RADIATION PROTECTION BY DESIGN – THE EPR

Patrick Jolivet, AREVA NP SAS, Paris, France
Ian R Terry, AREVA NP GmbH, Erlangen,Germany

1 Introduction

The EPR is the first third-generation PWR to have achieved a market breakthrough. The first steps toward realization of an EPR nuclear power plant were taken here in Finland at Olkiluoto. Concrete pouring for this FOAK EPR began in spring of 2005 and the unit will start commercial operation in 2011. Construction of a follow-up EPR was also given the go-ahead in France. The new reactor is being built as a forerunner of a later series at the site of Flamanville in Normandy. Construction of FA3 began in 2007.

Consideration of radioprotection in the early design stage involved several domains such as the choice of materials and the optimization of the thickness of biological shielding with regard to the expected nuclide source term while considering accessibility needs. With this perspective the iterative checking of different options for component design and layout for all systems of the controlled area is a key issue. For all these aspects, an ALARA methodology (As Low As Reasonably Achievable) was adopted during design, where the notion of dose became an additional design requirement. On this point, the EPR design constitutes a major improvement compared to most of existing plants. Keeping the doses received by operating and maintenance personnel to a level far below the limiting values was one of the main objectives of the EPR design. A unique feature of the design is also to allow post-accident management under radiation protected conditions.

Internationally comparable limits based on recommendations of the International Commission on Radiological Protection (ICRP) have been established for individual doses. These limits describe the framework within which the individual dose shall be kept as low as possible, applying the well-known principles of:

- Justification
- Optimization
- Limitation

In a nutshell the aim of these recommendations is to avoid doses without benefit on the one hand, and not to reduce doses at all costs on the other. In all cases doses have to be kept below actual limits set by regulatory bodies.

The first principle (justification) is very general. It has a practical application in the ALARA methodology when questioning the usefulness of a task to be performed for the operation and maintenance of a nuclear power plant. It is a complex theme since often the definition of benefit is not clear and is much discussed. For example, can something be achieved without dose, and if so, then what are the chances and risks associated with it? In the case of the EPR fortunately this could be based on sound pragmatic engineering judgment.

The second principle (optimization) requires the implementation of an optimization process at the design stage. In fact, because resources for protection are not unlimited, the engineering process should be such that a balance between the cost of protection measures (reduction of sources, shielding, and use of remote handling technologies) and the corresponding saving in doses is achieved. This can be performed either by drawing on experience or application of alpha-factor costing analysis if experience is not available. In the case of the EPR a wealth of experience in both countries could be applied.

The third principle (limitation) sets the boundary conditions for radiation exposure. Here the well-known 20 mSv per year is applied for workers. For members of the public the corresponding value for the upper limit of radiation exposure is 1 mSv per year for the effective dose.

The described basic principles combined with experience feedback from existing nuclear power plants in France and Germany are the basis for achieving the ambitious goals for EPR design.

2 Dose target

The collective exposure target, which shall be fulfilled by the EPR in normal operation, is specified as follows:

- A collective dose of 0.5 man-Sv per year has to be kept for EUR. Routine maintenance and a standard in-service inspection program have to be taken into account. This is an average over the years of normal operation.

By target we imply, of course, that the collective dose is constrained not to reach this target. The target is meant in the sense of expressing an upper ceiling below which design dose estimation results have to remain.

The target was based on an analysis of the actual data from French and German PWRs at the time of specification in 1992. The best results at that time were 0.2 man-Sv per year per unit for the newest Konvoi-plants (this value should be compared to the initial design target of 1 man-Sv per year for these plants).

The fact that the EPR target is below the Konvoi target (1 man-Sv per year) should be underlined. The clear fulfilment of the target by the Konvoi in reality is primarily based on the dose rate level which is considerably lower than originally expected. Thus comparison of Konvoi with EPR can only be made via the design targets, the EPR target being half that of the Konvoi.

After 1992 a general dose decrease was observed but for the following reasons it was decided to retain the 0.5 man-Sv target of the EPR in spite of the low doses later experienced in reality:

- The target itself has to meet the ALARA criteria in any case, i.e. the target should not be based on the lowest dose experienced.

