Safe Nuclear Power Plants Shall Be Built Underground

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ABSTRACT

Among first nuclear power plants, a few have been built in caverns, and later this way to a best safety has been abandoned, in spite of its high interest. The history of underground designs and works is recalled, with focus on the rock mechanics side of the problems. For long a taboo had been placed on the span of manmade caverns; the Norwegian Gjøvik ice-rink cavern removed it. Today there are new reasons for a renewal of the concept, any time and place when and where conditions are favourable, the more in countries entering the nuclear power era.

1. INTRODUCTION

Since their beginning, hydropower companies worldwide use to design, build and operate many plants underground. On the contrary, few thermal plants have been placed underground, and the less for nuclear ones. After some early attempts, this alternative looks definitely abandoned, while there are more and more reasons for reviving it. Hydro plants were built underground as soon as 1898 in the United States, then in Europe, and about 1950, they disseminated worldwide. Today Norway harbours about 200 ones, of a world number about 500 (45 in France). Among the biggest ones, the cavern of La Grande main plant, Canada is 22 m wide, 45 m high, 485 m long. Just as this one, many such caverns look like short tunnels, with a height greater than their span. Indeed, their span has for long been kept as narrow as possible, and many have very slender cross sections, looking like key holes (designers did not understand at first that the height may be more critical than the span). Later, caverns for oil storage brought more and more expertise in underground caverns construction and more recently neutrino research is asking for very large (and very deep) caverns. As a Rock Mechanics engineer, the author did discuss elsewhere many aspects of the problem (Duffaut 1982, 1990). As a supporter of underground space use, he wants to call attention to the ability of caverns to accommodate any dangerous plants, beginning wit nuclear reactors.

2. SHORT HISTORY OF UNDERGROUND THERMONUCLEAR POWER PLANTS

In 1960 Norway was the first country to place a reactor into a rock cavern (a 25 MW heavy water reactor at Halden). Norway is known to be world first, in time and/or number, for many kinds of underground works, including undersea tunnels. When the country banned nuclear power, this plant has been kept as a research reactor, up to now part of a European teamwork on nuclear reactor safety.
Sweden and Switzerland followed, about the mid sixties with Agesta, in the Stockholm suburbs, closed 1974, and Lucens between Lausanne and Bern (figure 1a). Lucens was closed after a partial core melt on Jan. 29, 1969. This accident, the first reported in the nuclear power production, did not harm any people nor any part of the environment, thanks to its location underground. All three plants were very small, by reference to surface plants built at the same time (and the more by reference to the today plants).

