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ENGINEERING STUDY ON UNDERGROUND
CONSTRUCTION OF NUCLEAR POWER
REACTORS

By
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April 15, 1958

Division of Construction and Supply
Washington, D. C.

Technical Information Service Extension, Oak Ridge, Tenn.

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UNDERGROUND CONSTRUCTION OF NUCLEAR POWER REACTOR

ABSTRACT

The purpose of this study is to outline and evaluate the pertinent factors, advantages, disadvantages, and cost of constructing a nuclear power reactor underground, as compared with contained above-ground construction. There are extensive reference data available on the subject of underground construction in rock, mostly related to underground hydroelectric plants, and to structures protected against enemy attack, but also some data on reactor installations built, or being built, underground in Norway and Sweden. The report is general in nature, although a portion of it covers a hypothetical underground design of the EBWR project, with a comparative cost estimate and a sketch illustrating roughly such an installation.

Major advantages of an underground reactor plant, aside from the superior protection afforded against blast and radiation resulting from enemy attack, include the following:

- (1) Effective containment in case of an internal

incident, eliminating the costly containment

shell required in above-ground construction;

(2) not subject to any extreme changes in temperature, or disturbing surface phenomena such as hurricanes, blizzards, etc., and is relatively invulnerable to earthquake shock; maintenance work is practically nil; and

(3) ventilation requirements are relatively light for an underground installation.

Some of the disadvantages or difficulties in the construction and operation of an underground reactor are:

(1) Generally the cost would be somewhat greater than a contained surface installation. The increase may be roughly estimated at from 3 to 7 percent of the total cost of the plant;

(2) difficulty in determining in advance the exact condition of the rock structure, such as heavy flow of water in the rock strata; and chance of contaminating the ground water in case of a reactor incident; and

(3) limited flexibility with respect to access and expansion.

Limestone, granite, and sandstone are regarded as the best geological formations for underground installations. They permit large spans, high ceilings and horizontal entries. Possible sites are plentiful, and have been surveyed by Bureau of Mines.

The economy of constructing an underground plant improves with the size of the installation, i.e. the unit cost of rock excavation is expected to go down with increased volume.

ENGINEERING STUDY
ON
UNDERGROUND CONSTRUCTION OF NUCLEAR POWER REACTORS

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ENGINEERING STUDY

ON

UNDERGROUND CONSTRUCTION OF NUCLEAR POWER REACTORS

1. PURPOSE AND SCOPE

The purpose of this study is to outline and evaluate the pertinent factors, advantages, disadvantages, and costs of underground reactor construction in this country as compared with contained above ground construction. The investigation should include the following:

- a. Review relevant data available on design and cost of constructing and operating various industrial plants underground (in rock), as compared with same plants built above ground;
- b. Outline the major advantages and disadvantages of an underground reactor installation as compared with a conventional one built above ground;
- c. Determine site requirements for selected types of reactors to be built underground in rock formation; relative to geological conditions, water supply, geographic location, etc.;
- d. Determine design requirements for protection against enemy nuclear attack, such as depth of rock cover, blast resistant doors, protected ventilation equipment, etc; (to be covered in detail in a classified Appendix).

PURPOSE AND SCOPE CONT'D.

- e. Analyse the containment requirements and conditions in case of a reactor incident;
- f. Analyse the various nuclear reactors, such as by size and type, and select one or more which appear suitable for underground construction and for which design and cost data are available;
- g. Outline the design features, including excavation and construction methods, of one or more reactors built underground and with protection against both external and internal incidents;
- h. Make comparative estimates of costs for the selected reactor types, built underground against the cost of above-ground construction; and
- i. Summarize the study and give general conclusions regarding feasibility and cost of underground construction of nuclear power reactors.

2. ADVANTAGES AND DISADVANTAGES OF UNDERGROUND INSTALLATION

The advantages to be gained by underground installation of a nuclear reactor plant and the disadvantages associated with such construction must be related to those of a similar surface installation for purposes of comparison and evaluation.

- a. The major advantages of an underground nuclear reactor plant may be listed as follows in suggested relative importance:

ADVANTAGES AND DISADVANTAGES OF UNDERGROUND INSTALLATION CONT'D.

- (1) Effective containment in case of an accident can be obtained in an underground rock excavation, particularly if provided with a leakproof lining. This feature, of course, eliminates the rather costly containment shell required in above-ground construction.
- (2) The underground building is not subject to any extreme changes in temperature, or disturbing surface phenomena such as hurricanes, blizzards, etc., and is relatively invulnerable to earthquake shock. In seismic studies, it has been determined that fracture surfaces, bedding planes or similar weaknesses in the rock have the ability to reflect, refract and dampen stress waves. Also maintenance work, as required for the exterior portions of an above-ground plant, is practically eliminated for an underground installation.
- (3) Ventilation requirements are relatively light for an underground reactor installation. Also transportation requirements are very light after the plant is in operation because of the long life of the nuclear fuel.
- (4) Superior protection against effects of enemy attack (such as blast and radiation) is possible in under-

ADVANTAGES AND DISADVANTAGES OF UNDERGROUND INSTALLATION CONT'D.

ground construction, for both personnel and equipment. This could be of considerable importance to civil defense in case of an attack on this country, in being able to provide electrical power for emergency use.

b. Major disadvantages and difficulties that may be encountered in the construction and operation of an underground nuclear reactor are listed in the following, without attempting to indicate their relative importance:

- (1) Generally the cost of an underground installation is somewhat greater than a similar sized surface installation. The increase may be roughly estimated at from 3 to 7 percent of the total cost of the plant.
- (2) Difficulty in determining in advance the exact conditions of rock structure, such as the possibility of encountering widespread or local areas with poor rock conditions, and unforeseen heavy flow of water in the rock strata.
- (3) The installation must be located close to a river or other water source with sufficient cabling water supply. Some difficulty may be experienced in obtaining such sites allowing the increase in water temperature and possible radioactivity accompanying

ADVANTAGES AND DISADVANTAGES OF UNDERGROUND INSTALLATION CONT'D.

the waste cooling water. This fact will tend to greatly restrict the number of suitable site locations. The other alternative would be to condition the cooling water in a forced fan cooling tower, which of necessity (because of the large amount of air required for the fans) would have to be placed outside the protected area.

