“CUT-AND-COVER” DESIGN OF A COMMERCIAL NUCLEAR POWER PLANT

W. KRÖGER, J. ALTES, K. H. ESCHERICH
Institut für Nukleare Sicherheitsforschung, Kernforschungsanlage Jülich GmbH,
Postfach 1913, D-5170 Jülich 1, Germany

SUMMARY

The Institute was requested by the Federal Ministry of the Interior to study the “cut-and-cover design” of a large KWU-PWR (1300 MWe) with support from external experts. The assessment of technical feasibility, costs and the potential protection from extreme accidents were required taking into account actual site conditions.

To ensure licenceability, major redesign of vital parts of the plant was avoided. Increased safety requirements were met by the addition of appropriate modules. An additional annular space accommodates the connection lines. The outer wall of the space acts together with appropriate closures and the adjacent soil, as a further containment. The protection from external effects is increased by lowering the plant and providing sufficiently thick coverage. Depths of 30 and 60 m were taken as limits of lowering.

The penetration of an aircraft is eliminated by a coverage of about 8 m thickness. Dense material is most suitable for this purpose. As a result of embedment and coverage the buildings can resist pressure wave loads up to 3 bar. Medium dense soil with high damping properties is the best material. The protection against conventional weapons attack requires coverage thicknesses between 8 and 20 m with a superimposed concrete slab.

Detailed earthquake calculations with finite-element-models have shown that comparing the aboveground and the underground sited plant it is necessary to differentiate between the reactor building and the internal systems. Stressing of the reactor building itself will be reduced by embedment. Stressing of the internal systems by the energy transmitted through the foundation slab is not reduced in every case. Essentially it depends on the local site conditions. The decisive factor is the thickness of the soil layer between foundation and the rigid rock boundary. In most cases large thicknesses resulted in higher loadings compared with the aboveground sited building. Moreover the frequencies for maximum response rise.

An analysis of the entire spectrum of internal events led to the following results:
— Safety up to the DBA will not be significantly influenced.
— New specific incidents will not contribute to the risk significantly.
— Protection from hypothetical accidents is improved by the additional containment system. The degree of improvement depends directly on the reliability of the closures. Fission products released into the soil or coverage do not cause direct danger for the public. The reactor building can resist the maximum hypothetical pressures and missile impact.

The technical feasibility of constructing pits (Slurry trenches, freezing technique) to a depth of 60 m and with a diameter of 70 m, even in the case of a high groundwater level, has been proved in a study by construction companies.

The main cost factors are pit construction, extended construction period (17 months) and reinforcements of the buildings. Cost estimates indicate an increase in plant costs of the order of 15% to 20%. Naturally a number of new technical problems arise which, however, can be regarded as solvable in view of the present state of science and technology. Economic disadvantages are balanced by the better protection from hypothetical accidents.
1. Introduction

Studies on the underground siting of large nuclear power plants are under way in USA, Sweden, Norway, and Switzerland. In the Federal Republic of Germany, the Minister of the Interior has ordered extensive studies aimed at a comparison of safety engineering effectiveness under extreme accident conditions and of the costs incurred, with an additional assessment of technical feasibility. In view of the topographical conditions, the cut-and-cover technique in soil plays a central role, since this is the only alternative design capable of contributing to the solution of siting problems in this country with its high population density and high level of industrialization. The present study has been carried out in collaboration with external institutions [1]. A pressurized water reactor (1300MWe) of Kraftwerkunion-design served as a reference plant for which a cut-and-cover plant design was to be developed. Actual site conditions were taken into account.

2. Plant Concept

In order to maintain the licensable safety status, a major redesign of the reference plant was avoided, and in particular all of the safety engineering plant components were taken over unchanged. Plant engineering modifications and additional components conform to the present state of the art. The plant concepts are designed according to the modular construction principle, their main features being the embedment and coverage of important buildings. A distinction is made between total embedment (fig.1) and semi-embedment of the reactor building (fig.2) as a possible range of variation for the depth of embedment. This depth would be optimized, in each individual case, according to economic considerations. The depth of embedment for other buildings is governed by plant and safety engineering requirements. The allocation of buildings is the same as that of the above-ground plant (fig.3). For connecting the buildings with the atmosphere, additional tunnels are provided, which are reinforced and located sufficiently high to prevent flooding. They are dimensioned so that transport operations are not impeded during construction, operation and repair phases. The difference of level between the reactor building and the adjoining buildings is made up by an additional annular space, which is divided into sectors and runs around the containment of the above-ground plant. Pipes and cables are run through the coverage in man-sized ducts.