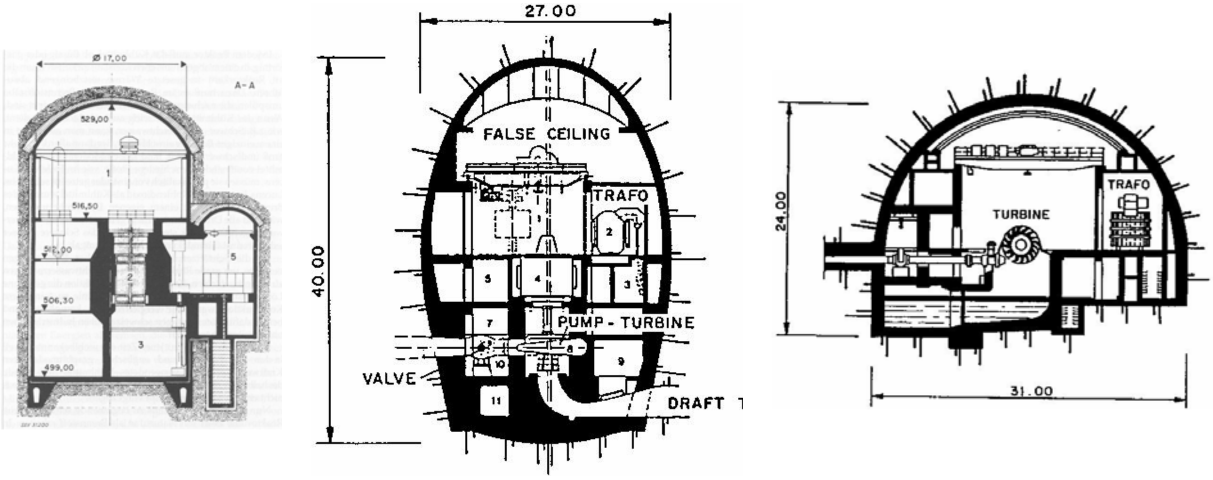


Fig. 1. Three typical cross sections of caverns, at about the same scale: **a:** standard cavern with vertical walls (Lucens nuclear plant, Switzerland, 1966); **b:** ovoid cavern (Porąbka Ĵar hydro plant, Poland, 1974; **c**: full half circle (Cirata hydro plant, Malaysia, 1980).

In 1966, the next step was at Chooz, France, the first underground plant with a significant 305 MW electric output. Only the nuclear parts were placed into two caverns, under rock cover about 70 m, the steam turbines and electric generators being in the valley along the hillside, close to the Meuse river. The reactor cavern span is 21 m, its height 44.5 m (about two times the span), its length 42 m, (also about two spans). This plant, operated from 1967 to 1991, has produced 38 TWh in about 19 years.

In the early seventies, in order to test the feasibility of caverns large enough to accommodate bigger size reactors, a large underground ice-rink was planned, close to Oslo, with a 61 m span. This project had no follow-up because Norway banned nuclear power. It will be revived 20 years later (see below).

In 1977, Ontario Hydro, a power company in Canada (Oberth, Lee 1979, figure 2) launched studies for a large underground project, four 850 MW CANDU reactors, 300 m deep in the Precambrian granite-gneiss basement, on the north shore of Lake Ontario; each one into its own cavern, 30 m x 40 m x 60 m high. No steel or concrete vessel was to be provided as the ground was supposed competent enough to contain the pressure in case of any accident, thanks to the high horizontal stresses in the Ontario bedrock; the depth offers a natural water head for the emergency coolant injection system. The machine hall is buried in an open pit excavation for aesthetic reasons, with its roof flush with grade level. A geotechnical test program has been performed, close to the Darlington surface plant, focusing on strength, fracturing, permeability and state of stress. Though all tests and analysis proved favourable, this fully elaborated project was unfortunately abandoned.

After a, general review by Watson et al (1975), the German government invited a conference in March 1981 on "Underground construction of nuclear power plants", 240 participants from 12 countries met in Hanover (Pahl, Schneider 1982) and discussed 36 papers on current research activities in this field. Main advantages quoted were the better protection of both the plant and the population, and the extended choice of possible sites. Certain financial and technical aspects concerning the operation of the plant would also be advantageous. To accommodate a reactor about 1000 MW, a span in the 60 m range was supposed to be needed. Two main concepts presented and compared were a true cavern at depth and an earth covered open cut (figure 3 left).

3. THE TABOO ON WIDE SPANS BEFORE THE GJØVIK CAVERN

Many drawbacks played against underground plants, such as cost and delay of works, geological uncertainties, etc. But the main one seems to be the fear of wide spans: most underground man-made caverns had spans below 20 m, a few reached 25-30- 33 m (figure 1 b,c and Hoek, Brown 1990).