- The Konvoi design, which shows the lowest personnel exposure data is not a model for an ALARA design, but rather for an ALAP one (ALAP = as low as possible)

- Reduction in radiation protection design of predecessor plants is applied when the experience feedback shows a degree of too high conservatism (for example, the shielding is too thick). This could lead to the logical consequence of an increase in collective personnel exposure.

- Fluctuations of operational parameters which can influence the dose rate level have to be taken into account by the target. It has to be considered that during single years the dose rate level and consequently the personnel exposure will be higher than in “normal” years. The operation should not be unnecessarily restricted because of such events. The design and the target should already cover such events.

3 Factors affecting dose

The limitation of personnel individual and collective doses is influenced by various factors.. The basis is created during the design process. The EPR design was aimed to use the latest developments and existing operating experience to improve on existing design. The utility which operates a nuclear power plant also exerts control on personnel doses. Finally, the nuclear authority which supervises plant operation and which forces the designers as well as the utilities to consider current national and international practice affects the collective doses.

The current paper is concentrated on aspects which are related to only the design process such as:

- Measures to avoid or to reduce sources of radiation
- Layout aspects
- Provisions made in the component design with respect to ease of operation and maintenance management
- Improved decontamination facilities
- Use of operating experience for design improvements.

Personnel exposure is influenced only to a very limited degree by the shielding design and the fission product level. During maintenance work and repairs, especially in the dose-relevant refuelling phase, personnel exposure is primarily caused by corrosion product deposits and the unshielded dose rate of the component to be processed. Therefore among other factors determining the source term, special attention is given to the choice of materials.

In order to avoid hot spots, components and piping in activity containing systems are designed so that deposits are limited, e.g. corners, gaps and dead zones of flow are avoided, a sufficient flow velocity in pumps, valves, piping is chosen. A suitable chemical specification is implemented. Purification means (demineralizers, degasifiers) are designed to reduce the fission and corrosion products in the primary coolant as much as possible.

Layout features contribute to reducing the collective dose, such features can be accessibility, separation, shielding, handling, set down areas, etc.

In addition to source term reduction and layout considerations, attention was also given to some component design features.

Experience feedback from French and German plants was used in the project. It was used for setting specific objectives for selected work areas and as a guideline for follow-up and review. This experience is used to evaluate qualitatively the effect of the respective radiation protection measure.

Based on the means to keep doses low and on a sound operation and maintenance strategy it can be reliably envisaged that the plant can be operated within its collective dose target. The implemented provisions to keep dose low have to provide the opportunity of outage preparing maintenance during reactor operation also within the containment. The calculations for this used advanced simulation tools for gamma and neutron propagation for the design of new reactors such as the EPR. The reactor availability foreseen for the EPR imposes short duration outages and thus access during power operation to certain areas of the reactor building is required for preparation of the outage in order to make the duration short. This constitutes a new situation with regard to the existing French units. As an example of consideration of radiation protection in the design dedicated Monte-Carlo calculations for radiation propagation for all walls adjacent to the accessible areas were made for optimization purposes. The issue was to verify that the general layout of the reactor building was compatible with the design targets for neutron and gamma dose rates.

One of the main radioactive sources in the steam generator and reactor coolant pump rooms is that of nitrogen-16. Neutron and gamma radiation originating from the core are also considered in these calculations. In particular, the low dose rate levels in the accessible areas of the annular spaces and service floor and the difficulty of consideration of the neutron streaming through the openings in the concrete required the use of Monte-Carlo type calculation codes, rather than the classic methods of analytical calculation. Because of the huge dimensions of the modeled geometry (Figure 1) the calculations implemented for the EPR by this method constituted a first-of-a-kind. Some modifications of walls were required with regard to the basic layout to take into account access to the reactor building during full power operation with doses lower than 25 µSv/h.

Furthermore, design involved narrow collaboration with particular disciplines such as layout, civil engineering and ventilation. It was necessary to assure the coherence of the radiation protection requirements which resulted from these calculations in parallel with the reactor or the civil engineering layout (available space, radiological classification of rooms, concrete density and composition).