- (4) There is a limited flexibility with respect to access and expansion, and also the vulnerability of entrances compared to that of the inside installation.
- (5) There is a slight chance of contaminating the ground water in the rather unlikely event of an accidental rupture of the reactor. This would have to happen concurrently with rock shifting or slight movement which may cause cracking in the rock lining.

3. SITE REQUIREMENTS

The most desirable site location for an underground reactor installation is one which will permit the most economical construction and operation of the installation with the most effective protection against the effects from a reactor incident as well as against the effects from enemy action.

SITE REQUIREMENTS CONT'D.

- a. The geologic characteristics of a site to look for are rock formations which are easily excavated, but should also be structurally stable at sufficient depth below the surface to provide adequate protective cover. It is important to point out those geologic factors which contribute to the stability of underground openings, as well as the factors which contribute to their instability, such as faults, joints, bedding planes, cleavage, etc. There are also certain factors other than structure, such as depth and occurrence of ground water, which have an important bearing upon the desirability of a given site.
- b. The topography of a given site is of considerable importance in site selection, particularly as it affects the length of the horizontal entry tunnels, and also as it affects the depth (or protective rock cover) of the excavation. In general there should be at least 50 feet of sound rock over the excavation. On the other hand, too great a depth may cause high stresses around the opening due to the greater pressures (or weight) of the overlying rock.

SITE REQUIREMENTS CONT'D.

- c. The preferred condition would be a site located close to a river or lake which would supply the water necessary for cooling purposes in reactor operation. If sufficient water supply cannot be obtained from lake and river water, or subsurface wells, it will be necessary to provide cooling towers. They will have to be built in the open, generally close to the main tunnel entrance.

In considering the adequacy of a source of water, the minimum flow of a stream or extreme low level of a lake is assumed a determining factor. On the other hand, sites above maximum flood level should be selected. Although specified water quality may not be available without treatment, such treatment should be economically feasible.

In connection with the utilization of lake or river water for reactor cooling purposes, it will be necessary to obtain approval for what may be termed pollution to the water, such as raising slightly the temperature of the water and some slight radiological contamination. Both actions may have injurious effect on both fish and plant life in the water.

SITE REQUIREMENTS CONT'D.

- d. The possibility of ground water (and subsequent water supply) contamination in case of a reactor incident must be investigated. A suitable lining of the excavation should help prevent seepage, although there is no certainty that tiny cracks might have opened up by the explosion allowing some contaminated seepage. In any case, it is deemed advisable to confer with the Ground Water Branch people of the U. S. Geological Survey when considering a particular site for an underground installation. If it is known that extensive seepage takes place, eventually leading into known water supply, the site should be rejected.
- e. The isolation requirements, normally established for above-ground reactor plants, may be somewhat modified for an underground installation due to better containment in case of a reactor incident. Also certain climatic conditions, such as unusually high winds, frost, etc., which may be of particular importance in the selection of sites for above-ground reactor plants, are of negligible importance in the selection of underground sites.
- f. The utilization of existing openings, such as mines or caves, in the area of consideration may be

SITE REQUIREMENTS CONT'D.

advantageous when they are sufficiently stable and readily adaptable to the requirements of the installation. Although caution should be exercised in such cases, large savings may be realized in the normally high excavation costs. In that connection, reference is made to the Corps of Engineers' 1946-47 survey of existing mines (Ref. 7, 8 & 9) potentially suitable for underground installations.

- g. Other factors, such as satisfactory labor supply, good transportation facilities, etc. will of course have a bearing on the time and cost of construction.

4. ROCK CHARACTERISTICS AND EXCAVATION

- a. Data accumulated to date indicates that granite, limestone, sandstone, and salt formations have the best properties for underground use. These formations usually permit wide spans, high ceilings, and regular pillar arrangement, if needed. Reasonable excavation is also possible in other foundations. Existing mining operations in granite are virtually unknown. Of the existing mines surveyed (Ref.7-g) as suitable, 65 percent were excavated in limestone, 10 percent were salt mines, and the remaining 25 percent were for the most part lead-zinc, sandstone, and gypsum mines.

ROCK CHARACTERISTICS AND EXCAVATION

The following gives a brief description of the most favorable rocks for underground installations:

Limestone is the most prevalent type of geological formation in the United States suitable for underground installations. The majority of existing mines and possible new sites investigated (Ref.7) are in limestone. These limestones are generally horizontally bedded. Many limestone sites are desirable because they permit horizontal entry, construction of large flat roof spans, and high ceilings.

Granite gneiss is second in importance of new possible sites surveyed (Ref. 7). With few exceptions the granite formations investigated are accessible by horizontal entries from sides of hills or cliffs. Granite formations usually permit large arched roof spans and high ceilings.