In Sweden, the "Rib-in-Rock" method for the safe excavation of big caverns even in case of a rather poor rock mass had been presented at the first "Rockstore" Symposium (Sallström 1977, figure 4 left):

in the first phase a lot of "ribs" are bored in vertical planes around the future cavern (small cross-section galleries and shafts filled up with concrete) providing a safe ground for the cavern excavation. The 1994 Winter Olympic Games provided the opportunity of reviving the Oslo ice-rink project. Just behind Gjøvik city, the cavern was dug inside a granite hill, yet accommodating a swimming pool and smaller caverns for telephone switches and safety services. The arched roof cavern (figure 4 right, down) is 61 m wide, 25 m high and 91 m long, to provide 5800 seats around the rink ; by far it is the widest man made span in the world for a permanent civil cavern built to receive people. The rock cover is about 25-50 m (less than the span). The rock quality was well known through former caverns, and no surprise was met during the works. The stability has been studied by two different teams with the latest methods available, but not any change has been brought to the initial design: the shape and support does not differ in any way from those of the many smaller caverns built in Norway. The only support is a fibre reinforced shotcrete layer, 10-15 cm thick, plus 6 m rock bolts at 2.5 m spacing). The excavation (165 000 m^3) took 8 months (6 less than scheduled). Formally opened by the King in May 1993, it hosted 16 hockey performances during the 1994 Olympics, without any problem. This successful experience has definitely abolished the taboo on wide spans.

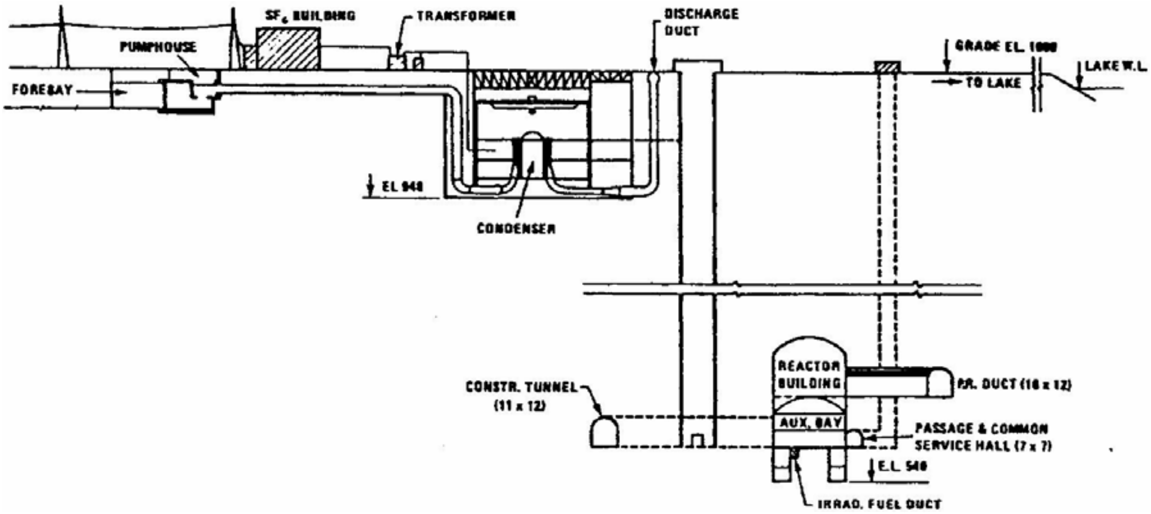


Fig. 2. General cross section for an underground CANDU power plant (after Oberth, Lee, 1979).

4. SHAPES AND SIZES OF CAVERNS, TENTATIVE UNDERGROUND ARCHITECTURE

4.1 Cut and cover or true cavern? The Myrrha project

In Belgium, a partially or totally underground facility is currently studied with name MYRRHA, Multipurpose hYbrid Research Reactor for High-Tech Applications (De Bruyn et al, 2006). In this new type of reactor, ADS, Accelerator Driven System, the neutrons produced by a particle accelerator control the spallation of a target in order to burn nuclear wastes and to manufacture radioactive materials. The initial design of the whole building, 100 m long, 30 m wide, 40 m high, is embedded 30 m below grade, with superstructures 11.4 m high. This partially underground location has been chosen for overall safety with two alternatives studied for a better safety level (figure 3, right):

- a 10 m earth cover on the top of the building,
- a true underground location, which may call for a different organization of non nuclear parts.