4 Reduction of radiation sources

The system sizing and the biological shielding are adapted to the expected dose rates estimated around the components. These are the result of the activity of the conveyed fluid (activated products, soluble fission or corrosion products) but also the build-up of surface contamination during the normal operation of the reactor mainly due to activated corrosion products. This latter nuclide "source term" is a function of the RCS-wetted materials, the capacity of purification systems, and the chemistry of the primary fluid. The design values in deposited corrosion products for the radiation protection studies of the EPR were determined in a realistic way, firstly from the experience gained in plants designed by AREVA.

An example is the optimization of the surface of cobalt-based hard-facings in the RPV and RPV internals. These materials are known for causing the long-term contamination of the plants because of the cobalt-60 half life (5.3 years). Figure 2 illustrates the link between the amount of cobalt hard-facing and the average dose rate measured around the loops on various generations of German power plants. To reduce dose rate and thus the collective exposure, a decrease in the inventory of cobalt is necessary particularly in the RPV and internals prone to large neutron fields. But the experience feedback from different generations of German plants shows that below a certain amount further suppression of cobalt-based materials has only a limited effect on doses. For the EPR the method consisted, in agreement with the specialists of materials and primary components, in optimizing the quantity and the location of these cobalt hard-facings to obtain a considerable reduction in the "source term" with cobalt 60 with regard to most of the existing units, while limiting the industrial risks connected to the life expectancy of EPR aimed of 60 years.

This result is made also possible by the fact that the amount of residual cobalt specified for impurity content in nickel-base alloys (SG tubing) and stainless steels wetted by the primary circuit is based on the lowest values observed on the most recent AREVA plants without over-cost for the main primary components.

This optimization of the nuclide "source term" in corrosion products is an example of the ALARA approach at the design stage which allows dose constraints to be met while keeping dimensioning of shielding in a realistic domain.

5 Layout aspects

Layout aspects contribute to collective dose reduction through features such as ease of accessibility, separation, shielding, handling, set down areas.

The buildings and compartments of the plant and their access routes, connecting corridors, personnel and equipment air locks are arranged and designed such that:

- the equipment and personnel required for the performance of work pass the health physics checks (checking of access permits and work clearance, contamination check etc.) without unnecessary hampering, and that the personnel is not unnecessarily exposed to radiation at other points on passage within the plant;

The basic concept for the controlled area provides for strict physical separation (shielding) of the systems as well as redundant trains.

Moreover, the layout features a separate and sequential arrangement in the form of (see Figure 3)

- passageways,
- service compartments or corridors,
- pump and valve compartments,
- compartments containing tanks, heat exchangers, etc.

The building concept ensures that those items of the plant which emit a high level of radiation can be accessed via the entrance and exit routes without significant exposure to radiation and that the dose rate at the individual components is influenced as little as possible by adjacent items.

Since increasing distance from the source does not significantly enhance the attenuation of the radiation emitted by large components such as tanks and heat exchangers, the plant is subdivided into individual compartments in which large components with high dose rates are installed.

Separately shielded compartments are provided for small components (valves, pumps) unless they must be installed near other components. Here, too, the components are separated, depending on dose rate, component size and processes involved.

Special piping ducts are foreseen to reduce the sources of radiation and to provide more space in other compartments.

Facilities for local normal operation are installed in special shielded compartments (service corridors, control stations, etc.) depending on frequency of occupancy and dose rate.

Generally, access to the individual compartments is via separate passageways or stairways in which the local dose rate is less than 10 µSv/h. The access route is designed such that the associated radiation exposure in passage is small compared with the radiation exposure in the compartment to be entered.

Sufficient space is provided for:

- work preparation and supervision in locations with low dose rate,
- dismantling and assembly within the compartments,
- setdown of radioactive/contaminated parts outside the passageways,
- wearing of protective clothing and respirators.

6 Component design

The amount of work spent on maintenance inspections shall be in a balanced scope for reasons of radiation protection. Components are designed to reduce the frequency of maintenance work and the necessary effort involved per operation.