Sandstone formations are in many cases adaptable for underground construction, but areas of massive deposits are not comparable in size or distribution to those of limestone and granite. Mines and possible new sites in sandstone comprise only 10 percent of the total sites surveys. These were located in Arkansas, Minnesota, Ohio, Wisconsin and Washington. The average strength of sandstone is less than limestone or granite and porosity usually much higher.

ROCK CHARACTERISTICS AND EXCAVATION CONT'D.

Of other rock formations, salt deposits are geologically favorable for underground construction, but entry is by means of shafts, generally deep ones. Where cost is not an important factor, industrial plants can be installed successfully in virtually all types of geological formations.

- b. Excavation in rock generally takes place in two main steps, namely (1) drilling and blasting and (2) loading and disposal of spoil. Simultaneously with these operations, provisions are made, as found necessary, for mechanical ventilation, safety and support.

The character of rock determines the most advantageous pattern of drilling and blasting. Rock characteristics governing excavation costs are strength of rock, relative freedom from defects requiring the addition of artificial support, presence of ground water and poisonous gases, easy drilling and breaking, etc.

Design factors tending to reduce excavation costs are large volumes, uniformity and large size of openings, simplicity of shape of openings, etc.

Unit cost of excavating high chambers in rock is relatively low because of the small amount of horizontal development

ROCK CHARACTERISTICS AND EXCAVATION CONT'D.

work required. Preparatory to enlarging the chamber to the desired size, a small tunnel is driven at the bottom of the chamber and a shaft of relatively small cross-section is driven to the roof of the chamber. A bench is cut from the top of the shaft exposing the complete top of the chamber. The remainder of the chamber is excavated by drilling down holes, and the broken rock is removed at the bottom of the shaft through the excavated tunnel.

5. Containment Against a Reactor Incident

According to the best judgment of experts in the reactor field, the likelihood of a major reactor accident is, fortunately, extremely small. Nevertheless, the possibility exists that through highly unlikely combinations of mechanical and human failures such an incident may occur. The principal element of danger to the general public in nearby areas is the possibility of radiation exposure and contamination, if the fission products in the reactor should be released. The subject is covered extensively in the AEC report "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants" (Ref. 3).

Basic requirements for the design of a containment vessel must take into consideration system failures or reactor incidents even though their probability of occurrence may be minute. The containment structure, whether built above-

ground or underground, must be designed to withstand, without rupture, all shock waves, missiles, increases in temperature, and increases or decreases in pressure resulting from these occurrences. Possible events which might effect the container are included in the following categories:

- a. Nuclear Incidents. Nuclear power reactors do not have the high concentrations of fuel nor the triggering mechanisms as found in nuclear weapons, and do not present anything like the hazard expected in a nuclear incident. It is understood that nothing like an explosion really occurs and the total energy released is only of the order of that released in burning several gallons of gasoline.
- b. Non-nuclear Reactions. Power reactors of certain types, particularly pressurized water reactors, are designed to operate at high pressures, contained by the reactor vessel and coolant systems. The energy stored in these systems is considerable for large reactors. In the event of a rupture in these reactor systems, the containment vessels would be required to withstand the shock waves and pressure increases released by the stored energy. Other possible non-nuclear accidents include sodium water reactions and possible reactions between water coolants and some fuel element cladding materials.
- c. Coolant System Failures. A major piping failure in a power reactor system using water as the coolant, such as in a boiling water reactor system, would result in the superheated water in the system flashing into steam as it escapes inside the containment vessel. The design of the containment vessel then involves determination of a volume sufficiently large to permit containment at a reasonable pressure, and an economic

determination can be made of optimum vessel size above the minimum as required for functional use.

Special provisions may sometimes be made to prevent damage to the container shell by flying missiles resulting from such accidents as reactor turbine-or pipe rupture. The EBWR has the entire shell lined with concrete except for the upper hemispherical dome. The latter is protected by a steel plate and concrete ceiling over the main floor. In addition, the reactor structural arrangement includes features to prevent a dangerous condition in the event of an explosive zirconium-water reaction within the core. The shock pressures developed would cause the bottom head of the vessel to be blown, together with the bottom shielding, into the basement, so that the vessel itself would tend to act as projectile. The large upward force developed would be restrained by 3 heavy beams located across the top of the reactor and pinned by wedges to 6 columns whose bases are firmly anchored in the large mass of concrete forming the basement floor of the building. Laminated blast shields of compressible material and steel are interposed between the reactor and the columns (in the vicinity of the core) to protect the latter from side shear. The missile hazard has an extensive range of variations, such as the determination the the mass, velocity, shape, etc. of the flying objects.

d. Missiles and Forces of External Origin. A conventional type containment must be designed to withstand high winds, earthquakes, etc. In addition, it can be imagined that missiles of external origin, such as crashing aircraft and, of course, enemy weapons, might rupture the above-ground containment shell, then damage part of the reactor system

releasing radioactive materials. In regard to protection from this occurrence, the underground scheme is by far the superior than the thin-skinned steel container of the above-ground scheme.

An underground installation in rock is expected to give an almost perfect protection against any internal excursion, as well as superior protection against any external forces. As far as structural strength is concerned, there is ample inherent strength in the rock cover plus a solid rock lining, to resist an interior explosion of any reasonable magnitude, involving blast and missiles as well as high temperatures. There remains the possibility of contamination of underground water supplies through opening up of tiny cracks in the rock lining by the explosion and subsequent contaminated seepage into the rock. A suitable concrete lining supplemented by a light-gaged metal lining (see sketch SK-1) for the lower, or bottom part of the Reactor Building (where contaminated water is likely to collect), would give the required protection. Of course, sites with very rapid water seepage may be excluded from consideration altogether, because of the contamination possibility as well as excavation difficulties associated with it.