To increase protection against the worst conceivable internal accidents an additional containment will be provided, consisting of the insulated outer wall of the annular space and the adjoining soil or coverage material together with the closures of the remaining connections to the environment. This additional barrier can be designed so as to withstand any potential accidents.
The embedment and coverage of relevant buildings provides an extended protection against external effects. Protection against conventional weapons can be achieved by increasing the thickness of the coverage and superimposing a concrete shield plate with adequate overlap (fig.2, right). In addition to the scope of protection shown in fig.3, the switchgear building (SAG) and the emergency diesel power supply could be incorporated within the coverage, thus being fully protected as well. To secure the supply of energy in times of war it is, moreover, necessary to extend protection to cover all those plant components which are vital for a continued operation and which cannot be repaired immediately after damage or destruction. These include the turbine building, transformer station, cooling water pump house and cooling water lines.

3. Building Pits
The technical feasibility of constructing open pits up to a depth of approx. 60 m in soils, as required for implementing the plant concept, has been proved by construction companies for the site conditions applicable in the Federal Republic of Germany, even in the case of high ground-water levels. For construction of the building pit it will be necessary, in order to avoid extensive lowering of the ground-water, to provide a water-tight enclosure, inside which the ground-water can be lowered during the construction phase. Waterproof bentonite or ice walls are suitable for this purpose and these have already been built down to a depth of more than 100 m.

According to the present state of the art, slurry trenches and freezing techniques may be used for the vertical walls of the excavation (fig.1). Waterproofing of the buildings against ground-water is effected by using either steel plates or a bituminous sealing. Because the excavation walls are vertical, the simultaneous erection of the various ancillary buildings would be possible.

4. External Effects
4.1 Aircraft Impact
As in the case of the above-ground buildings, the military aircraft "Phantom II" (flight weight 20 M, impact velocity 215 m/s) serves as the design basis. Based on about two thirds of the flight weight and a diameter of 2 m, a penetration depth of about 7 m in gravel and sand has been calculated, using the Petry formula. An essential advantage of soil coverage over a concrete wall lies in the fact that the loaded surface of the structure is increased, resulting in more favorable stressing conditions.

4.2 Pressure Wave
The coverage with soil and embedment of the buildings will generally increase their resistivity against pressure waves and preclude overturning.
For the concept of total embedment, calculations assuming the atomic detonation of a large bomb have led to maximum acceptable horizontal free-field pressures of up to 2.2 bars, and up to 5.5 bars for a small bomb. The higher permissible pressures for small bombs result from the shorter positive pressure phase. Finite element calculations have led to maximum permissible values of up to 4.5 bars for vertical free-field pressures caused by detonating gas-air mixtures.

4.3 Weapons Effect
Protection against the conventional weapons which might be used by saboteurs or terrorists or in time of war requires coverages of between 8 and 20 m, depending on the type of weapon assumed, with a superimposed shield plate made of concrete (fig.2). This will give protection against even the heaviest types of bomb. The turbine building and the pump house could be incorporated into the protection against weapons to ensure supply security.

4.4 Earthquake
Embedding the buildings in soil changes their seismic response behaviour as compared to surface buildings, i.e. a higher stiffness and increased radiation damping is attained. Finite element models are best suited for determining the effects of embedment and of a layered subsoil. The code used was the LUSH2-programme, which is applicable to 2-dimensional problems and provides an approximate treatment for non-linear dynamic soil behaviour. For embedded buildings there is, according to [2], a good agreement between 2- and 3-dimensional models of the response for points below the soil surface. It is therefore permissible to use the less costly 2-dimensional programmes.

To simulate earthquake excitation, three different acceleration-time histories, derived from actual measurements and from artificial synthesis, with differing response spectra were fed in. The soil characteristics assumed are applicable to a representative site in Germany.

Three different types of models were examined, using analytical models with only a few elements for parametric studies and with up to 716 elements for more precise calculations. A comparison was made between the semi-embedment, the total embedment (fig.4), and installation of the reactor building above-ground (fig.5).

The results of the calculations show that the three acceleration-time histories lead to different peak stresses due to different spectral intensities, but that the acceleration pattern as a function of depth are similar. It does not even change significantly with variations in the dynamic shear modulus and critical damping of the soil layers. As was to
be expected, high shear moduli (dense or hard soil) and low damping values result in higher stresses than small shear moduli and high damping values.

The acceleration pattern is strongly influenced by the thickness of the soil layer between the rigid base and the foundation plate of the building. In the case of thick strata, accelerations will decrease towards the soil surface, whereas they increase with less thick strata (amplification) (fig.6). This phenomenon is independent of the level of embedment of the reactor building.