Work areas giving the most important contribution to the exposure doses have been selected to be subject of design recommendations, including possible use of remote control, e.g.:

- pressurizer and reactor coolant lines inspection
- steam generator inspection (primary and secondary side manways, plugs, tube material)
- opening, closing the reactor vessel head
- inspection of the reactor pressure vessel (number of welds)
- primary valve maintenance
- reactor coolant pump maintenance
- fuel inspection
- reactor pit draining and cleaning.

Attention has been paid to potential dose reductions in the scope of in-service inspections; in particular, the number of welds to be inspected in areas with high local dose rates is kept to a minimum. The welds are designed so as to facilitate in-service inspections.

Areas and components provided for in-service inspections as well as areas of nozzles, man-ways, support brackets, etc., will be fitted with quickly removable and reusable thermal insulation. A further basic design aim is to install as far as possible maintenance-free components in areas with relatively high dose rates. Components which include moving parts that require maintenance are designed to permit maintenance intervals which are as long as possible and to require only a minimum of maintenance effort. The amount of in-situ inspections is kept as low as possible in the light of the local dose rate. Whenever possible, inspections are performed from areas with low dose rates (e.g. functional tests are performed from shielded areas).

Valves and pumps are designed to eliminate the occurrence of leaks which would necessitate repairs. Components and piping are designed such that deposits of radioactive materials will be avoided as far as possible (e.g. avoidance of traps and pockets). Large vessels in which higher dose rates are to be expected due to deposits are provided with a flange connection, if necessary, via which decontamination can be performed to reduce the dose rate prior to major maintenance work. These connections are located separately, not in the vessel room.

Components and their elements are arranged such that they can be:

- tested for operability on the scale required
- maintained, inspected and repaired as prescribed in the operating instructions
- replaced if they have a shorter lifetime than the plant

in a manner that will ensure that the exposure to the personnel engaged in these operations will be ALARA.

Auxiliary equipment makes it possible to complete work in a shorter period of time or with less personnel or at a lower local dose rate. Such facilities are planned and introduced where necessary.

Utilization of special tools and remote controlled equipment is planned with a view to reducing exposure to radiation. This applies especially to:

- handling of the core internals and fuel assemblies under water,
- stud tensioning devices for RPV cover and the man-way covers of the steam generators and pressurizer,
- special weld inspection rails on primary piping and on steam generators (see Figure 4)
- special filter changing equipment for replacing intensely radiating water purification filters,
- handling of intermediate-level radioactive waste drums in the drum store,
- valve stem penetrations through shielding walls for remote actuation of certain valves.

The following examples of features are considered and are implemented on a case-by-case basis:

- Shielding of non-radioactive supply systems from radioactive components (e.g. the seal water supply to certain pumps).
- Sampling points and transducers are installed in compartment areas with a low local dose rate.
- Within the compartments, components are arranged according to their anticipated dose rates. Components with the highest dose rates are installed at the rear of the compartment.
- Permanent platforms are provided to avoid scaffolding work.
- Components requiring operator actions or servicing are not installed in piping ducts (exceptions are necessary where system requirements take priority: e.g. isolation valves in the containment).
- Where contamination can be expected, the concrete structures is provided with a suitable coating to achieve an easily decontaminable surface.

7 Post-accident management

One design feature of the EPR is the retention and spreading area below the RPV to control severe accidents, i.e core meltdown with RPV failure. Subsequently provisions have to be made for accessibility to equipment maintaining safe-conditions during management of the accident. These are basically the sampling system, which provides information on the accident, and the heat removal systems. Since the core melt scenario is the worst case the EPR radiation protection design uses this accident as a basis.

Full occupancy of the main control room without restrictions is another feature of the EPR, the external radiation level not exceeding 1 µSv/h during the course of the accident. Full accessibility to the site is also ensured.

