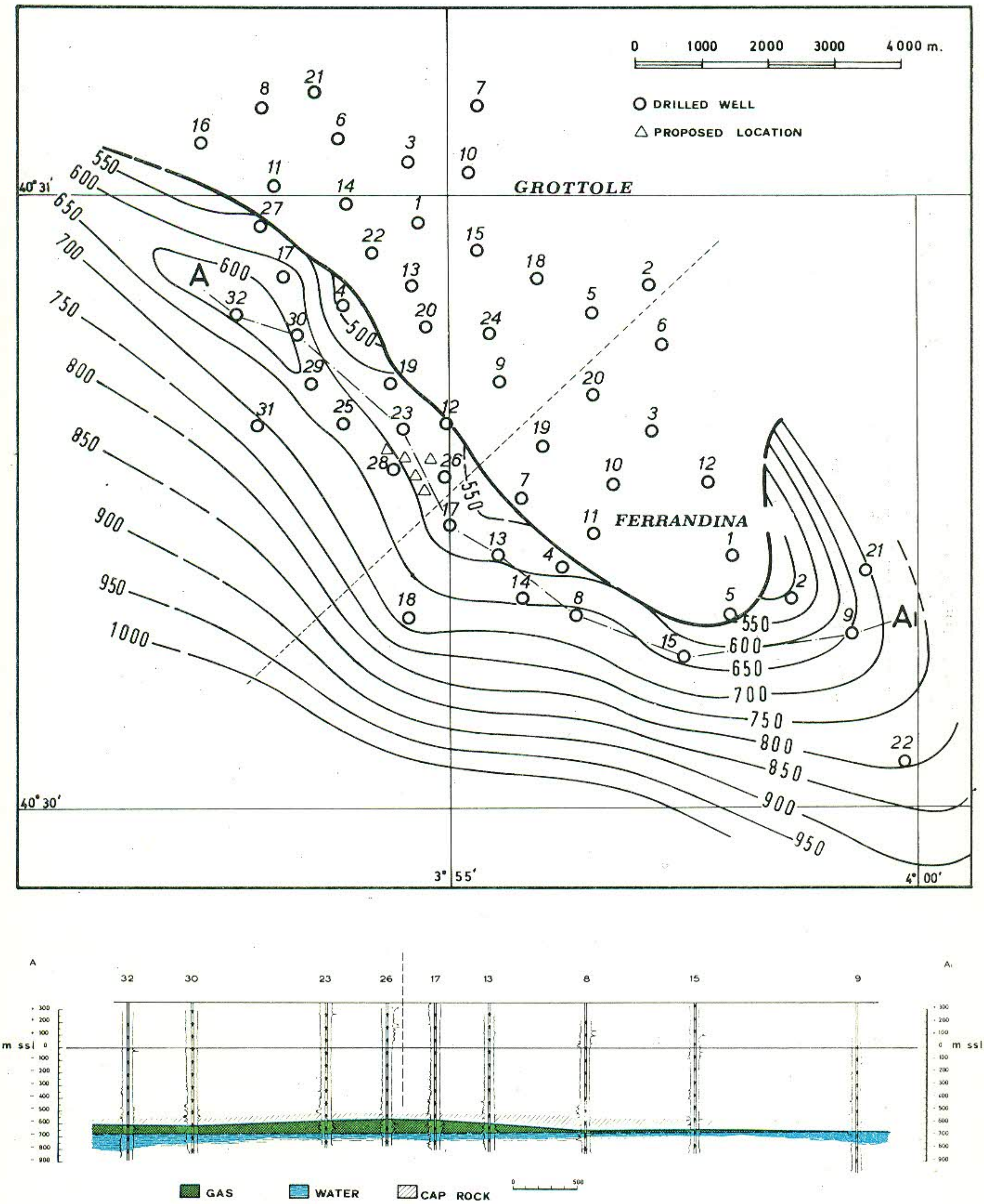


Fig. 26 GROTTOLE – FERRANDINA Field

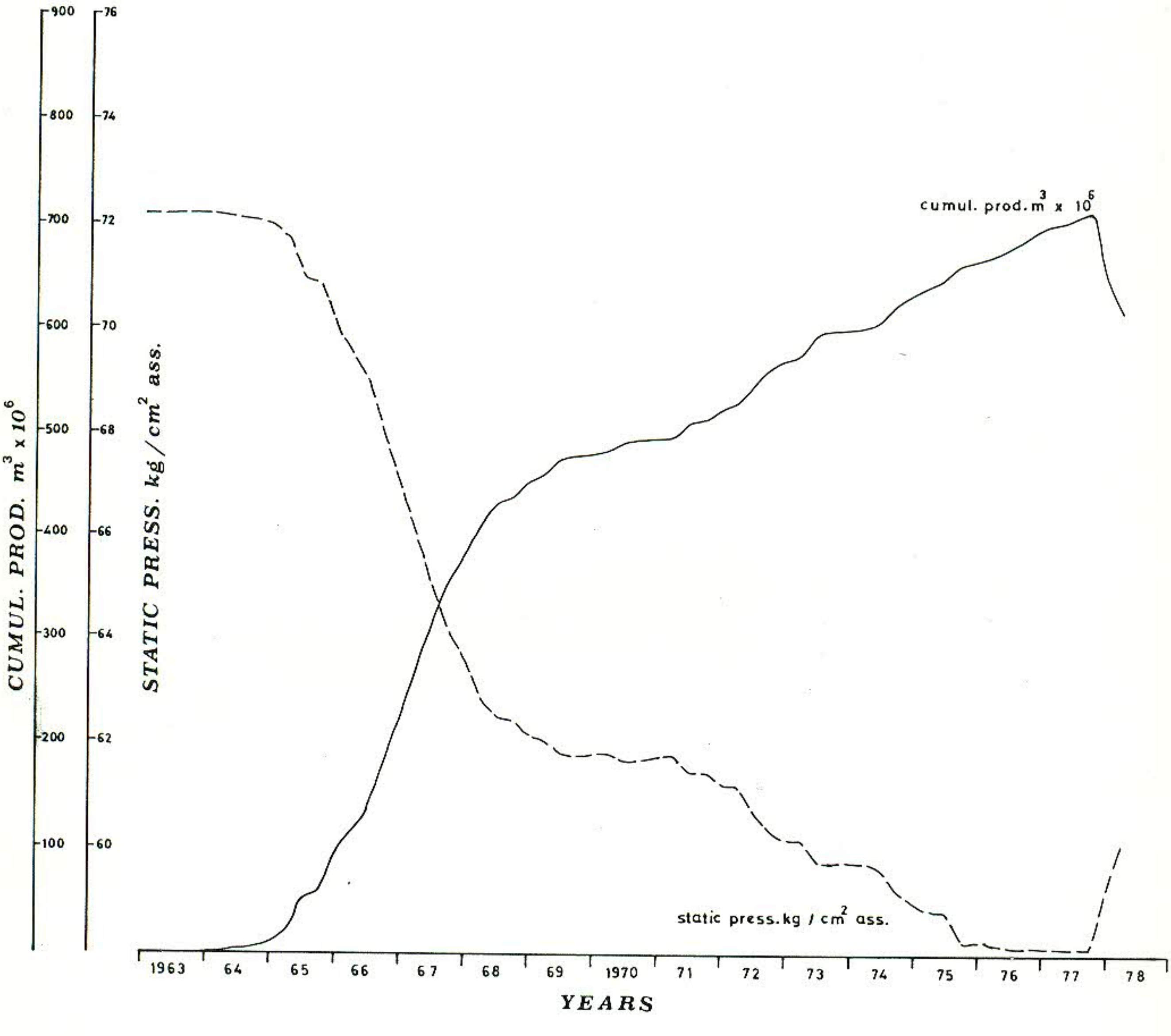


Fig. 27 – *GROTTOLE–FERRANDINA storage – reservoir average static pressure and cumulative production*

