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ROCK SITING
OF
NUCLEAR POWER PLANTS
FROM A
REACTOR SAFETY STANDPOINT

Status Report
October 1974

CDL

Centrala Driftledningen –
a Joint Organization of Major
Swedish Power Producers

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Contents **Page**

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1. Outline and Commentary

The power requirements of a war situation are lower than those of peacetime. Should the power consumption rise according to the forecast published by the CDL in 1972, it would be desirable to be able to operate some nuclear power units during a war situation from 1985 and on. To protect these from air attacks siting underground, in rock cavities, can be considered.
A study completed earlier this year conducted by the CDL in co-operation with the Swedish Defence Staff, has shown that siting in rock cavities is technically feasible. Before deciding on siting nuclear power plants underground from war-protection or other reasons, the advantages and disadvantages from a reactor-safety point of view must be clearified.

On May 30, 1974, the CDL therefore appointed a study group to investigate these matters. A first stage of the study is accounted for in this report. The principles and design presumptions in the report are preliminary.

According to the instructions a BWR-type unit of 1000 MW electric power has been studied. A PWR-type plant will be treated in the following stage.

During the present study the general consequences of rock siting from a reactor safety point of view are investigated. The possibilities for further improving reactor safety beyond the level presently accepted by all countries constructing nuclear power plants above ground will also be studied.

In order to enlighten the differences in safety between the two methods of siting, also serious and very improbable accidents must be studied. Accidents with reactor pressure vessel rupture and core melt-down will be discussed, which they also were in the government study on urban siting [x/].

[x/] SOU 1974:56, with 30 p. summary in English.

Investigations of the mechanical stability of the rock, and the draining conditions have been started, and a more accurate evaluation will be made. The risks for falling rock must be convincingly proven to be very small. Rock siting requires new designs in certain aspects, e g for the case where the rock is used as containment.

To achieve maximum safety against disruptions of all kinds it is desirable to use reliable and preferably standardized designs and components. The study group has therefore judged it to be important to use established technology and to strongly limit system alterations from now existing reactor designs.

The study group judges it probable that a rock sited plant can be given the same level of safety against activity releases at the established design basis accidents (DBA) as an above ground plant. A clear advantage for the rock sited plant is the good protection against external impact and external sabotage.

The safety at accidents more serious than the DBA is more difficult to assess. Generally rock siting should give better possibilities to contain the released activity for the first period of time after such an accident. After a longer period of time the conditions are hard to assess. It is, however, probable that rocksiting gives larger prospects for reducing the activity releases, as does siting above ground.

The influence of siting nuclear power plants in rock on operation, maintenance and communications etc has been discussed by the study group. An assessment of these questions must await a more thorough study of the technical design of an underground plant. The problems seem soluble with a satisfactory safety, but it is likely that an underground plant requires somewhat larger operational staff than a plant on ground level.

At the places in Sweden where nuclear power plants are under construction siting in rock is hardly feasible due to topographic and ground conditions.

The costs for siting in rock with improved reactor safety will be assessed more accurately towards the end of this study. It is, however, likely that the extra cost compared with the cost for an above ground plant will be more than that of the war-protected nuclear power plant presented in a previous CDL-report, having an additional cost of approximately 12 %.

Closing down a nuclear power plant is made easier with an underground plant. This question will be further enlightened by the continued study work.

Summarily it can be established that siting a nuclear power plant underground has advantages from a reactor safety point of view, e g protection against external impact and external sabotage, as well as prospects of reducing the consequences of extreme, very improbable accidents. These advantages are counteracted by problems due to the technical design of the plant and its operation and maintenance, which will be enlightened in this report.

A nuclear power plant above ground can also be improved from a reactor safety point of view. Additional safety systems can be considered, stronger concrete constructions can be chosen to reduce the effects from external impact and a development towards reactor pressure vessels in pre-stressed concrete has been discussed to give better safety. Siting a nuclear power plant in rock is thus only one of several methods of reducing the consequences of serious and very improbable accidents.