It is suggested that the U. S. Geological Survey (ground water branch, Water Resources Division) be requested to examine each proposed location to determine the ground water conditions. They would have the necessary data at hand and experience in pointing out possible problems and difficulties which may be encountered. Possibly, even steam under pressure could penetrate into the rock causing some contamination of the surroundings.

The question of how deep it would be necessary to go to get down into dry rock, cannot be answered directly. In most cases the dry igneous rock would be down several thousand feet, generally impractical for consideration.

A shale formation would be the better geological formation as far as retaining contaminated fluid is concerned; structurally, however, shale would be less desirable. Sandstone and, to some extent, limestone formations have too many cracks and fissures to meet the requirements and would in all probability need a good, tight lining.

The cost of containment features constitute a considerable portion of the total cost of an installation. According to a cost study on boiling water reactors by Sargent & Lundy (Ref. 20), it was concluded that the upper cost limit for containment for EBWR (5 megawatt electrical capacity) would be approximately 17 percent of the published total construction cost of \$4,628,000 (including the containment features), or 21 percent of \$3,826,000 of such a plant (with no containment features). The other boiling water reactor cost study was based on a hypothetical large-scale nuclear power plant with an electrical capacity of approximately 180 megawatt. The cost of containment features was estimated at approximately 8 percent of the total cost of \$45,000,000 (based on published costs of a comparable large-scale plant) or 9 percent of the total cost of \$41,317,000 for the plant with no containment features.

6. DESCRIPTION OF REACTOR(S) SELECTED FOR INVESTIGATION

Detailed data on design and cost are readily available on the Argonne Experimental Boiling Water Reactor (EBWR) power plant, and it was decided to make the initial study based on that reactor placed underground. Very good data, both as to cost and design details, are now becoming available on the ARBOR reactor (also a boiling water reactor), which has a 60 MW electrical capacity, vs. 5 (or a possible 10) MW for the EBWR. It is suggested that

eventually the ARBOR and also a pressurized water type reactor (PWR) be investigated for underground construction in rock

The EBWR plant, which was put in operation in December 1956, is a direct-cycle boiling water reactor power plant producing about 5 MW of electricity from 20 MW of reactor heat in the form of 600 psig steam. The EBWR is primarily an experimental plant intended to provide as much information as possible for future use in designing large units.

The present EBWR facility consists of essentially two adjoining buildings, namely, the Reactor Building and the Service Building. The Reactor Building is a gas-tight steel pressure shell of 80' diameter which houses the boiling reactor vessel, the spent fuel storage well, and the steam power plant and related auxiliaries. The steel containment (cylindrical) shell, which is the main cost item to be deleted in subject underground scheme, was designed for a pressure of 15 psig due to accidental pressurization.

The Operation and Service Building, which is of conventional masonry construction, houses the main control room, electrical equipment room, service area, laboratory, offices, and miscellaneous other facilities.

The Cooling Tower is located about 150 feet from the Reactor Building.

For detailed description of the design of the EBWR, reference is made to ANL 5607 report "The EBWR experimental boiling water reactor," prepared by Argonne National Laboratory, May 1957 (Ref. 16).

7. HYPOTHETICAL UNDERGROUND DESIGN OF THE EBWR PROJECT

a. Paragraph 6 above gives a brief description of the EBWR Reactor Building as built and contained in a cylindrical steel shell of 80' diameter. Drawing SK-1 shows a suggested underground design of the EBWR project, functionally laid out in identical shape, size, and arrange-

ment as the above-ground design. An alternate scheme showing the Reactor Building of rectangular shape and of 45' span of opening has been shown only schematically. The decision as to size and shape of the large chambers must be governed by the geologic factors of the site selected. It was deemed advisable, at least for the initial phase of the study, to make the functional layout the same as the above-ground design. Actually, as far as cost of excavation is concerned, there is probably very little difference between the various schemes. In sound rock the 80' diameter dome-shaped scheme shown on the drawing SK-1 should be entirely feasible, particularly with a substantial lining; in structurally less sound rock, however, functional rearrangement may be made to obtain a rectangular shape of the Reactor Building (such as the Alternate Scheme shown) with a short-span and greater length of the opening for the large chamber.

There is definitely advantageous, in excavating the large chambers, to run the tunnel at the bottom of the openings and excavate as explained in par. 4b above. Cost of excavating large chambers may in that way be held to a minimum, possibly as low as \$8. to \$10. per cu. yd. for larger openings (50,000 cu. yds. or more).

The Emergency Tunnel which runs into the Service Building at the basement floor level may be utilized in the excavation of the Service Building Chamber. In this way the excavation of the two large chambers may go on simultaneously, i.e., with separate crews, thereby reducing considerably time of construction and possibly the construction cost.

b. The surface of the excavated chambers and tunnel openings should (as found necessary) be provided with a concrete liner, ranging in thickness

from 12" for the main tunnel to 24" for the Reactor Building. The liner will give increased protection against rock spalling and "popping rock" condition, and generally add to the structural strength of the opening. The liner required for adequate protection will depend upon the type of rock, the depth of the opening, and the function of same. In the two large chambers, the liners serve a double duty in that they also serve as exterior structural supports for the various floors as well as the main crane.