These designs recall the German projects presented at the Hanover conference; and the paper discusses the construction methods available for each solution, which are out of the scope of this report. Clearly a true cavern only is acceptable in a competent rock ground.

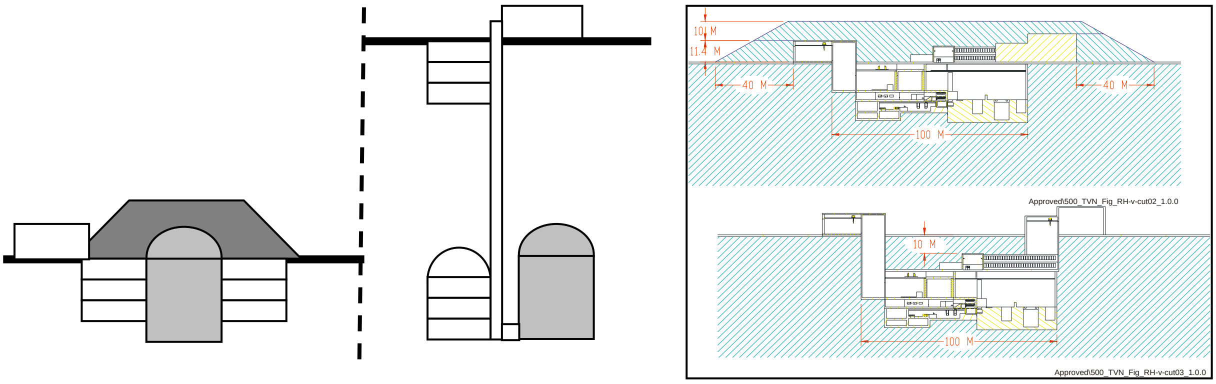


Fig. 3. Left: main Hanover concepts, either earth covered pit in soft ground, or deep cavern in rock, in both cases, the machine hall keeps at grade; Right: Belgium MYRRHA concepts, either earth covered or fully underground (De Bruyn et al, 2006).

4.2 Cavern shape and Rock mechanics

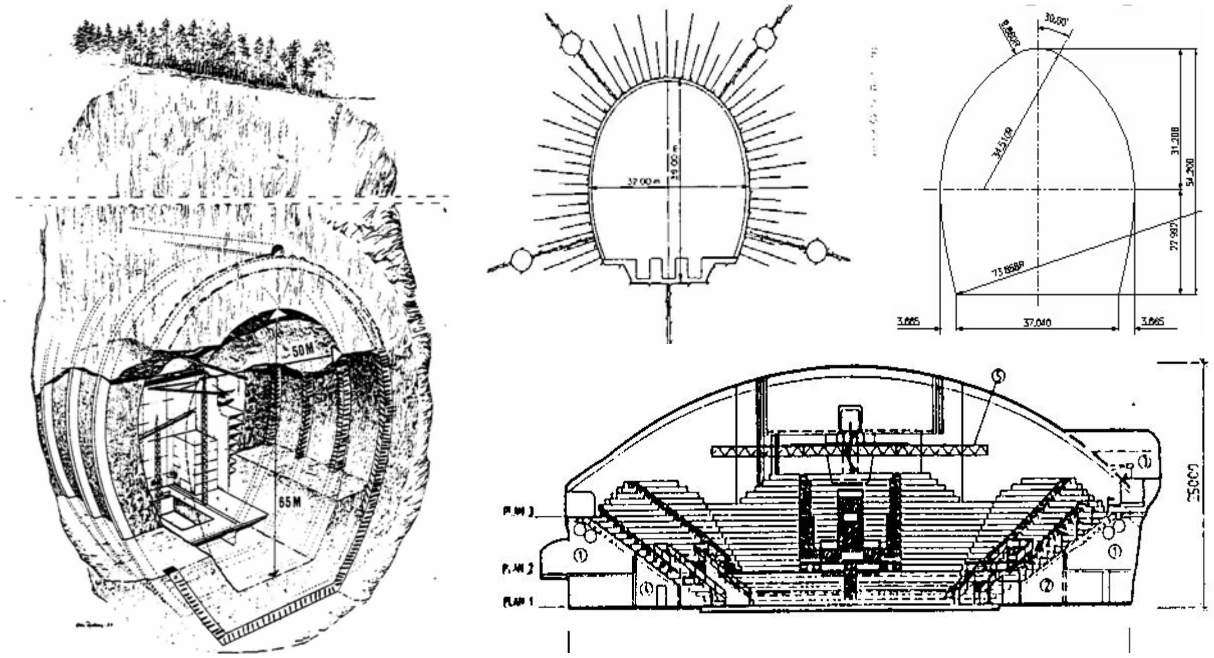
Natural caves show far bigger spans than any manmade cavern: they split into two groups, depending on the ceiling shape: either along a bedding plane, with spans no more than 100 m, or roughly arched, with spans extending more farther (about 400 m in the largest known room cave today, Lubang Nasib Bagus, Sarawak, Indonesia. Mining voids are excavated along the structure, to remove the valuable material of e.g. a coal seam. Such natural limits, like stamps between perforations, give the voids a better stability. Many chambers left by mining span 100 m and more (Tytyry limestone quarries, Finland, iron ore mines in Newfoundland, Canada, and May-sur-Orne, French Normandy, etc.