2. Instructions and work order

The board of the CDL appointed on May 30, 1974, a group to study siting of nuclear power plants underground in rock from a reactor safety point of view. The CDL had earlier, together with the Defence Staff, studied war protection of nuclear power plants. The new study should be completed in one year's time. The work was to be planned so that a status report could be presented in October 1974.

A rock sited 1000 MW electric power BWR-type unit should be studied on the first stage. Later also the PWR alternative should be treated.

The aim of the study is to clearify the advantages and disadvantages of an underground nuclear power plant from a reactor safety point of view, compared to a plant above ground. Principles and principal solutions for the rock alternative are to be presented. Also questions of sabotage and closing down the plant at the end of the operational period are to be treated.

The study is to be completed by summer 1975. By then sufficient data are to be available to make an assessment of the feasibility of rock siting of nuclear power plants.

The study group consists of the following members:

Ingvar Wivstad	Statens Vattenfallsverk - The Swedish State Power Board (chairman)
Tord Lindbo	Statens Vattenfallsverk - The Swedish State Power Board
Ebbe Forsgren	Statens Vattenfallsverk - The Swedish State Power Board
Emil Bachofner	Oskarshamnsverkets Kraft-grupp AB - Oskarshamn Power Group, OKG
Rune Overup	Sydsvenska Kraft AB - The South Swedish Power Co Ltd
Per Almqvist	Stockholms Energiverk - Energy Supply Authority of Stockholm

Additional contributors to the study are:

Statens Kärnkraftinspektion - Swedish Nuclear Power Commission through	Arne Hedgran Tore Nilsson
AB Atomenergi - Atom Energy Company of Sweden through	Lars Carlbom Kjell Johansson
Vattenbyggnadsbyrån AB - V B B through	Kurt Eriksson Rolf Lindskog Staffan Lagergren
AB ASEA-ATOM through	Cnut Sundqvist
Statens Vattenfallsverk - The Swedish State Power Board through	Anders Bergström Karl-Erik Sandstedt

Nuclear reactors have previously been sited in rock in Sweden, Norway, France and Switzerland. They have all been experimental or prototype plants. Numerous studies on underground siting have been made, but most of them have a survey character.

The question has lately gained renewed actuality. In January 1974 the IAEA organized an expert symposium on underground siting of nuclear power plants. In Sweden the question has been actualized from a war protection point of view.

The study of safety and design questions has been based on different accident scenarios with their consequences. The study group has based its work on a general plant design, that was presented by the previous CDL-study on war protected rock siting of nuclear power plants. Another starting point has been the use of conventional reactor systems used in above ground plants. The work is conducted in contact with different organizations in Sweden, Norway, Germany and the United States.

3. Aims and design presumptions

The aims for the study from a safety-technical point of view are that the plant should be war-protected, that the safety level of the above ground plant is maintained, that no unacceptable new risk factors are introduced, and that the opportunities of increasing the safety are taken care of. These generally formulated aims are specified during the course of the study, as for example the calculations of the dimensioning loads.

The study work is based on a general design in which the reactor and the central auxiliary systems are placed in a special cavity, designed as a containment. Estimations of loads on the rock cavity containment from improbable reactor accidents have been made, and preliminary designs have been drawn up.

A general principle has been to keep, to the largest possible extent, the same design of systems and components as in an above ground plant. This to avoid introducing more new technical problems or untried designs than necessary.

A primary presumption has been to maintain a conventional reactor containment of Pressure-Suppression (PS) type. Some reduction in the demands for strength and tightness may be possible, with respect to the new barrier that the cavity wall represents.

The cavity can be designed to serve as containment at more serious accidents. The largest loads on the rock containment are anticipated to be in connection with a reactor core melt-down. In such a case large portions of the fission products are discharged from the core as gases or aerosols. The foundation for judging possible scenarios at such serious accidents is very incomplete. Therefore, conservative assumptions have been used in the assessments made.

At improbable, serious accidents missiles may be discharged, that affect the rock containment. Shock waves may also occur in the atmosphere of the cavity. The discharged steam at such accidents gives a pressure on the walls, which however is reduced by condensation on the concrete areas in the cavity after one hour or so.