The importance of a concrete liner (plus a light-gaged metal lining) to give the required protection against contaminated seepage into the rock in case of an internal excursion in the Reactor Building has been pointed out variously in paragraphs 3 and 5 above.

Appendix "C" gives an estimate of cost of the containment features for underground construction of a nuclear power plant (see Sketch SK-1) similar to the EBWR, as compared with the actual cost of the EBWR. The estimate shows this cost, which includes rock excavation, concrete linings, tunnels, ventilation and blastproofing features, etc., to be approximately \$940,000 for the underground scheme, or about 20 percent of the total cost of \$4,628,000 for the EBWR. The increase in cost for underground construction of EBWR compared to the plant, as built, was estimated to be about \$322,000 or 7 percent of the total cost of the plant.

The cost of the underground scheme may be somewhat reduced by placing the major portion of the Service Building area outside; i.e., in a conventional type building near the entrance to the main tunnel. Also the lengths of the access tunnels may be reduced to a minimum or

considerably less than the 500' and 700' lengths assumed in the Appendix "C" estimate for the two tunnels. If no consideration is given protection against possible nuclear enemy attack, additional savings are possible by eliminating such items as blast-proof doors in the tunnels.

It may be possible in certain cases to take advantage of the natural rock for shielding purposes. In any case, there will be an abundant supply of rock aggregates for use in any concrete construction, such as for shielding, lining, and floor slabs.

The clear opening of the main tunnel and doors, through which major equipment will be brought in, must be governed by the dimensions of the largest such equipment item or equipment parts, if assembled inside. It may be necessary to modify the design of these items in order to arrive at an economical size of the tunnel opening.

The 15,000 gallon water storage tank for the safety sprinkler system is placed in an excavated space to one side of the Reactor Building dome (See Drawing SK-1).

Similar to the EBWR, as built, and in order to prevent excessive pressure buildup in case of an incident, the sprinkler system is provided to spray water into all parts of the building and condense any steam released.

8. CONCLUDING NOTES

a. A decision to build a reactor installation underground in rock must be based on careful studies of such factors as site conditions, containment requirements, cost comparison with an above-ground installation, and possible requirement for protective features against enemy attack. If the criteria requires dual-purpose safety, i.e., both possible internal

and external explosive action, then an underground project would be a most practical and economical scheme to pursue.

b. In site selection there is no particular need to look for an excessively thick rock cover. A minimum of, say, 50 feet depth of fairly sound rock cover is considered more than enough for containment in case of an internal excursion, and also, if required, gives excellent protection against a near-miss surface burst of a large thermonuclear enemy weapon.

c. There may be real problems in obtaining a suitable site located close to a river or other water source with sufficient cooling water supply, in particular in regard to getting approval for increasing the temperature and some radioactive contamination of the waste cooling water. A possible solution, and also one which may in some cases prove an economical one, would be to combine the reactor installation with that of an underground hydroelectric power plant, utilizing, through a bypass, the water in the tail-race tunnel. The reactor building must, of course, be safely separated from the hydroelectric plant.

d. Cost of rock excavation has not gone up as much as other construction costs, principally due to improved methods and equipment. Excavation cost is considerably higher here in the United States than for instance in Sweden, where most of the underground construction is in good rock (such as granite and gneiss) and where labor rates are lower and equipment quite advanced. Unit excavation costs in U. S. may vary from \$10. to \$30. a cu. yd. as compared to unit costs in Sweden ranging from \$3.20 (16.50 Sw. Kr.) (at the 500 MW underground hydro-electric plant at Stornorsfors) to \$15 a cu. yd.

e. Concrete lining of the excavation faces can be an expensive item, in some cases amounting to as much as two-thirds of the rock excavation cost. In reasonably good rock the lining may be limited to the ceiling using either a reinforced concrete arch or by rock anchors and gunite as used in many of the underground installations around the world.

f. The apparent success and advantages experienced abroad in underground power plant construction have evoked increased interest in this country, and it is expected that in the future more of our hydro-electric plants will be built underground. The economy of constructing an underground plant goes up with the size of the installation, i.e., the unit cost of rock excavation is expected to go down with increased size. It is therefore reasoned that the cost of a large size underground nuclear power plant might compare favorably with the same size plant built above-ground with conventional containment provisions. However, generally the cost of an underground reactor installation may be assumed somewhat higher than a similar sized surface installation. The increase may be roughly estimated at from 3 to 7 percent of the total cost of the plant.

g. Some of the advantages of an underground reactor building may be pointed out, such as the fact that it is not subject to any extreme changes in temperature or disturbing surface phenomena (hurricanes, blizzards, etc.) and is relatively invulnerable to earthquake shock. Of the problems involved may be mentioned the difficulty in determining in advance the exact conditions of the rock structure, such as the possibility of encountering widespread or local areas with poor rock conditions, and unforeseen heavy flow of water in the rock strata.

AVAILABLE DATA

Reference is made to the recent study, "Underground Construction of Power Reactors", by D. R. Inglis and G. R. Rings of Argonne National Laboratory (Appendix "B," Ref. 1). Their report gives a rational discussion of the special considerations as to site selection and design, as well as a rough cost analysis for a 150 megawatt reactor, which indicates the estimated additional cost of underground installation to be the excavation cost only, or about 3.5% of the total cost of the plant.

The office, Chief of Engineers (OCE), Department of the Army, has since the end of World War II conducted a number of studies and investigations to determine the feasibility and cost of constructing and operating strategic defense plants underground (Ref. 8).