To answer the question as to which siting will involve lower accelerations a distinction must be made between the reactor building proper and the internals which are excited via the foundation plate. In general, the embedded reactor building is less stressed than in the case of siting above-ground.

In general it may also be said, that in the case of thick soil strata, the internals are slightly less affected by stressing due to the increase in accelerations than in the case of the building being sited below ground level (fig.7).

The shift of maximum response towards higher frequencies was confirmed by the investigations conducted. Calculations have resulted in a similar behaviour in earthquake conditions for semi- and totally embedded reactor buildings. The height of the coverage and the thickness of the superimposed concrete slab have no significant influence on earthquake response. The protection potential of embedded buildings, erected on thick soil strata, is assessed as being similar to that of above-ground buildings.

5. Safety against Internal Accidents

The safety analysis has been based on a number of representative accidents. Design basis accidents will, essentially remain unaffected, since the systems concerned have been taken over unchanged. The probability of occurrence of a rupture in the live-steam or feed-water lines increases by a factor 2 on account of the increase in length by a maximum of 20 m only for each line. These lines will be accommodated in a pressure-proof annular space sector, so that any effects are confined to this area.

Only in the event of hypothetical accidents, involving a loss of all heat sinks and failure of the primary containment, the additional confinement will become effective. The maximum internal pressure of approx. 4 atms. is reached immediately after failure of the containment.

Load limit studies show that the reactor building can be made to be capable of withstanding such loads as well as concentrated surface loads.
Pressure balance processes via the lower annular space are considerably less probable in German plants and will not lead to higher loads. Owing to the large surface involved, the post-accident concentration of non-rare-gas fission products in the free atmosphere is reduced by at least a factor of 10.

If, in addition to this, the occurrence of continuous cracks from the building wall to the surrounding soil and coverage is also assumed, the solid material will constitute a large heat sink and fission product barrier.

The rupture of a secondary cooling water line with flooding of the reactor building is the most significant design-specific accident. However, the mere fact of its low probability of occurrence, estimated to be $10^{-10}$/a or $10^{-13}$/a in conjunction with a melting accident, prevents it from contributing to the overall risk and, by taking additional design measures, it can be eliminated almost entirely. The gain in safety for hypothetical accidents is directly dependent on the reliability of closures between the remaining connections and the atmosphere. For this purpose, redundant, diverse shut-off devices and air locks will be provided and the tunnels and shafts will be designed so as to meet extreme requirements. The overall reliability will be about $10^{-3}$/requirement and this is governed by the big tunnel locks.

6. Cost and Time of Construction

The underground siting will result in additional costs, which have been calculated on the basis of comparable costs incurred for an above-ground plant of equal unit power (~1.51 thousand million DM). Depending on the scope of protection, the contract prices for a total embedment will be higher by about 11 to 14% and by only 8 to 10% for semi-embedment. These additional costs are essentially accounted for by the cost of the building pit (2-4%), soil coverage (~1%), concrete shield plate, if any (~1%), and additional expenses incurred for tunnels, etc. (~3%), and not so much by increased costs of building construction (~1.5%).

In principle, the construction phase itself does not involve any particular difficulties, apart from an extension of the construction period by 1.4 years in total, caused by the construction of the pit. This will entail longer price escalations and higher tax and interest costs, resulting in an increase in construction cost of 16 to 19% for total embedment and 13 to 15% for semi-embedment. On the other hand, lower decommissioning costs may be assumed, permitting a reduction of the absolute additional expense in total capital expenditures by about 50%.
However, the effects of these additional costs incurred for the plant will not be reflected linearly in the cost of electricity production, partly on account of the concept-independent share of variable costs. Despite higher estimates for operational expenses, the specific cost of electricity will only rise by 6 to 8% in the case of total embedment and 5 to 6% in the case of semi-embedment. Even if it is assumed that substitute power will have to be procured for a period of 1.4 years due to the delayed commissioning of an underground sited plant, the additional costs incurred will in no case reach 20%.

References


Fig. 1: Total embedment of the reactor building; section with open pit

Fig. 2: Semi embedment of the reactor building; section with different coverage
Fig. 3: Site plan of a totally embedded plant

Fig. 4: Finite-element model for the totally embedded reactor building

Fig. 5: Finite-element model for the reactor building sited above-ground

Fig. 6: Influence of the thickness of the soil layer on the accelerations

Fig. 7: Horizontal and vertical accelerations for the totally embedded and above-ground sited reactor building