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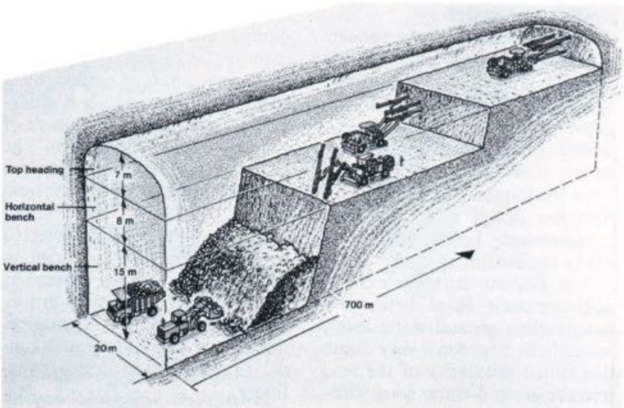
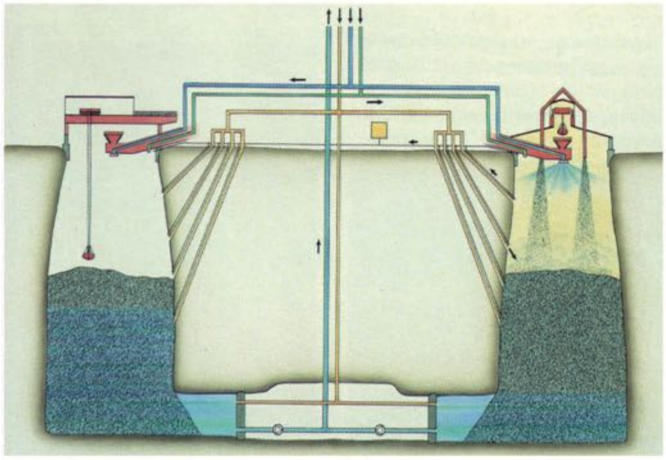
GOING UNDERGROUND AN EXCAVATION METHOD FOR LARGE VERTICAL CYLINDRICAL CAVERNS

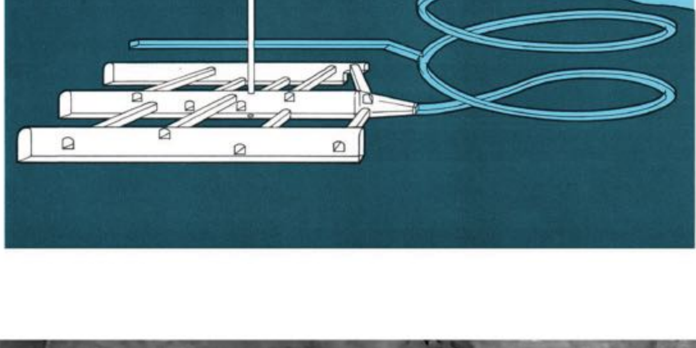
Oil and gas storage - traditional way



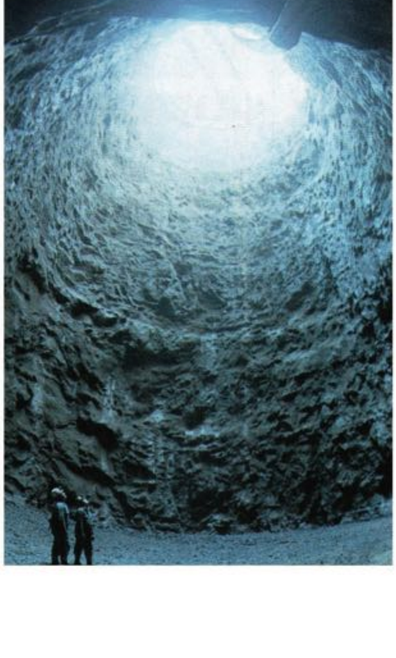
Clean coal-handling at the coal-fired power station



Underground storage of liquefied petroleum gas



The LPG installation at Lavera.

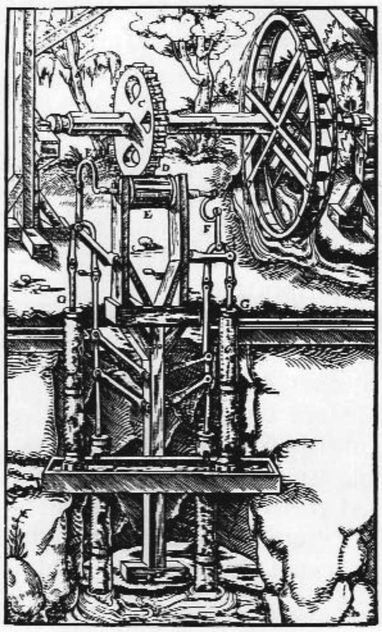


An Excavation Method for Large Vertical Cylindrical Caverns

RCI AB Ivar Sagefors and Per-Anders Daerga

Abstract—*Construction of underground storage chambers in rock has traditionally adopted a construction-oriented approach; the cavern design and the method of excavation have been governed by the capabilities of the equipment available. One example is oil storage in unlined horizontal caverns. Today, however, equipment is no longer a limiting factor. The time has come to integrate the construction and operational aspects in the design process. This paper presents a construction concept developed for large vertical rock caverns with a circular or elliptical horizontal cross-section. The method of excavation, called PBM (Pillar Blasting Method), is condensed into a few main operations which are geometrically separated but overlapping in time. PBM is characterized by two main working sites per cavern, and by long-hole bench-drilling, massive blasting rounds, continuous loading and easy ventilation. Recent developments in drilling and blasting techniques are incorporated, such as the water-driven in-the-hole hammer and the electronic ignition system. PBM enables a high rate of excavation and provides a satisfactory working environment with respect to labour safety and human health (a limited exposure to large openings, no exposure to oil mist and to combustion and explosive fumes, etc). Considerable construction cost savings and time savings may thus be achieved compared to conventional methods of excavation for vertical and horizontal caverns of equal storage volume. A preliminary PCT patent (application No PCT/SE95/00324) has been granted. Examples of applications are fresh-water reservoirs, natural gas reservoirs, subsurface hydroelectric pump power plants, and similar objects which require a large underground storage space in preferably unlined rock caverns.*

The significance of mining



1. Introduction

The design of underground constructions in rock for storage applications has, in the past, typically pursued a construction-oriented approach; the cavern design and the method of excavation have been governed by the capabilities of the equipment available. A demonstrating example is oil storage facilities in unlined horizontal caverns, now used worldwide. Today, however, equipment is no longer a limiting factor. The time is right to also consider the operational aspects, guided by functional demands for the stored product. This is logical, considering that the operational phase of an underground storage plant far exceeds the construction phase.