In one of the studies, three specific plants, representative of a wide range of requirements which would be encountered if a general underground construction program should become necessary, were studied (Guy B. Panero, 1949, reports under Contract with OCE-1, Ref. 7). These were:

- a. A precision manufacturing plant (approximately 600,000 sq. ft. Floor Area).
- b. A chemical process plant (approximately 140,000 sq. ft.)
- c. A storage depot (approximately 3,500,000 sq. ft.)

Both construction and operating costs in each instance were estimated, comparing costs above ground, costs in existing mines, and costs in sites excavated solely for the purpose.

Foreign underground installations, working conditions, sites and geological formations strategically located in this country, excavations

and construction methods, and problems relating to emergency use were also investigated, and reported on.

It was concluded from these investigations that, in the face of a nuclear war, the only safe course is to build essential defense plants underground. It is the best possible insurance against an unexpected attack, and, of course, also in case of a long drawn-out war.

The Corps of Engineers, assisted by the Bureau of Mines, conducted in 1946-47 a detailed survey of the existing underground mines and caves throughout the country; certain types of mines possessing desirable characteristics as sites for underground plants received primary consideration (Ref. 8 & 9).

More than two-thirds of the potential mine sites in this country lie within or near the borders of a quadrangle containing 70 to 80 percent of the industry and manufacturing of the United States. This industrial quadrangle includes most of New England; all, save the northern tip of New York; all of Pennsylvania, Ohio, West Virginia, Kentucky, Indiana, and Illinois; and parts of Michigan, Missouri, New Jersey, North Carolina, Tennessee, and Delaware. The proximity of mine sites and industry in this rough quadrangle means that the migration of labor, involving new housing, water systems, schools, etc., would be comparatively negligible.

Geological formations of almost unlimited extent lie in or near the quadrangle and would provide excellent sites for excavation of space for underground plants.

It was first thought that the use of shaft mines would constitute a hopeless task. Further considerations, however, developed the conclusion that they could be used economically, even though the sinking of additional shafts and other special provisions for accommodating the installation might be necessary. These additional shafts and other provisions would make tremendous underground areas accessible and usable.

Investigations of geological formations in the United States indicates that limestone, granite, and sandstone are best for installation of industrial and storage facilities underground. These three formations adapt themselves to the most economical layouts since they permit the construction of large spans, high ceilings, and horizontal entries. Where cost is not a material factor, industrial plants can be installed successfully underground in virtually all existing formations.

Cost of excavation varies widely depending on such factors as size of underground installation, clear roof span, flat or arched roof, type of rock lining required, and, of course, type of rock.

Roof spans (between rock walls, or between pilasters) seldom exceed 50' for underground layouts; ceiling height, however, could be 60' to 80', or more.

Bureau of Mines has recently completed a classified "Manual on Underground Installations in Rock" for the Corps of Engineers, U. S. Army (Ref. 4). The manual was prepared to provide a basic guide for engineers in the planning and designing of underground installations in rock, constructed to provide optimum protection against enemy attack. Basic data

are presented on the requirements for depth of rock cover and size of opening related to penetration and explosive effects of weapons in rock. The Manual also contains basic design criteria to be considered for design and planning of any underground installation, including geographic, economic, and geological factors, excavation and construction methods, ventilation and protective devices, and certain cost data.

The Argonne Report makes reference to a research reactor built underground in Stockholm, Sweden (Ref. 1). The December 12, 1955 issue of LIFE Magazine has a picture of this, the only atomic reactor in Sweden, which is buried 85 feet underground in solid granite (Ref. 15).

There is fairly detailed information available on the underground Halden Reactor in Norway (Ref. 5). This 10 megawatt heat (can be increased to 20 MW) reactor is, according to the report, being built as an experimental reactor mainly to test physics and engineering design of a boiling heavy water system. This reactor will be housed in a rock excavation. A tunnel of approximately 165' will lead into a large room of 100' length, 32' width and approximately 40' height. The reactor and some of the associated equipment will be mounted in a pit below floor level of this room. The pressure locks will be designed for about 40 psi over-pressure. The report says that "...the reason for putting the reactor in a rock excavation is to obtain a building which can be made gas tight in a fairly simple and inexpensive way."

Other articles dealing with the subject of underground construction are listed in the attached "List of References" (Ref. 12, 13, and 14, Appendix "B").

LIST OF REFERENCESUNDERGROUND CONSTRUCTION OF NUCLEAR POWER REACTORS

- (1) ANL - 5652, "Underground Construction of Power Reactors," by D. R. Inglis and G. R. Ringo, Argonne National Laboratory, January 1957. (U)
- (2) TID - 4562, "Experimental Power and Test Reactors," Nov. 1956. (U)
- (3) "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," March 1957. (A study of possible consequences if certain assumed accidents, theoretically possible but highly improbable, were to occur in large nuclear power plants - performed by a study team from Brookhaven N. L. with assistance of consultants.) (U)
- (4) "Manual on Design of Underground Installations in Rock," prepared for Corps of Engineers, U. S. Army, by Bureau of Mines, U. S. Dept. of Interior. (Preliminary Draft, April 1957). (C)
- (5) "Information on the Halden Reactor," (Translation of Norwegian description of Underground Nuclear Reactor project at Halden, Norway; and copies of drawings). (U)
- (6) TID - 7517 (Pt. Ia & Ib), "Sanitary Engineering Aspects of the Atomic Energy Industry." A Seminar sponsored by the AEC and the Public Health Service, held at the Robert A. Taft Engineering Center, Cincinnati, Ohio, December 6 - 9, 1955, "October 1956. (U)
- (7) Investigations by the engineering firm Guy B. Panero for the Corps of Engineers. Nine reports, dated February 1949:
 - (a) Underground Installations - Precision Manufacturing Plant Report, Appendix Volumes I and II and Definitive Drawings.
 - (b) Underground Installations - Chemical Process Plant Report, Appendix and Definitive Drawings
 - (c) Underground Installations - Storage Depot - Report, Appendix and Definitive Drawings
 - (d) Underground Installations - Foreign
 - (e) Underground Installations - Working Conditions
 - (f) Underground Installations - Sites and Geological Formations
 - (g) Underground Installations - Adaptations of Existing Mines for Emergency Use.