Unlike other philosophies the EPR post-accident radiation protection design does not allow excessive doses to the staff during accidents as based on probability. The individual dose is basic to health and safety regardless of how it is caused. Thus the EPR design ensures that the individual doses for post-accident management are below 50 mSv. This value is more in line with annual dose limits from normal operations. Radiation protection is ensured by designing the appropriate shielding to maintain low dose rates. Thus the shielding is designed to prevent an individual dose of 1mSv on the routes to the sampling and heat removal areas. This is ensured by a dose assessment analysis.

Since the continuous operation of the pumps removing the excess heat is essential they are of separate redundant design. These are the residual heat removal pumps in the case of a LOCA and the containment heat removal pumps for the core meltdown case. If a pump fails then it must be repaired in order to maintain the redundant feature. The shielding design allows the pump rooms to be approached by holding the dose rate to 0.1 mSv/h outside the room at a preparation position. This can be seen in Figure 5. At this position hose connections and valve actuation controls are provided to allow for the remote draining and flushing of the pump in question. Thus the extremely high dose rates in the pump room are reduced to levels ensuring accessibility to the room – essential for further measures and subsequent pump repair.

8 Conclusion

In this limited paper we have shown that unique radiation protection features in the EPR will constrain both individual doses and the collective dose to low levels, -by ALARA-based design. This applies not only to normal operations but also to the unlikely extreme accident event.