During the past decade, vertical caverns have been constructed for various purposes. Examples include:

Forsmark, Sweden	1985–86	a rock silo (diameter 30 m, height 70 m) for final disposal of low- and medium-level radioactive waste, located in the bedrock beneath the Baltic sea, offshore from the Forsmark nuclear power plant.
Olkiluoto, Finland	1986–88	a cavern for disposal of low- and medium-level radioactive waste, close to the Olkiluoto nuclear power plant.
Harare, Zimbabwe	1993–94	a silo-type storage cavern for jet fuel.

All of these facilities were constructed by conventional methods, normally characterized by a top heading and sequential benching. However, recent developments in drilling and blasting techniques have created new possibilities for a different type of excavation.

This paper describes a construction concept for excavation of large vertical caverns with a circular or elliptic cross-section. The so-called PBM (Pillar Blasting Method) takes advantage of modern mining techniques. It presupposes a diameter of about 30 m as a minimum; the height can exceed 100 m.

Possible fields of application are for freshwater reservoirs, storage facilities for natural gas, hydroelectric pump power plants, and similar facilities that require a large underground storage space, preferably in unlined rock caverns.

2. General Aspects of Cavern Design

The construction of underground caverns is an optimization problem. Various requirements, some severely conflicting with others, have to be integrated into a common framework.

For bulk storage, a cavern design in the form of a vertical cylinder generally can accommodate different demands and conditions—geology, rock stresses, construction technique, construction cost and operational demands—into a more holistic solution than other design alternatives. Following are some important advantages of this cavern shape:

- A vertical cavern alignment promotes site localization and site investigation. Because the layout is considerably denser in the horizontal plane than is the case for horizontally oriented caverns, there is a greater likelihood of finding a suitable rock formation. The core drilling is made parallel to the long-axis, thereby directly providing relevant information on rock mass characteristics within or close to the proposed cavern(s).
- Caverns having a vertically oriented long axis induce relatively small stress concentrations in the surrounding rock mass. The design improves the stability and allows for a larger span compared to horizontal caverns. The cross-section is easily adapted to the existing horizontal stress field and can be varied from a circular to an elliptical shape. Moreover, several caverns can be arranged to form a compact and appropriate geometrical pattern with respect to geology and rock stresses, as demonstrated by Sagefors and Calminder (1980) and Calminder and Hahn (1982).
- The ceiling area is small relative to the storage volume in comparison to horizontal, tunnel-shaped caverns. Since reinforcement of the ceiling is the most expensive and time consuming of all support efforts, this is very important. Such a design can thus help minimize the reinforcement measures needed.
- The floor area is also small relative to the storage volume in comparison to horizontal caverns. This arrangement yields operational advantages in storing liquids. It permits complete emptying of the storage facility; and, moreover, in the case of petroleum products, it facilitates the cleaning of the wall and floor surfaces and promotes preservation of the product quality.

  Scandianavian experiences in storing oil in unlined horizontal caverns on a waterbed have demonstrated the importance of a good operational performance. Petroleum products are likely to cause sludge deposits to accumulate due to gravitational separation, and quality degradation due to microbial activities (Roffey et al. 1983, 1985). Operational features are important, but thus far have not received proper attention (see Section 4 below).
- Vertically oriented caverns are easy to construct. Large-scale mining methods can be employed without significant modifications. Recent developments in drilling and blasting techniques permit rapid excavation of large volumes (see also Sections 3.3.1 and 3.3.2, below).

Some of the above-mentioned advantages were recognized early, and were included in proposals such as the following:

Polytank — a multi-purpose storage facility (Sagefors and Calminder 1980)

WP-Cave — a high-level nuclear waste repository (Åkesson et al. 1980),

Funnel Store — a large-scale storage concept for petroleum products (Daerga et al. 1986).

Although no truly large-scale vertical rock cavern has yet been realized, the concept is now even more competitive than before. Versatile uses, functionality, well-understood construction methods, consideration of labour safety, and environmental aspects are increasingly important factors that favour a vertical cavern design over a similar horizontal one.

3. Construction Principle of the PBM

Modified large-scale mining techniques are used in the proposed PBM construction concept. The *standard* excavation procedure is described below. The excavation process may be modified if the geological conditions are considered to endanger the stability of the cavern during excavation (see Section 3.4). The essential features of the standard procedure are as follows:

- Only two main working sites per cavern—the top and bottom sections.
- Improved working environment and reduced risk of work-related accidents; limited human exposure to large openings, and no exposure to oil mist or to combustion and explosive fumes.
- State-of-the-art technology for drilling and blasting. More than two-thirds of the total cavern volume is excavated by long-hole drilling and large blasting rounds.
- The excavation cycle is condensed into one large cycle of drilling, charging, blasting, and loading/transportation. Because the unit operations are separated in space but overlap in time, they do not interfere with one another.
- Cost savings and time savings on the order of 20 percent in comparison to vertical caverns excavated by conventional methods.

The excavation procedure is illustrated in Figures 1 and 2. The main phases, in chronological order, are:

1. Conventional excavation of the top (roof) section including drill levels, and conventional excavation of the bottom section including drawpoints and peripheral trench;
2. Excavation of the peripheral bench;
3. Excavation of the core pillar; and
4. Removal of the bottom cone.

3.1 Access

Access can be provided by either a decline or a shaft. The decline alternative implies a downward spiral to the bottom of the planned cavern(s). For a single cavern, the decline preferably should orbit the cavern. Alternatively, if several caverns are to be arranged in a group, the decline may be located in the interspacial rock or encircle the whole group.

The decline/shaft provides headings to the top and bottom sections of the caverns. In shallow locations, the decline can be used to transport the blasted rock. A deeper location suggests that a shaft be used for the hauling operation.