- (h) Underground Installations - Excavation and Construction Methods
- (i) Underground Installations - Summary (U)
- (8) Progress Reports Nos. 1 to 9, "Underground Installations Program," Dept. of the Army, Sept. 1947 to March 1949. (Much of the data based on the Panero reports.) (C)
- (9) Dept. of Defense Manual, "Underground Plants for Industry," January 1956. (Much of data based on Panero reports.) (U)
- (10) Study by Tarbox on Volume Requirements for Various Nuclear Reactors. (U)
- (11) Miscellaneous Data (C. Beck, Jan. July, 1957):
 - (a) "Review and Relevant Data Re: Underground Construction of Power Reactors." (C)
 - (b) "Tentative Preliminary Outline of Scope for Proposed Study on Underground Construction of Power Reactors." (U)
 - (c) "Tentative Criteria for Selection of an A-E to Handle Proposed Study on Underground Construction of Power Reactors." (U)
 - (d) "Firms Suggested for Underground Reactor Study." (U)
 - (e) Report of Meeting with Bureau of Mines on March 18, 1957, re: Underground Construction of Nuclear Reactors (Sherman and Beck from AEC, and Allsman and Hill from Bu. of Mines.) (U)
 - (f) Report of Meeting with Ground Water Branch, USGS re: ground water contamination, April 25, 1957. (U)
 - (g) Memo, Davis to Derry, April 3, 1957, subject: "UNDERGROUND CONSTRUCTION OF REACTORS." (U)
 - (h) Report of Meeting with McCoy of Morley Corp. on July 18, 1957, re: Underground Cooling Towers.
 - (i) Report of Meeting with Reactor Development Division, July 24, 1957. Memo, Beck and Tarbox, to Files, dated July 29, 1957.
- (12) Civil Engineering, January 1957 issue pages 50-53, Article: "Underground Warehouse excavated in granite," in Oslo, Norway.

- (13) Engineering and Management Section, February 1954 issue, pp. 85-89 & 196. Article: "High-Head Underground Hydro Plant....will serve huge aluminum refinery in British Columbia."
- (14) Engineering News Record, Sept. 1, 1955, pp. 34-37, 40, 42, & 44. Article: "Swedes Make Rock Tunnel History," by Waldo G. Bowman, Editor, ENR.
- (15) Life, Dec. 12, 1955 issue, pp. 121-127. Article: "Underground Sweden: Operation Granite."
- (16) ANL 5607, "The EBWR experimental boiling water reactor," prepared by Argonne National Laboratory, May 1957.
- (17) Corps of Engineers, Engineering Manual, Military Construction
 - (a) Part XXV, Draft 1956 - "Heating and Air Conditioning of Underground Installations"
 - Chapter 1 - Introduction
 - Chapter 2 - Principles and Design Objectives
 - Chapter 3 - Design Information and Data
 - Chapter 4 - Heat Absorption of Rock and Underground Spaces
 - Chapter 5 - Air Conditioning Processes and Systems
 - Chapter 6 - Equipment and Operation
 - (b) Part XXVI, Draft 1956 - "Collective Protection Against Chemical, Biological, and Radiological Warfare Agents"
 - Chapter 1 - Introduction
 - Chapter 2 - Design Criteria
 - Chapter 3 - Operational Requirements
- (18) "Containment for the EBWR," by Heinsman and Fromm, Argonne National Laboratory, presented at the 1957 Nuclear Engineering and Science Congress, Philadelphia, Pa., sponsored by Am. Soc. of Mech. Engrs.
- (19) Report of Papers on Underground Construction, presented at ASCE Convention in New York, October 15-17, 1957.
 - a. "Underground Power Plants in Sweden", by Tore Nilsson, Techn. Director, Swedish State Power Board, Stockholm, Sweden. (Abstract article in "Civil Engineering," January 1958 issue).
 - b. "The Haas Underground Hydroelectric Power Project," by J. Barry Cooke, Supervising Civil Engineer, Pacific Gas and Electric Co.

- (20) Report SL-1443, "Cost of Containment Features for Boiling Water Reactors," for Argonne National Laboratory. Prepared by Sargent & Lundy, Engineers; October 15, 1957.