maximum thickness of the hydrocarbon bearing reservoir was around 60 mt.
The cap rock consists of a shaly bank, more than 50 meters thick.
The porosity and water saturation are 25% and 27% respectively; permeability is in the range of 100-300 mD.
The production started in september 1963, and continued until 1977, the period when storage operations began. In this production period around 0.7 billion cubic meters were produced, equal to 309 of the original gas in place. The static pressure declined from the original 72.2 Kg/cmq to 57 Kg/cmq. Ten wells have been producing reaching a maximum daily rate of around 0.5 million cubic meters. The production history (fig. 27) indicated a mechanism due to partial water drive, and an absence of sand problems as well as water coning.
Production tests carried out during this period ascertained a low productivity of the formation but the location of the field in the pipeline system, was a sufficient element for selecting the reservoir as a natural gas storage.
After preliminary studies, gas injection started in September 1977 by ten existing wells (Nos. F13, F17, G19, G23, G25, G26, G28, G29, G30, G32) and five new wells (Nos. G33, G34, G35, G36, G37) that have been drilled for storage purpose during 1977. Threshold pressure will be calculated after analyzing cores in AGIP laboratories: in any case the Italian storage law allowes a maximum storage pressure equal to the original static pressure.
The gas in place (1,8 billion cubic meters at the beginning of storage) will be increased up to 1,9 billion cubic meters.
The maximum available peak will be around 1 million cu m/day.
The working gas is expected to be 100 million cubic meters.
Figure 27 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.

9.7 Pisticci Storage

The Pisticci field, discovered in September 1960, is near the homonymous village, in the province of Matera (fig. 14).

The hydrocarbons were discovered in Pliocene and Quaternary at a depth of around 900 meters in gas phase (ten pools) and in Mesozoic limestone in liquid phase (1 pool).

The main pool which was conventionally called "Q", afterwards used for storage, contained practically all the original gas reserves. The gas reservoir (fig. 28) is a stratigraphic trap determined by sands deposit of the Quaternary, interrupted by Alloctonus. The area of the reservoir is 2 Km x 1.5 Km; the main axis is located in an North - Sud direction. The aquifer is on the bottom, and the original gas-water contact was at 772 mt. below sea level. The maximum thickness of the hydrocarbon bearing reservoir was around 35 mt.
The cap rock consists of Calabrian shaly bank, more than 500 meters thick.
The porosity and water saturation are 22% and 25% respectively; permeability is in the range of 400-500 mD.
Production started in September 1964, and continued until December 1977. Gas injection started in February 1978. In the production period around 0.4 billion cubic meters were