3.2 Preparation of Working Sites

A deeply located single cavern with decline access is basically constructed as follows:

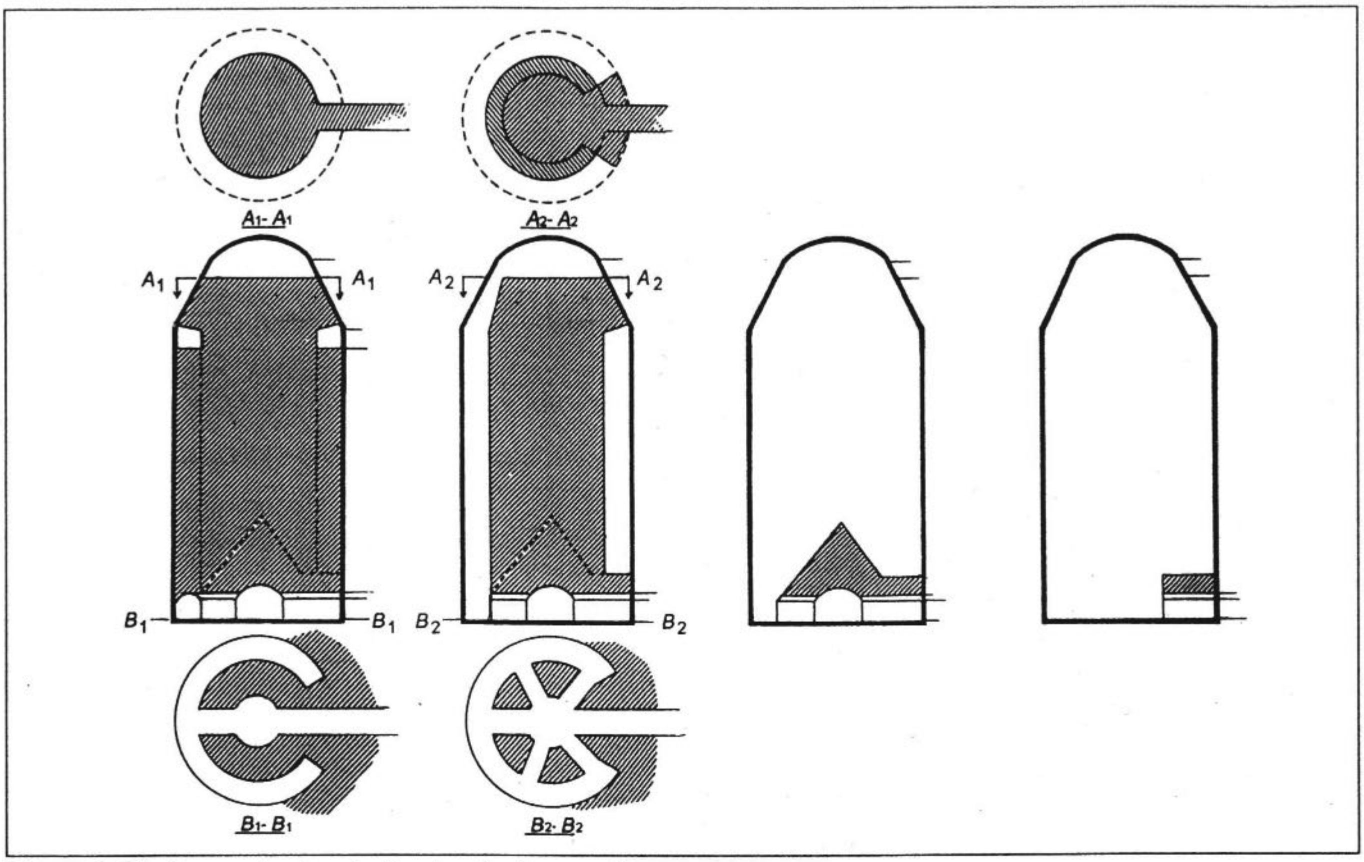


Figure 1. The four major steps in the standard excavation sequence.

The cavern is reached by branch drifts from the decline. Because of the construction scheme employed, only entrances to two regions—the top and bottom sections—are needed for each cavern.

At the top section, drill levels are prepared for the subsequent long-hole drilling operation. The drill levels can be developed in parallel with the remaining decline excavation. When the decline reaches the bottom of the cavern, several simultaneous operations are begun (e.g., shaft boring for haulage of the excavated rock and tunnelling from the shaft location to the bottom part of the cavern). During the construction phase, the tunnel is used to transport the blasted rock; in the subsequent operation phase, it houses equipment for operation and maintenance of the plant.

Typical of the PBM construction concept is that several operations are undertaken simultaneously, thus minimizing construction time and construction cost. The main operations are briefly described in the following subsections.

3.2.1 Top section

A branch drift from the decline gives access to the top section. From the top site, production drilling is performed from two or three sublevels (see Fig. 2). The lowest sublevel is an annular tunnel that encircles the envelope of the cavern, and hence covers the peripheral region of the cross-section. The upper one(s) covers the remaining, central region of the cross-section. A horizontal ring pillar separates the lowest sublevel from the one above it. The vertical distance between the levels depends on the curvature of the ceiling, which in turn is dictated by geological structures and rock stresses.

The ceiling of the cavern is reinforced from the sublevels. The portion that is covered by the intermediate ring pillar can be reinforced from the sublevel below or from the optional multipurpose annular tunnel above. The multipurpose tunnel may also be used for monitoring the roof stability, and for rock mass grouting of both the top section and the envelope wall, if it is considered necessary. The top section is illustrated in Figure 3.

3.2.2 Bottom section

During the excavation phase, the bottom section is given a rather unconventional design: a provisional circular cone occupies most of the space. At its base, it is circumscribed by a horizontal annular tunnel (located right beneath the lowest drill level). The annular tunnel is discontinuous at one point, to provide space for the transportation adit. When the excavation commences, the annular tunnel turns into a trench for disposal of the broken rock. From the annular tunnel, the cone can optionally be shaped by inclined, radially drilled holes to the top of the cone. The holes are preblasted prior to the main excavation.

The rock is extracted from within the cone. In addition to the transportation adit, the cone accommodates several drifts extending radially from the centre out to the peripheral trench, thus creating drawpoints at the points of intersection. The cone directs the gravitational rock flow to the trench, from which it is mucked out at the drawpoints. The arrangement allows for continuous loading under sheltered conditions, similar to the sublevel stoping mining method. The bottom section is depicted in Figure 4.

3.3 Construction Procedure

As noted above, in the PBM construction method the excavation process in principle is reduced to one large cycle. Production drilling, as well as the loading and transportation operations, is executed in a continuous single operation. Charging and blasting are divided into sequential rounds for the peripheral bench, whereas the core pillar is blasted in one or a few massive rounds.