UNDERGROUND REACTOR STUDY
ESTIMATE (EBWR PROJECT - SEE DRAWING SK-1)

1. Cost items to be added for Underground Construction

	<u>QUANTITY</u>	<u>UNIT*</u> <u>PRICE</u> \$	<u>COST</u> \$
<u>Rock Excavation</u>			
Reactor Building - $(\pi \times (42)^2 \times 86/27) +$ $(\pi \times (10)^2 \times 44/27) =$	18,500 C. Y.	@ 15 =	280,000
Service Building - $46' \times 97' \times 35' \times 1/27 =$	5,780 C. Y.	@ 15 =	86,500
Main Tunnel - $15' \times 13' \times 500' \times 1/27 =$	3,600 C. Y.	@ 25 =	90,000
Emergency Tunnel - $11' \times 9' \times 700' \times 1/27 =$	2,570 C. Y.	@ 25 =	64,000
Cooling Tower, Mech. Equipment			
Storage Room - $20' \times 20' \times 15/27 =$	220 C. Y.	@ 25 =	5,500
TOTAL - Excavation (incl. Overhead & Contingencies) =			526,000
<u>Concrete Lining</u> (4" added for overbreak; \$10 added to C. Y. price for Reinf'g)*			
Reactor Bldg. (24" Lining) - $\left[\frac{(\pi \times 80' \times 70' + (\pi \times 120' \times 17'))}{27} \right] \frac{2.33}{27} =$	2,070 C. Y.	@ 52 =	107,800
Reactor Bldg. (Floor) - $\pi \times (40)^2 \times 4.5 \times 1/27 =$	830 C. Y.	@ 30 =	24,900
Service Bldg. (18" Lining) - $\left[\frac{(150' \times 100') + (45 \times 62)}{27} \right] \frac{1.83}{27} =$	1,210 C. Y.	@ 52 =	62,800
Main Tunnel (12" Lining) - $\left[\frac{(\pi \times 7' + 14' + 14') \times 500}{27} \right] \frac{1.33}{27} =$	1,230 C. Y.	@ 61 =	74,800
Emergency Tunnel (Floor only) - $1' \times 10' \times 700' \times 1/27 =$	260 C. Y.	@ 30 =	7,700
Cooling Tower, Mech. Equipment			
Storage Room - $\left[\frac{(20^2 \times 15) - (18.5^2 \times 13.5)}{27} \right] \frac{1}{27} =$	50 C. Y.	@ 47 =	2,400
Corr. Metal Lining, 16 ga. welded = $(\pi \times 76 \times 48) +$ (Basem't Floor; walls up to Main fl.) $(\pi \times (40)^2) =$	16,500 S. F.	@ 2 =	33,600
TOTAL - Lining			314,000
<u>Misc. Items</u>			
Blast-proof Doors (in Tunnels)	2 pcs.	L. S. =	25,000
Water Pipes - Add'l. Length			
30" diameter	550 L. F.	@ 51 =	28,000
24" diameter	550 L. F.	@ 36 =	19,500
6" diameter	550 L. F.	@ 10 =	5,500
Air Ducts, etc. (incl. closure valves)		L. S. =	22,000
TOTAL - Misc. Items			100,000

*Reference Bu. of Mines' "Manual on Design of Underground Installations in Rock," page 11-32; Prices, based on 1954 Index, increased by 14% for 1957 Index.

Underground Reactor Study (Cont'd)Total

Excavation (Rock).....	\$526,000
Concrete Lining	314,000
Miscellaneous Items	<u>100,000</u>

Total \$940,000

2. Cost Items to be deleted from Cost of Above-ground Plant (See EBWR Cost Reports)Power Plant Building

Excavating and Backfill	\$ 87,000	
Steel Shell (incl. Water Tank)	288,000	
Shell Coatings and Thermal Insulation	54,000	
Concrete Footings for Shell Supports	2,000	
Fill under Shell (concrete).....	40,000	
Concrete inside Shell-1,220 C.Y. @ \$75.....	91,000	
Suspended Ceiling (Missile Protection)	<u>36,000</u>	\$598,000

Service Building

Excavation & Backfill 44' x 37' x 100/27 = 6,000 C.Y. @ \$2.50 = \$ 15,000		
Concrete-Footings 6 x 6 x 2/27 x 16 = 43 C.Y.		
Concrete-Col's. (2.5) ² x 48 x 7/27 = 78 C.Y.		
Concrete Basement Fl. (1.25) ² x 48 x 83/27 = 230 C.Y.		
Concrete Basement Fl. B'ns (2.5) ² x 2 x 83/27 = 38 C.Y.		
Concrete Basement Fl. B'ns 2.5 x 1 x 19.5 x 7/27 = 13 C.Y.		
Concrete Basement Wall 1.25 x 16 x 236/27 = 175 C.Y.		
Concrete 1st Fl. .75 x 90 x 45/27 = 113 C.Y.		
Total of 690 C.Y. @ \$75 =	<u>\$ 52,000</u>	<u>\$ 67,000</u>
Total		\$665,000

3. Summary

Total - Cost of Additional Work	\$ 940,000	
Total - Cost Items to be deleted	<u>665,000</u>	
Difference in Cost	\$ 275,000	
Plus 17% Engr. Contingencies	<u>47,000</u>	
Estimated Increase in Cost for Underground Construction	<u>\$ 322,000</u>	
Total Cost of EBWR (Constr. & Equipment)	\$ 4,628,100	
Estimated Increase in cost for Underground Construction	<u>322,000</u>	= 7%
Estimated Total Cost of EBWR (Underground Construction)	\$ 4,950,100

SECTION A-A
Scale: $\frac{1}{8}'' = 1'-0''$

UNDERGROUND CONSTRUCTION OF POWER REACTOR
 ENGINEERING STUDY BASED ON EBWR PROJECT
 U.S. ATOMIC ENERGY COMMISSION, WASHINGTON, D.C.
 C. Beck, Engineering Br., Division of Construction & Supply
 DRAWING NO. SK-1
 Aug. 28, 1957