The shape of civil manmade caverns (energy plants, fuel storage, military purpose, etc.) first depends on their use, what it will have to accommodate, then on Nature, the ground structure and the stress field, and lastly on the working methods. As far as possible, the direction of a long cavern must be chosen at right angle with the dominant structural planes, bedding or fractures. Except the case of caverns along bedding planes, as well sharp angles as plane walls (as on figure 4 right) are to be replaced by curved surfaces with slowly changing radiuses, in order to minimize the stress concentrations. In rock masses without a conspicuous structure, the best natural stability is obtained by vertical shafts or horizontal tunnels with circular cross-section (or elliptic where principal stress components in the perpendicular plane are very different). Blasting favours plane walls and cylindrical ceilings. Tunnel boring machines provide circular cross sections below 15 m diameter. Roadheaders have been used for metro stations and storage caverns up to 8x12 m cross section.

Excess of stress may become a problem in overstressed rock masses and in very deep tunnels or caverns. A general way of tackling them is to make radial cuts (through close parallel drill holes), but this method cannot be extended to very large cross sections; after Lombardi (1986) and Duffaut (2005), the cuts may be replaced by small galleries all around the perimeter and their efficiency will be the better in plastic grounds. Seismic and heat stresses (in case of gas release from a nuclear plant) may be controlled by cuts (Oberth, Lee, 1979).

5. BEST SAFETY THANKS TO UNDERGROUND LOCATION

Rock caverns provide together containment of any explosion and gas release (protection of the Environment against dangerous phenomena from inside the plant), and protection of the plant against menaces from outside, either natural (hurricanes, flooding, slope instabilities, seismic motion, volcanism) or man induced (intrusion, bombing, missiles, aircraft collision, spiteful actions and terrorism). A cushion of crushed rock may be used for cooling and condensing the gases from a failure of the containment. This twofold protection also holds good for any dangerous factories & depots, nitrate fertilizers, explosives, etc. (Duffaut, 2002, following the Toulouse AZF factory explosion).



RIB in ROCK: sketch of a construction method for a very large cavern in poor ground Sallström, Sweden, 1977

above: left, design of a cavern for a neutrino lab in Italy, Lombardi, 1986, right, cavern for neutrino detection in Japan, Nakayama, 2005
below: cross section of the Gjøvik cavern, as built, 1994

Fig. 4. Designs of 3 very large caverns, all ovoid cross section, compared to the wide span ice-rink.