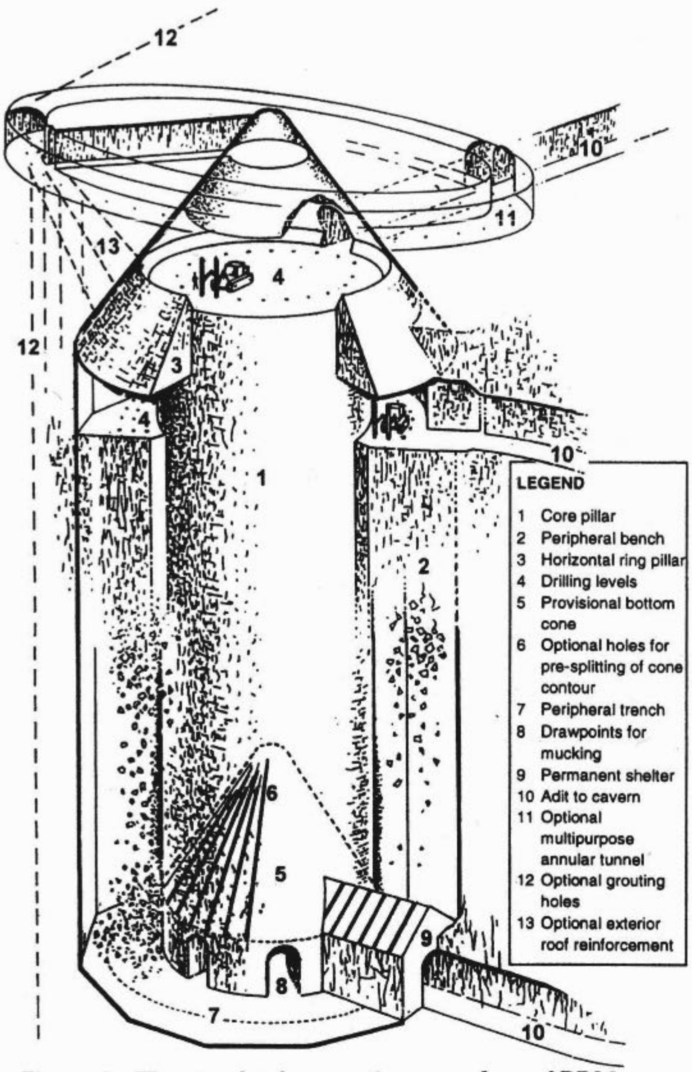


Figure 2. The standard excavation procedure of PBM (Pillar Blasting Method). Drilling is performed from the top section only. The excavation starts with the peripheral bench, continues with the central core and terminates with removal of the provisional bottom cone. The cone directs the gravitational rock flow to the peripheral trench. Mucking and transportation are done from within the cone, under sheltered conditions. (Design: Ivar Sagefors. Drawing: Olle Rydberg. November 1995)

3.3.1 Drilling

The entire body of the cavern is drilled with vertical long-holes, extending down to the bottom section, in a single and continuous operation. As shown in Figure 2, the production drilling is carried out from two or three levels. The drilling operation does not interfere with any other activity.

Because the amount of rock excavated by long-hole drilling, generally exceeds two-thirds of the total cavern volume, considerable cost and time savings can be attained with efficient drilling equipment. Drilling technology has advanced a step further with the introduction of hydraulic in-the-hole (ITH) hammers. G-drill, a subsidiary of the Swedish mining company LKAB, has developed a water-driven ITH hammer called Wassara[1], which exhibits several important features (see Marklund 1994, Miller 1994), including a considerably higher penetration rate (2.5 to 3 times) and a smaller hole deviation than can be attained with pneumatic ITH hammers. Compared to hydraulic top hammers, Wassara's advantages are a significantly lower drill rod cost, higher efficiency, and a considerably smaller reduction in efficiency with increasing hole length.

3.3.2 Blasting

Thanks to recent developments in blasting technology, large blasting rounds may be used for the blasting of the peripheral bench and the core pillar.

Electronic detonators are now commercially available. The ignition system is incorporated on an electronic chip, which corresponds to the pyrotechnical delay unit of conventional interval detonators. The delay time is software programmable and downloaded via a PC. All caps in a round can be assigned individual delay times, with an accuracy of 1 millisecond, ranging from instantaneous ignition to several seconds.

The standard deviation of the delay time is in the range of microseconds, compared to milliseconds with the former type of detonator. The increased time precision results in reduced ground vibrations, improved rock fragmentation, smoother rock contours, the possibility of reducing the size of the explosive charge, increased options regarding the choice of interval times (Svärd 1993) and improved worker safety. Field tests carried out at open-pit mines, quarries and tunnelling projects in Sweden with the electronic ignition system of Nitro Nobel, have shown considerably better control of the blasting sequence as compared to today's prevailing ignition systems. For a given set of

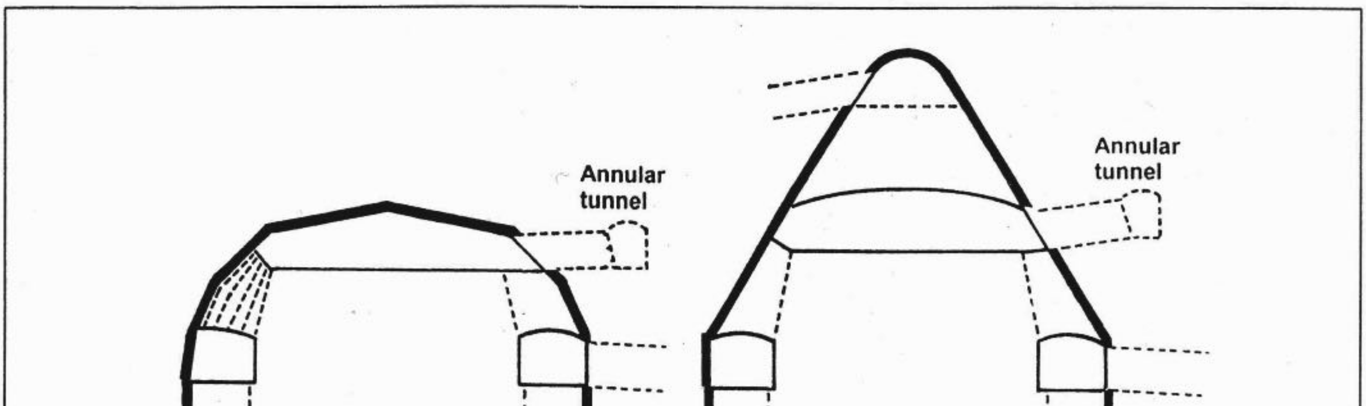


Figure 3. The top section with the drilling levels and the optional multi-purpose annular tunnel. The design of the top section depends primarily on geological and rock mechanics conditions, and can be given a shape in between the two extremes. (a) a low semi-dome; (b) a high cone.