Malfunction of the ordinary core cooling systems combined with failure of several safety systems may lead to a core melt-down that starts within approximately one hour. If the melt, or parts of it, with a temperature of some 2500° C falls down into the water that may be left on the bottom of the reactor tank, or into the lower parts of the containment, violent steam explosions may occur under certain conditions. Such steam explosions may cause missiles. Short lasting shock-waves and built-up pressure and temperature would also be caused.

At the high temperatures that come with the absence of core cooling and possible meltdown of the core metallic materials, primarily the zirconium alloy enclosing the fuel, will react with steam forming hydrogen gas. The amount of hydrogen may under unfavourable conditions be large, but it is probable that it is ignited by the hot fuel and combusted gradually. This will build up pressure and temperature in the cavity. The formation of hydrogen will be slowed down when the metal surfaces are covered by oxides from the reaction with steam or atmospheric oxygen.

The accident scenarios mentioned above are extremely improbable, and also difficult to calculate. Using conservative assumptions the study group has made assessments and calculations on the maximum credible dynamic loads from missiles and pressure on the rock containment that occur during different accident situations. These assessments and calculations give the conditions for the dimensioning of the plant from a strength point of view.

The load on the cavity from long-term pressure situations is significantly lower than what may occur shortly after a serious accident. A lasting high temperature, may, however, need attention for the dimensioning. It is presumed that the cavity is cooled through a spray system a few hours after an improbable, serious accident.

A long-term pressure situation may, however, determine the demands on the tightness of the cavity. The aim for the dimensioning of the containment is to keep the leaks to the environment lower than one percent of the contained volume per day. The ambition must be to keep this tightness even if the containment should be penetrated by a melted core.

4. Preliminary proposal for the technical design of a rock sited nuclear power plant

The study group has as stated outlined a proposal for the technical design of a rock sited nuclear power plant. The necessary rooms are placed in five cavities connected by communication tunnels. Three cavities containing auxiliary power equipment and control room with staff accommodations, reactor with auxiliary systems and equipment for waste treatment and workshop are placed in a row. The other cavities are parallell to the above mentioned and contain turbine with auxiliary equipment and cooling water systems together with diesel building. The rock cover is about 50 meters thick.

As a result of the demand for extended safety at serious accidents the reactor and its auxiliary systems have been placed in a separate cavity that will be strengthened and tightened to reduce leaks to surrounding areas even at these serious accidents. The equipment in the reactor cavity is similar to that in a conventional BWR reactor building type Forsmark 1.

The rock surface is given a reinforced concrete plaster with sufficient thickness to maintain the integrity and tightness of the cavity even if the surface is penetrated by missiles and pressure from an improbable serious accident with a melted core. The thickness of the concrete layer should be 0.5 to 3 meters for different parts of the cavity. Some form of plastic or steel lining will probably be needed as leakage barrier. There are high demands on the design of penetrations for piping and cables. Transport openings must be given missile protected locks. Experiences from bomb-shelters indicate that such penetrations and locks are technically feasible.

Penetrations for ventilation requires special considerations. They may for example be given shock wave valves similar to those used in bomb shelters, completed by fast closing isolation valves. The fans are placed outside the reactor cavity and intake and outlet go through a high chimney to prevent possible activity releases on ground level. The demands for smoke ventilation after a fire must be met.

To avoid ground water pressure on the back side of the concrete plaster, the rock around the reactor cavity is drained through a system of drilled holes a few meters into the rock. This system may be completed by a draining system in the concrete plaster between the lining and the rock wall. The draining system may also be used to handle possible leaking activity after a serious accident.

The rock has a tightening and delaying function on possible activity leaks. Leakage is only possible through cracks in the rock. The mineral itself is tight. If the cracks are filled with ground water the leakage is reduced, and may theoretically be totally prevented if the ground water pressure is sufficiently high. By adding water to the rock through a system of drillholes and tunnels the cracks in the rock may be kept full of water to give a tightening curtain in the rock. Such a curtain may complete other tightening measures. The curtain may, however, cause increased water problems in the cavities of the plant during normal operation. The value of the curtain probably has to be verified in a reduced scale experiment.