The class 9 accident implies a total core melt, a case no containment can survive without being breached. David Willett, vice president of Acres US Company (1980, a leading civil engineering firm in the US), recalls that the experiments on nuclear weapons have proven the ability of the ground to sustain very high pressures and temperatures (these experiments were carried out at the Nevada Test Site into volcanic tuff over the water table, at depths from tenths to hundreds metres). Instead of the "Chinese syndrome" a molten mass will stay there for a long time, losing along the years temperature and radioactivity without any harm on the surface environment.

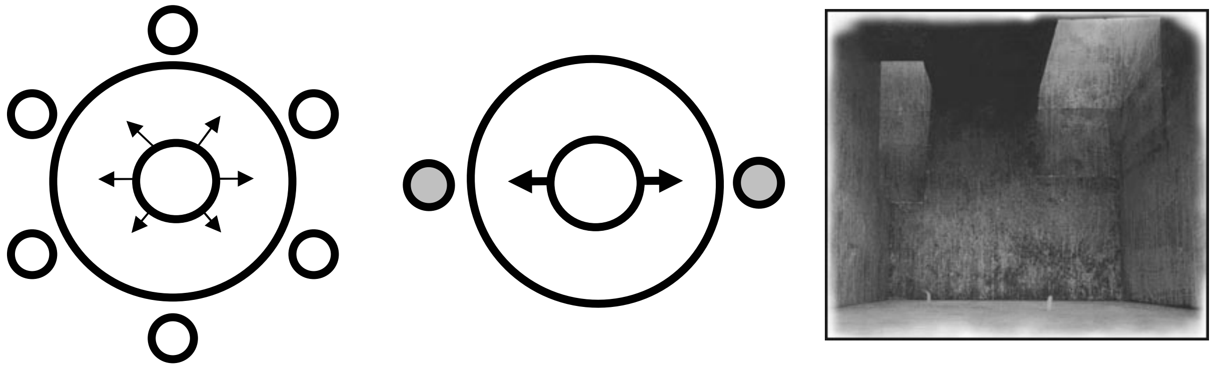


Fig. 5. Left: From destressing cuts around a tunnel to destressing tunnels around a cavern; centre: with an anisotropic stress field, one pair of cuts, or tunnels is enough; Right: proposed cavern by sculptor Chillida (close to a cube, about 40 m side, plane faces, sharp angles, just what is not to do).

6. SUPPORTS AND CONCLUSIONS

In France, in the early seventies, a leader in the prestigious newspaper "Le Monde" by Robert Poujade, world first ministry of the Environnement, urged to build all nuclear plants underground in order to escape any impacts. Before any (reported) accident had occurred, that was an early application of the precaution principle. At the international level, top Russian scientist Andrei Sakharov stated in his preface to Medvedev book that mankind cannot ban nuclear energy and he called for an international legislation imposing all nuclear parts be sited underground. There is an increasing society pressure for decentralization and scale reduction: smaller power stations could be considered, including in the range 10-20 MW as in warship propulsion, close to the cities, providing both hot water and power, with less power transmission lines and less transportation losses.

Nuclear power plants can be placed underground. Therefore, nuclear power plants must be placed underground everywhere suitable conditions are available. Just as for high and steep slopes, the stability of large caverns cannot be proved through any analysis, whatever the accuracy of data collected and the reliability of the behaviour model. The same occurs for high and steep mountain slopes. For sure, natural peaks and large span natural caves cannot stand indefinitely but the long term of Nature has no common measure with the life of engineering structures. We must recognize that there are very few groups and specialists in the world with enough expertise to emit conclusions neither evasive, nor questionable. Each new project is a prototype (a monotype) requiring a close adaptation to the natural site just as is made for large dams. A great confidence is needed on the expertise of teams in charge of the design and the worksite (You, Vaskou, 2002).

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