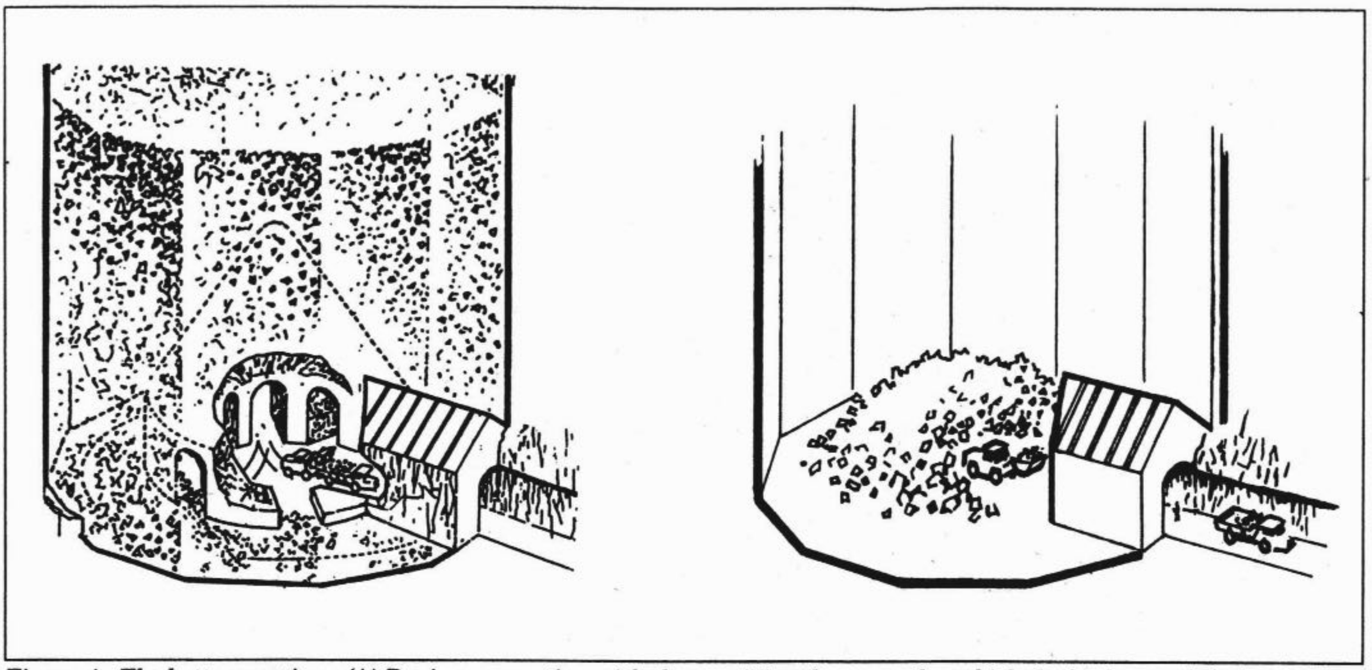


Figure 4. The bottom section. (A) During excavation with the provisional cone under which the broken rock is drawn, loaded and transported. (b) The final stage, clearing up the debris from the bottom cone with a remote-controlled loader.

bench height, hole diameter, drill pattern and blasting round, a smoother rock surface and smaller ground vibrations are attained with the electronic ignition system (Svärd 1993).

When it is applied in PBM construction, for example, the same hole diameter can be used for both the contour holes and the body holes. The use of electronic detonators greatly facilitates the excavation process and enables large rounds to be blasted with good performance, without violating environmental restrictions.

3.3.3 Loading and transportation

Loading and transportation are to be carried out by conventional electrically powered front-end loaders and dumpers, respectively. The compact overall layout of a set of caverns ensured by the vertical cavern alignment creates short hauling distances to the underground crushing station. The volume of rock to be excavated determines whether load-haul-dump (LHD) machines should be used exclusively or in combination with dumpers.

3.4 Limitations and Possible Modifications of the PB-Method

Some limitations of the PB Method are described below:

- The space required for the bottom cone limits the minimum cavern diameter to approximately 30 m.
- The maximum allowable diameter is dictated only by the rock quality.
- The excavation method, based on long-holes and large blasting rounds, places high demands on the drilling equipment and on the ignition system.
- The holes have to be accurately drilled.
- The timing of the ignition system must be precise in order to provide good fragmentation and to minimize ground vibrations.

The excavation process presented in Section 3 is a *standard* procedure intended to be applied in competent rock. However, rock quality may vary widely and the standard excavation procedure may not always be the most suitable. The excavation procedure can be adapted to the prevailing geological features. A tentative strategy is discussed below for some hypothetically unfavourable site conditions.

The most severe situation envisioned is a jointed rock possessing systems of deeply dipping cracks, such that subvertical oriented zones of weakness and heterogeneities may threaten the stability of the core pillar and the final cavern wall. In such a case, the integrity of the core pillar may be enhanced by introducing side-support. If there is only one set of (parallel) deep dipping joints, this can be achieved by leaving a section of the peripheral bench as a side-support in the direction of dip. The excavation of the core pillar is basically identical to the standard procedure, although the blasting sequence and the size of the rounds may be altered.

For the general case, with several sets of joints with deep dip and irregular strike, the situation is more complicated. A plausible strategy is to let the excavation of the peripheral bench move ahead that of the core pillar, in order to create free space for the latter. Hence, the excavation sequence alternates between the bench and the pillar, and the sizes of the blasting rounds are adapted to what is judged to be reasonable.

The blasting rounds always extend the full height of the bore holes. Modification of the excavation process does not involve any changes in the arrangement of the drilling levels or the bottom cone; they are intended to remain unchanged.

4. Operational Features

The operational features are of paramount interest to the client. For bulk storage applications, operational features generally encompass qualities such as ease of filling, ease of emptying, complete emptying, preservation of product quality, easy removal of grime, etc. The last two items are especially important for storage of petroleum products in unlined caverns. More specific requirements may be added to these, depending on the product stored.

Good operational performance is a quality inherent in proper cavern design. Artificial measures introduced after the completion of construction can only mitigate problems with a faulty design. For example, horizontal unlined caverns have demonstrated severe shortcomings when used for oil storage. The combined difficulties of emptying the caverns completely, accumulation of hard-to-remove sludge deposits, and quality degradation due to microbial activities in the oil-water interface because of an overly extensive bottom surface have led to the abandonment of this storage method in Sweden for certain heavy petroleum products and jet fuel.