At extreme reactor accidents with melted core it is possible that the melt penetrates the bottom of the containment. According to a recently presented American study (Wash - 1400) this is not a serious safety problem. The study group will investigate this question further.

The safety systems in an underground plant should in large get the same designs as in an above ground plant, but with some supplementary equipment. For the long-term cooling after an accident the cavity is supplied with a spray system as stated above.

To guarantee the tightness of the cavity penetrating piping must be equipped with isolation valves. The piping to the reactor also passes the PS-containment where isolation valves are mounted, as is the normal above ground practice. It is necessary to study further how the containing function is to be devided between the PS-containment and the rock containment.

5. Special issues

Size and design of the rock cavity

The proposed cavities have spans, that exceed those now constructed. Since rock siting of nuclear power plants require high quality rock the study has judged it possible to construct cavities with the required spans, over 40 meters, by using a number of strengthening methods. The quality of the rock must be at least second highest grade on a five grade scale. The quality can be determined through comprehensive geological studies, drilling of probe holes etc. The rock is presumed to be granite or gneiss, which dominate the Swedish primary rock. From a rock-mechanical standpoint a design with an oval level section is preferable to a rectangular, whereas a rectangular section is better from a layout point of view.

Safety against falling rock

Since falling rock may cause accidents in nuclear power plants this issue needs special attention. The study group will calculate the probability for rocks to fall to put in relation with other probabilities for accident causing events. A Swedish study shows that the falls in unplastered cavities and tunnels usually were caused by layers of foreign material, such as clay, in the rock. Falling rock is not known to occur in concrete plastered cavities.

To reach adequate safety against falling rock different independent measures can be taken to strengthen the surfaces. The rock can be secured with a large number of independent prestressed bolts together with different concrete supports on the inside. The risk for earthquake must be considered.

Steam pressure relief at pipe rupture

In the case of a pipe rupture in the cavity the safety systems must be protected from effects of the rupture, such as steam releases. At an external pipe rupture, for example in the turbine hall, in an above ground plant the steam is relieved directly to the surroundings through hatches in the turbine hall wall. In an underground plant the pressure relief can be arranged through some transport tunnel, that then is unusable for staff evacuation.

Fire

The risk for fire is not judged to be larger than of an above ground plant. Fire fighting is, however, obstructed by lower accessibility. Evacuation facilities for the staff and ventilation of smoke fumes are issues to be given consideration.

Sabotage

Siting underground gives larger protection against external sabotage actions. As for sabotage by staff with access to the plant there should be little difference between rock and above ground siting.

Operation and Maintenance

Operation and maintenance of an underground plant are judged to require somewhat more personnel as an above ground plant. The longer walking distances may require larger shift groups and also more maintenance personnel.

Unplastered rock surfaces may require some observation and scaling while maintenance of buildings due to weather penetration is not needed. Overhaul operations will require more personnel due to lower accessability and a more difficult transport situation for personnel and material. Demands for safe evacuation facilities affect planning and carrying out of overhaul.

Closing down

Dismantling of non-active systems in a nuclear power plant can be done practically immediately after termination of operation, while the dismantling of central reactor systems may have to wait, for economic reasons, a few years until the activity is reduced. Neither can the buildings surrounding the active components be torn down immediately.

The study group has started an investigation of the cost for a total dismantlement of an above ground plant. Important conditions are the value of recovered material and whether certain active components can be deposited at the site.

An advantage for the underground plant is that dismantling of the equipment and tearing down of the buildings are not necessary to restore the landscape.

An underground plant, as well as an above ground plant, can in principle be sealed off after closing down, but both types require some recurrent control.

Location

In addition to the demands on a site for a nuclear power plant above ground, siting in rock raises demands for a mountain of sufficient size and quality.

It would be desirable to locate a first underground plant above the recipient level. Sufficiently high mountains (100 m) for siting above sea level near the coast are available in Sweden only on the West coast and the Northeastern coast and on isolated spots on the Baltic coast.

Siting below the recipient level gives a risk for flooding the plant, which probably can be mastered, however, at extra costs. A reduced demand for high level rock gives a larger number of possible sites.

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SOU 1974:56, with 30 p. summary in English.