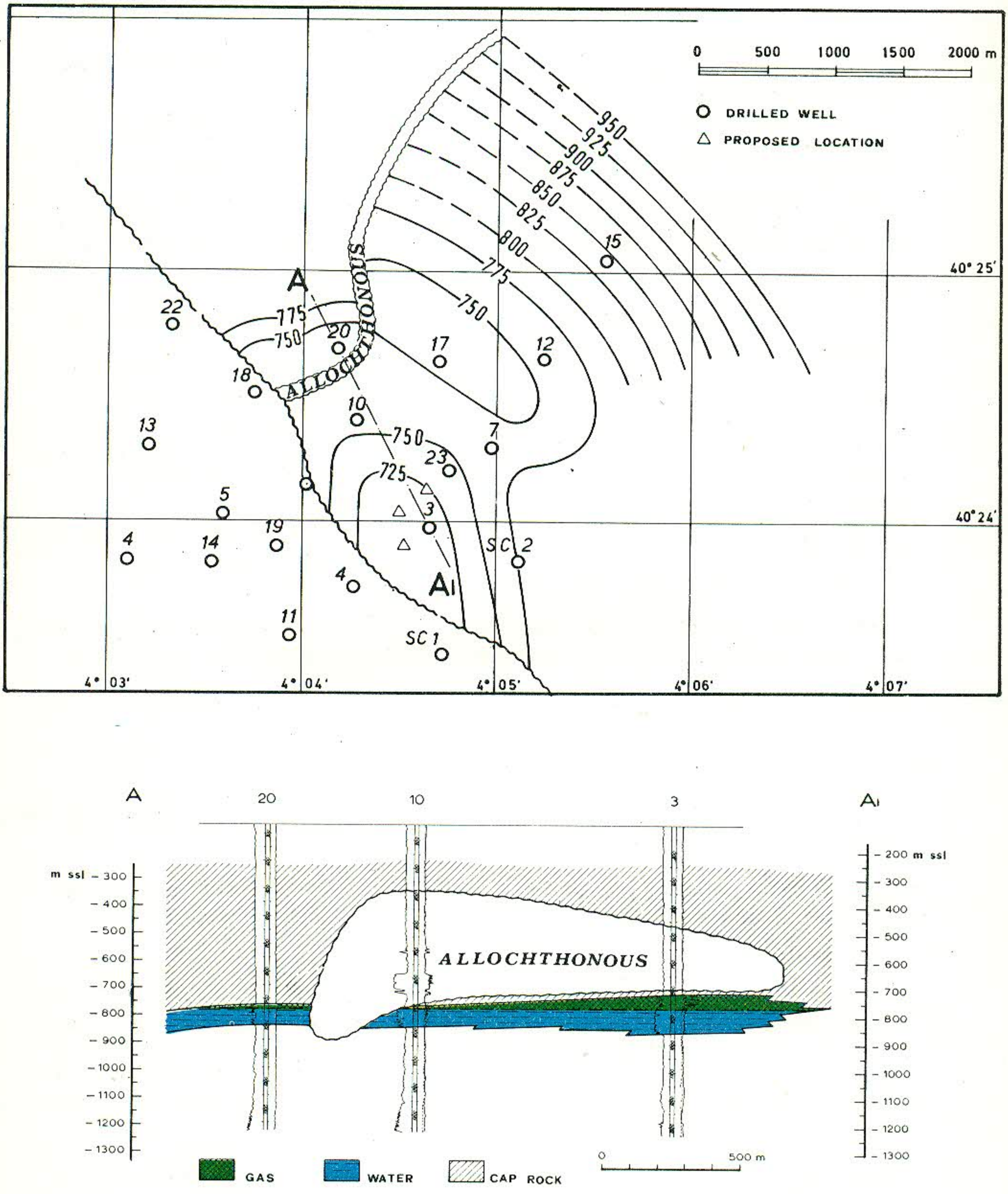


Fig. 28 **PISTICCI** *Field*

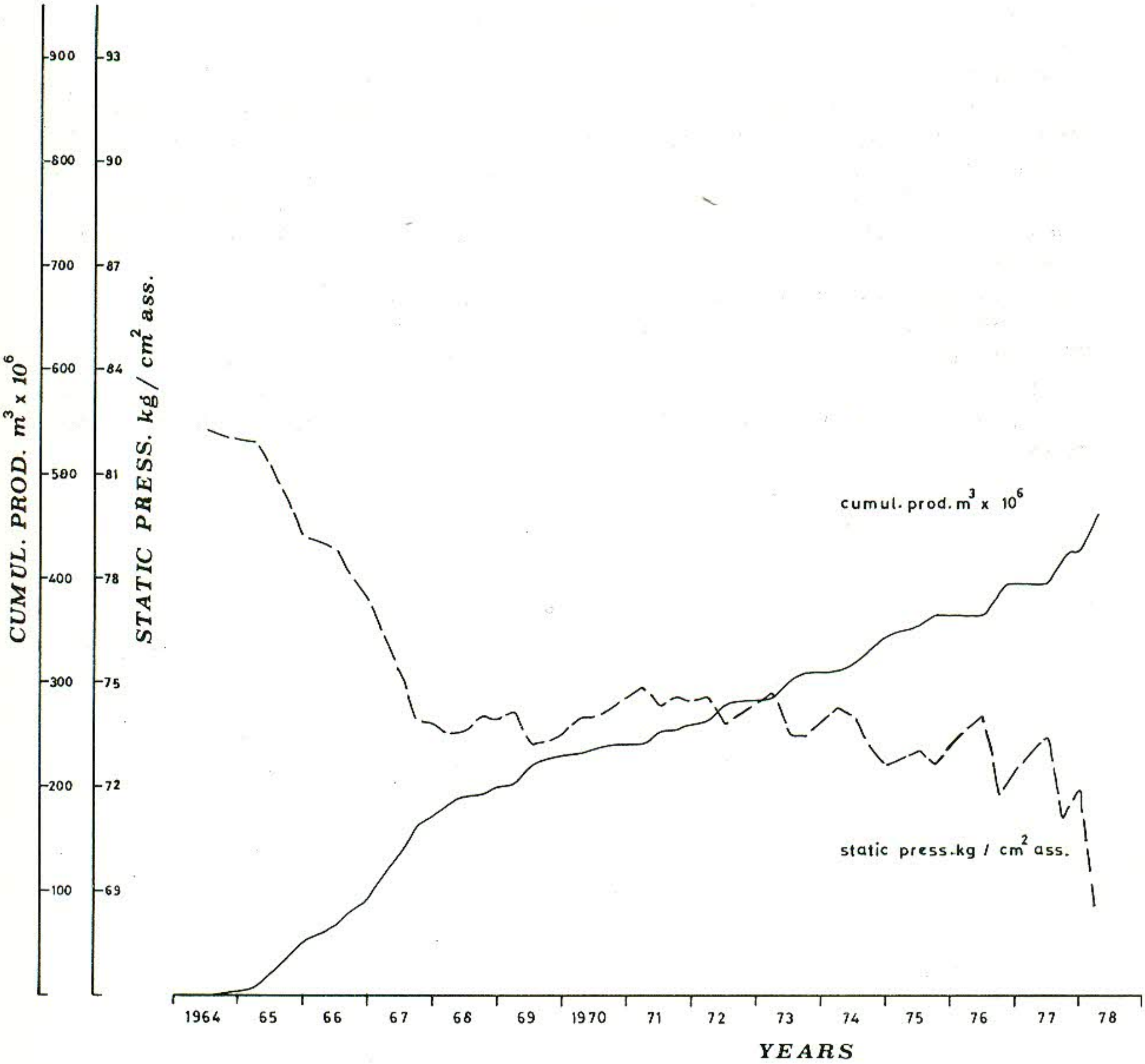


Fig. 29 – PISTICCI storage – reservoir average static pressure and cumul.production

produced, equal to 42% of the original gas in place. The static pressure declined from the original 82.2 Kg/cmq. to 70 Kg/cmq. The water table rose up to 756 meters. Six wells have been producing reaching a maximum daily rate of around O.3 million cubic meters. The production history (fig. 29) indicated a mechanism due to water drive.
The location of the field in the pipeline system was critical for selecting the reservoir as a natural gas storage.
After preliminary studies, gas injection started utilizing three existing wells (Nos. 3 - 10 -17) and three new wells (Nos. 25 - 26 - 27) that have been drilled for storage purposes in 1977. Threshold pressure will be analyzed in AGIP laboratories: in any case by Italian storage law the maximum pressure allowable during the storage is the original static pressure. In 1979 well No. 23 will be completed after workover in the storage pool.
The gas in place (O.6 billion cubic meters at the beginning of storage) will be increased up to around 0.7 billion cubic meters.
The maximum available peak will be around 1 million cu m/day.
All the necessary works to enlarge the old treatment plants are now in progress.
The working gas is expected to be 60-100 million cubic meters.
Figure 29 shows both the gradual pressure drop and cumulative production trend during the primary production as well as the behaviour of these parameters during the storage period.