Vertical cylindrical caverns provide fundamental operational improvements over horizontal caverns. The bottom surface is small relative to the storage volume and the vertical walls are to a large extent self-cleaning. If a cavern is to be used to store several types of products during its time of utilization, cleaning technology from the marine transportation industry can be transferred and applied to rock caverns. Companies like Consilium Marine have a long experience from cleaning of sea carriers, and possess a broad range of cleaning equipments. Figure 5 shows a tentative installation of a cleaning device for oil removal in a vertical cavern.

5. Example of Applications

5.1. Storage of Fresh Water

Access to pure fresh water is a global issue of growing concern. Several countries around the world today are encountering increasing difficulties in supplying the basic need of fresh water. The situation is severe in regions with low precipitation such as the Middle East, southern Europe, Northern Africa, and the Arabian peninsula. But in temperate regions as well, such as continental Europe, the situation is deteriorating as a result of a combination of vast consumption and increasing contamination of surface and ground water reservoirs. The *United Nation Environmental Program (UNEP)* considers the supply of fresh water to be one of the most important global tasks to resolve in the beginning of the next millennium.

A limited number of rock caverns for fresh water storage are now in use, for example, in Hong Kong and the Middle East. These caverns, which are exclusively of the horizontal tunnel-shaped type, are used to store catch water. During rainy seasons, water is captured and stored in the caverns for subsequent consumption. The operational conditions are similar to those for oil storage. River water may contain large amounts of sediments. The combination of organic matter and high temperatures stimulate microbial activity. Since a high degree of self-cleaning ability is a prerequisite for preserving the water quality, a wise strategy would therefore be to design the caverns as vertical chambers in order to minimize the cross-sectional area and to facilitate cleaning and removal of organic slime.

The *Scandinavian Water Environment Council (SWEC)* is developing a logistical system for redistributing large amounts of fresh water from surplus regions to areas of need. Underground storage facilities in the receiving countries will be a substantial part of such a system.

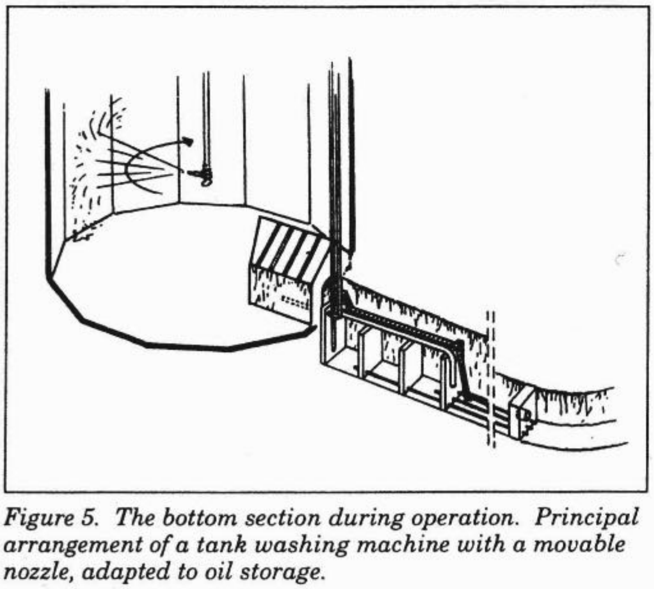


Figure 5. The bottom section during operation. Principal arrangement of a tank washing machine with a movable nozzle, adapted to oil storage.

5.2 Storage of Liquefied Natural Gas (LNG)

For a number of industrialized countries, energy production policy has reached a crossroad. The heavy dependence on fossil fuels such as oil and coal does not comply with the principles of a sustainable society, and counteracts the politically outspoken visions and ambitions of *Agenda 21*. A recent proposal from the EU Commission on a combined CO_2/energy tax, if it is accepted, would guide energy production towards more environmentally friendly sources such as sun, wind, biomass, and natural gas.

Currently there is no apparent substitute that is both environmentally friendly and capable of replacing the prevailing sources of basic energy. The most realistic alternative at present seems to be Liquefied Natural Gas (LNG). Although politically debatable (because it increases the CO_2 content), LNG is readily available and is less detrimental to the environment than both coal and oil. Accordingly, it can be expected to receive increased importance for some countries until other, improved renewable sources and distribution systems for energy supply have been developed.

Since a distribution system for LNG requires buffered storage capacity, economic and environmental considerations point to a subsurface location. It would be most favourable to store compressed LNG at low temperatures, which implies a location at least 500 m below ground surface. The storage technique places high demands on the stability of the rock cavern. The stability requirements and the rock stresses suggest a compact cavern layout, with a large ratio of volume to surrounding area. Vertically oriented cylindrical caverns appear to offer the most beneficial overall solution—one that includes efficient excavation methods and good operational features.

5.3 Hydroelectric pump power plants

Underground hydroelectric pump power plants produce additional electricity to meet peak power requirements. The main components are

- an upper reservoir located at ground surface level;
- a subsurface lower reservoir;
- a subsurface power house with pump turbines adjacent to the lower reservoir; and
- shafts connecting the surface and the underground facilities.

During peak hours, electricity is generated by utilizing the head between the reservoirs. During the following off-peak period, the water is pumped back to the surface reservoir. The economy is based on the difference between peak hour and off-peak period electricity costs. The concept is primarily of interest in markets where the basic energy is produced by nuclear and/or thermal power.

Underground hydroelectric pump power plants place fewer demands on the topography than ordinary schemes, in which both reservoirs are located at ground surface. Consequently, there is more freedom in site location, and the plant has less impact on the environment. Conceptual studies have been performed on plants with power capacities between 1000 and 3000 MW, an operating head in excess of 1000 m, and a storage capacity of several million cubic meters (Bergh-Christensen 1993).

From a geotechnical point of view, a lower reservoir consisting of vertically oriented caverns is feasible and should be more attractive than a reservoir consisting of horizontal tunnel-shaped caverns. A cluster of vertical caverns forms a compact storage with short water paths. The construction aspects described in Section 2 and some of the operational aspects discussed in Section 4 are relevant to this application. The larger the volume of the lower reservoir, the more advantageous is the vertical cavern concept.