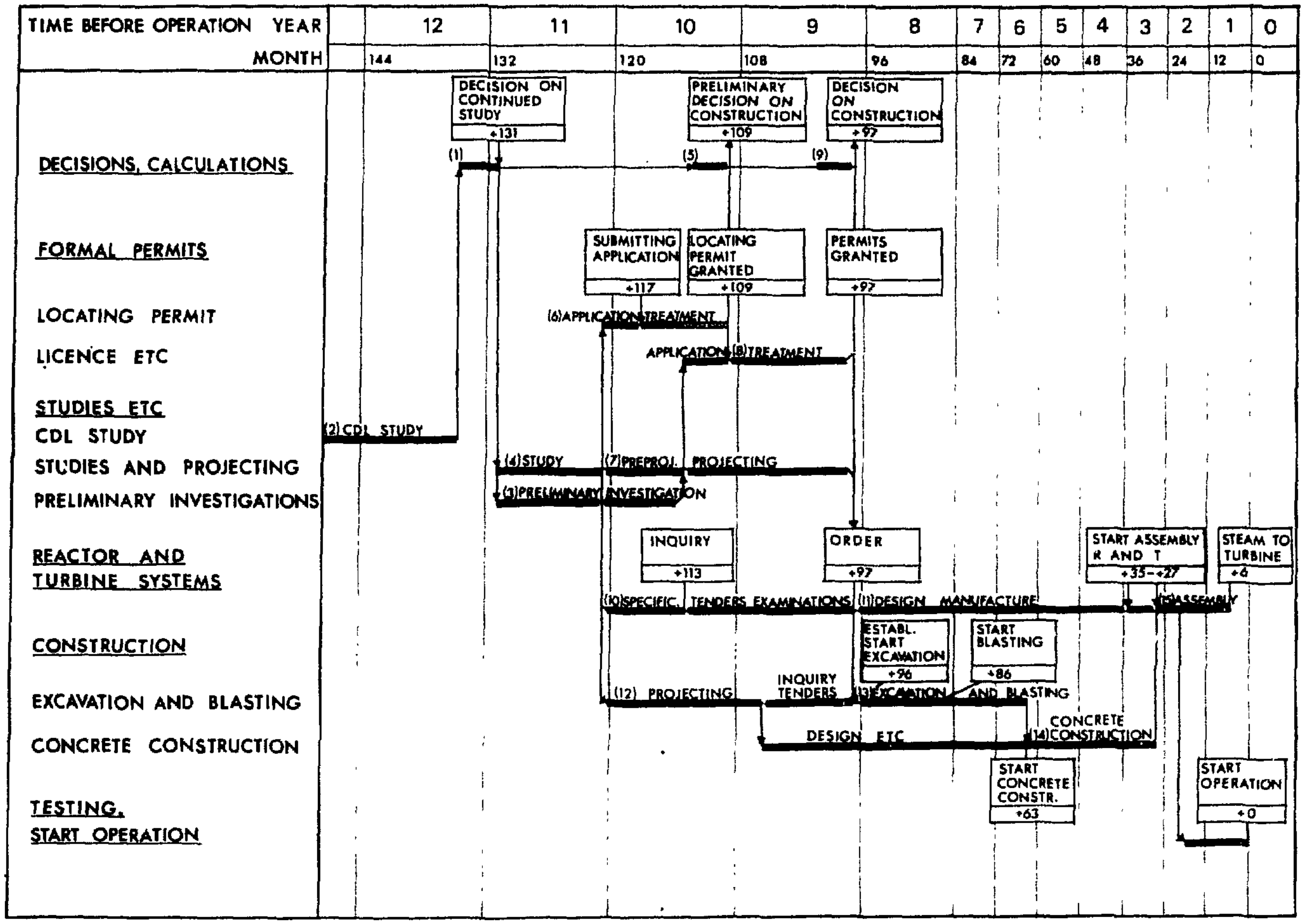
6. Time Schedule and Costs

A preliminary assessment has been made of the time consumption for the construction of the outlined nuclear power plant. The result is presented in the enclosed time schedule. The schedule gives the following checkpoints counted from the completion of this study:

- application for locating permit, 18 months
- inquiry to reactor and turbine manufacturers, 22 months
- granted locating permit and application for licences, 26 months
- granted permits, decision on construction and orders for equipment, 38 months
- taken into operation 135 months or 11 years 3 months

If this schedule is to be followed a rock sited nuclear power plant can be in operation in 1986, at the earliest.