From an energy production point of view, however, the vertical cavern concept introduces some disadvantages in comparison to the horizontal cavern concept. The total energy storage capacity is reduced because the hydraulic differential (the distance between the center of gravity for the upper and the lower reservoir at filled up state) decreases as the center of gravity for the full lower reservoir is elevated. Vertical caverns also yield a larger variation in the operating head of the pump turbine in both turbine and pump mode. This slightly reduces the overall efficiency and increases the demand for power input to the pump turbine during pumping.

6. Summary

Large underground caverns place great demands on efficient excavation techniques, operational performance and management (planning and execution).

- Vertical cylindrical caverns are able to accommodate fundamental demands and conditions, such as geology, rock stresses, construction technique, construction cost, and operational demands, in a more suitable overall solution than other design alternatives. Some specific advantages of the vertical arrangement are listed below.
  - A vertical cavern alignment promotes site localization and site investigation. Because the layout is considerably denser in the horizontal plane than for horizontally oriented alternatives, it is easier to find a suitable rock formation. The core drilling, made parallel to the long-axis, provides direct, relevant information on rock mass characteristics.
  - Caverns in which the length axis is oriented vertically induce relatively small stress concentrations in the surrounding rock. The design improves stability and allows for a larger span in comparison to horizontal caverns. The cross-section can easily be adapted to the horizontal stress field and can vary from a circular to an elliptical shape. Several caverns can be arranged to form a compact and appropriate geometrical pattern with respect to geology and rock stresses.
  - The ceiling area is small relative to the storage volume in comparison to horizontal tunnel-shaped caverns. This is very important because it reduces the extent of reinforcement measures needed.
  - The floor area, which is small relative to the storage volume, yields operational advantages when storing liquids. It simplifies complete emptying and cleaning of the storage, and promotes preservation of the quality of the product stored.
- PBM implements today's large-scale mining methods with very little modification needed. Recent improvements in drilling and blasting techniques permit fast and efficient excavation of large volumes of rock.
- The PBM offers good working conditions with respect to labour safety and environmental restrictions, including limited human exposure to large openings, and no exposure to oil mist or to combustion and explosive fumes.
- The PBM makes it possible to modify the excavation sequence, if necessary to satisfy prevailing rock conditions, taking into account the orientation of discontinuities.
- Vertical cylindrical caverns constructed according to the PBM result in cost savings and time savings of the order of 20 percent compared to vertical caverns of equal storage volume constructed by conventional methods of excavation. □

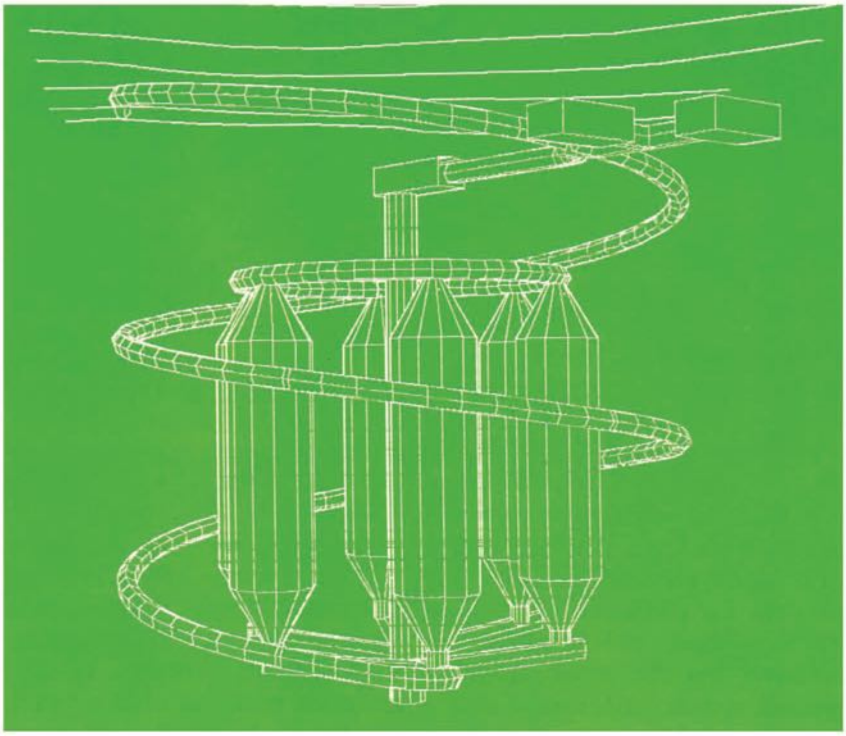
Acknowledgment

We acknowledge the kind cooperation of Consilium Marine AB, LKAB, Nitro Consult AB, Nitro Nobel AB, and Scandinavian Water Environment Council (SWEC).

THE FUTURE

Polytank — a new way of storing oil

An alternative design for oil storage in rock caverns has been put forward by Ivar Sagefors, an engineer with Boliden-Contech, who recommends that each storage unit should consist of a cylindrical rock cavern. This shape has strength advantages, and the diameter can be made very large up to 60 m in sound rock while in theory the cylinders can be any height needed.



CAD-generated view of a 500 000 m³ Polytank storage facility for crude oil. For strategic reasons the control facilities are also located underground.

The surface area of the roof section is extremely small in relation to the total volume, which is advantageous as this section is the most expensive part of the rock cavern to construct. Against this, however, is the fact that the greater depth necessitates longer access tunnels.

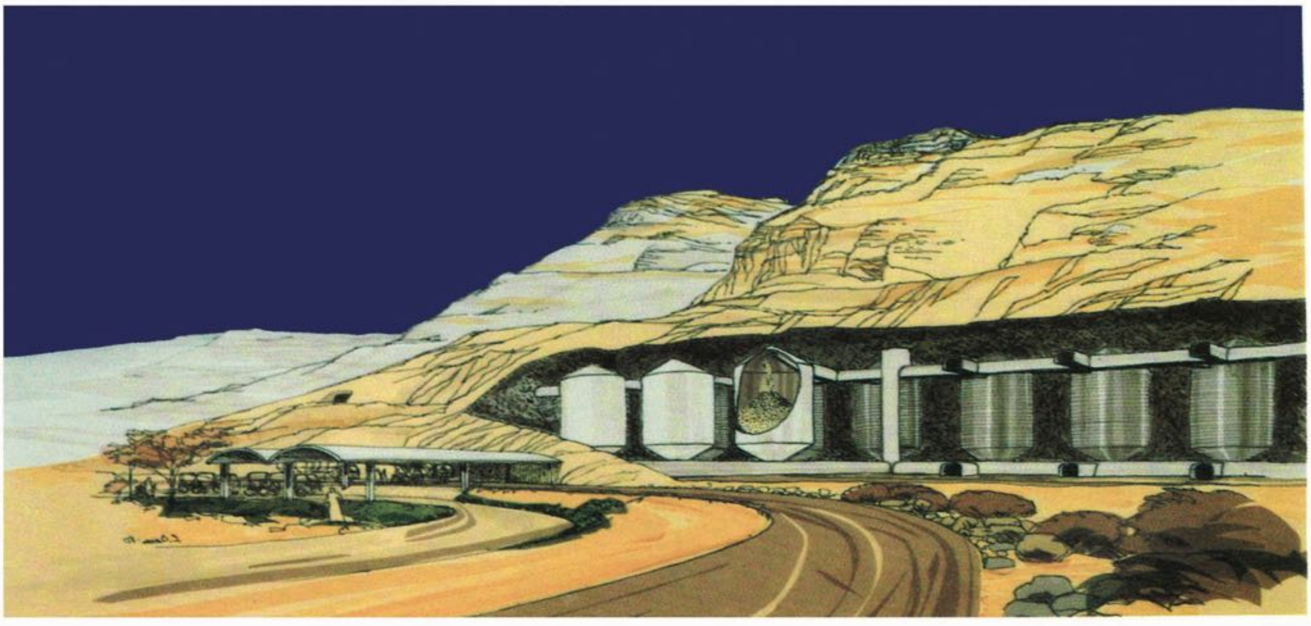
Drilling and charging are carried out from raises, which means safe working conditions, and several storage units can be built as a group, arranged in a hexagon to form a stable and compact installation. This is similar to the silo for nuclear waste built at Forsmark (70 m high and 31 m in diameter).

The position of the water bed at the tap point below the rock cavern ensures that the contact surface between the oil and the water bed is kept small, giving several operational advantages.

In some cases oil products stored in rock caverns have deteriorated due to microbiological activity at the water/oil boundary — a problem familiar from steel tanks containing condensation water. In the Polytank, however, the problem is avoided by minimizing the boundary surface. The design also makes it possible to take care of heavy particles in the oil. In conventional rock-cavern designs — they sink to the bottom as sediment.

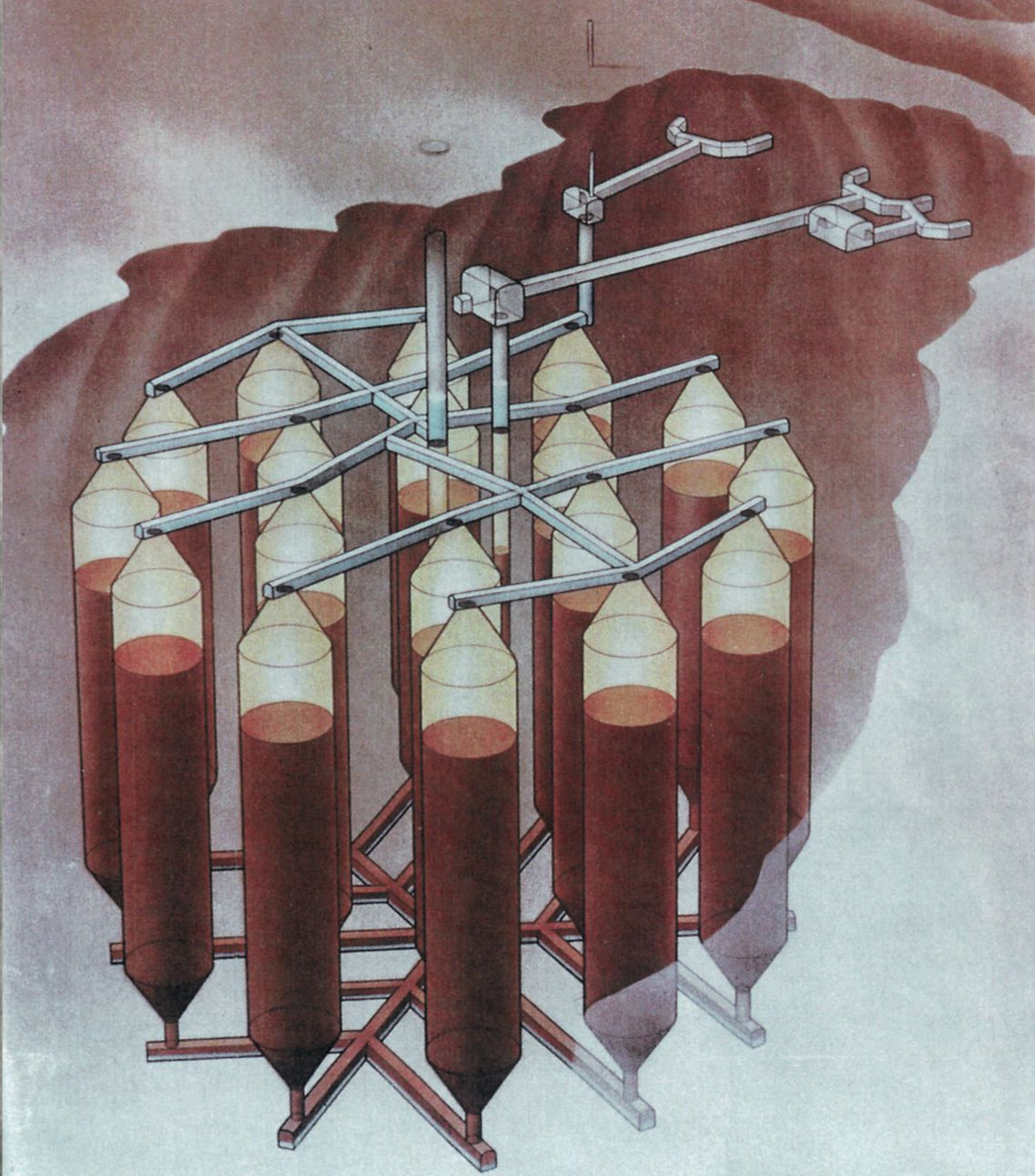
Estimated plant costs are comparable with horizontal rock caverns, and can possibly be lower in sedimentary rock as the dimensions can be enlarged. However, the most important advantages are those concerned with operation.

Suez grain-storage facility



POLYTANK

A
SAFE SYSTEM FOR STORING
OF
SENSITIVE FUELS



RCI AB
SWEDEN

TIDELIUSGATAN 23
11 869 STOCKHOLM

Phone: +46 73 331 00 05
www.rciab.se

design and print: www.intranetcentar.rs