No calculation of the cost of the outlined underground plant has yet been made. The cost for a plant with the technical aims here presented will, however, be higher than the extra 12 % of the war protected plant presented in an earlier CDL study.


TIME BEFORE OPERATION YEAR
MONTH
12
11
10
9
8
7
6
5
4
3
2
1
0
144
132
120
108
96
84
72
60
48
36
24
12
0
DECISIONS, CALCULATIONS
FORMAL PERMITS
LOCATING PERMIT
LICENCE ETC
STUDIES ETC
CDL STUDY
STUDIES AND PROJECTING
PRELIMINARY INVESTIGATIONS
REACTOR AND TURBINE SYSTEMS
CONSTRUCTION
EXCAVATION AND BLASTING
CONCRETE CONSTRUCTION
TESTING, START OPERATION
DECISION ON CONTINUED STUDY +131
PRELIMINARY DECISION ON CONSTRUCTION +109
DECISION ON CONSTRUCTION +97
(1)
(5)
(9)
SUBMITTING APPLICATION +117
LOCATING PERMIT GRANTED +109
PERMITS GRANTED +97
(6)APPLICATION TREATMENT
APPLICATION (8)TREATMENT
(2)CDL STUDY
(4)STUDY
(7)PREPROJ.
PROJECTING
(3)PRELIMINARY INVESTIGATION
INQUIRY +113
ORDER +97
START ASSEMBLY R AND T +35–+27
STEAM TO TURBINE +6
(10)SPECIFIC.
TENDERS EXAMINATIONS
(11)DESIGN MANUFACTURE
(15)ASSEMBLY
ESTABL. START EXCAVATION +96
START BLASTING +86
(12) PROJECTING
INQUIRY TENDERS
(13)EXCAVATION AND BLASTING
DESIGN ETC
CONCRETE (14)CONSTRUCTION
START CONCRETE CONSTR. +63
START OPERATION +0

Footnotes to the time schedule for an underground nuclear power plant

A rough analysis of the construction time for an underground nuclear power plant has been made. The analysis has been based on the following conditions and judgements.
The numbers refer to the time schedule.

1. Project assessment. Decision on further study and projecting on specific site.

2. CDL study on reactor safety in rock sited underground nuclear power plants.

3. Ground surveys etc to form the basis for the work under item 4 and for projecting on the site.

4. Determining basic data. Demands on safety, war protection, sabotage etc are specified and studies on containment, transport roads, cooling water, power lines etc are conducted to provide for a technical treatment of systems and construction and for the order inquire specifications. During this period a preliminary lay-out is also worked out.

5. Preliminary decision calcule is set up. Preliminary decision is made based on this calcule and on locating permit.

6. Application for locating permit is worked out and submitted.

7. Studies and projecting of consequences of underground siting on system designs, constructional problems etc. When the licence application in accordance with the atomic energy act is turned in necessary documentation for the treatment of safety aspects must be available. Documentation of project design and the feasibility of crucial technical solutions must be available before reactor and turbine systems are ordered.

8. Application for permits in accordance with environmental,

water and atomic energy acts. Some prolongation in the treatment time relative to above ground plants is anticipated.

9. Definite decision calcule is set up. Definite decision is made based on examined tenders, decision calcule and granted permits.

10. Technical specifications are worked out and order inquiries are made while the locating permit is treated.

11. Ordering after granted permits and decisions.

12. Layouts etc are revised together with main equipment contractors. Foundation for blasting the cavities is anticipated to be available some 4 months after order.

13. Construction contractor's establishment on the site, excavation and blasting require, depending on rock quality 8 - 14 months longer time than with above ground siting. 10 months extra time has been scheduled, or in all 32 months.

14. Concrete constructions have been estimated to the same time as above ground.

15. Assembly time is assessed equal to above ground.