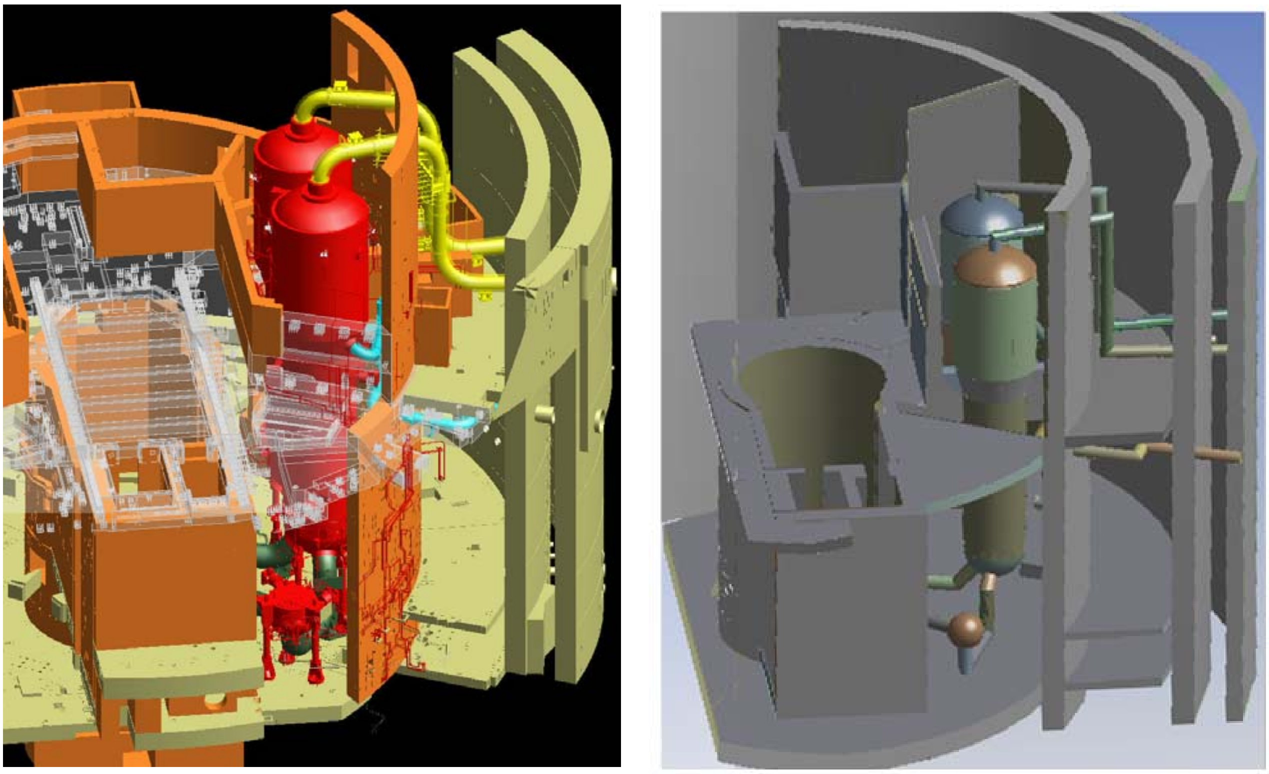

Figure 1. Comparison between the 3D model (left) and MCNP modelling

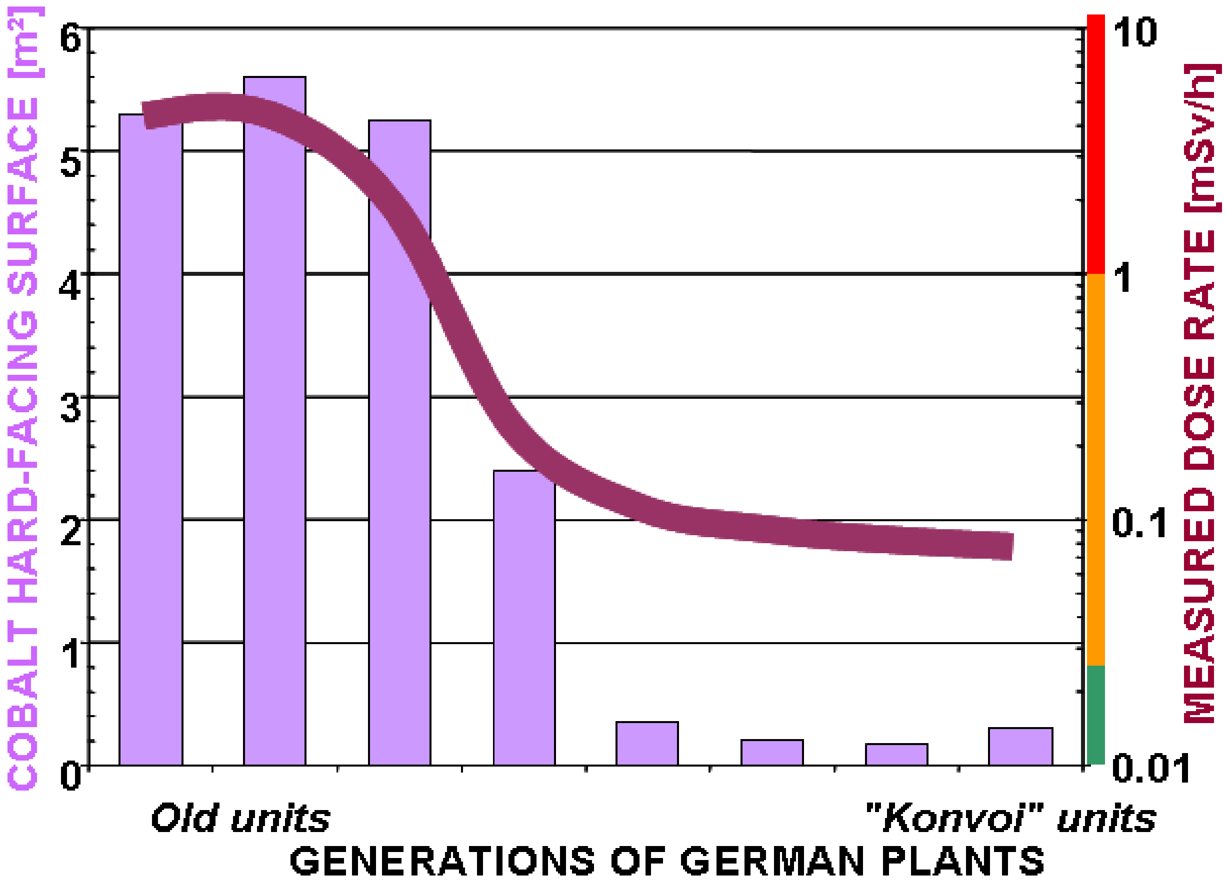

Figure 2. Illustration of the link between cobalt hard-facing and dose rate

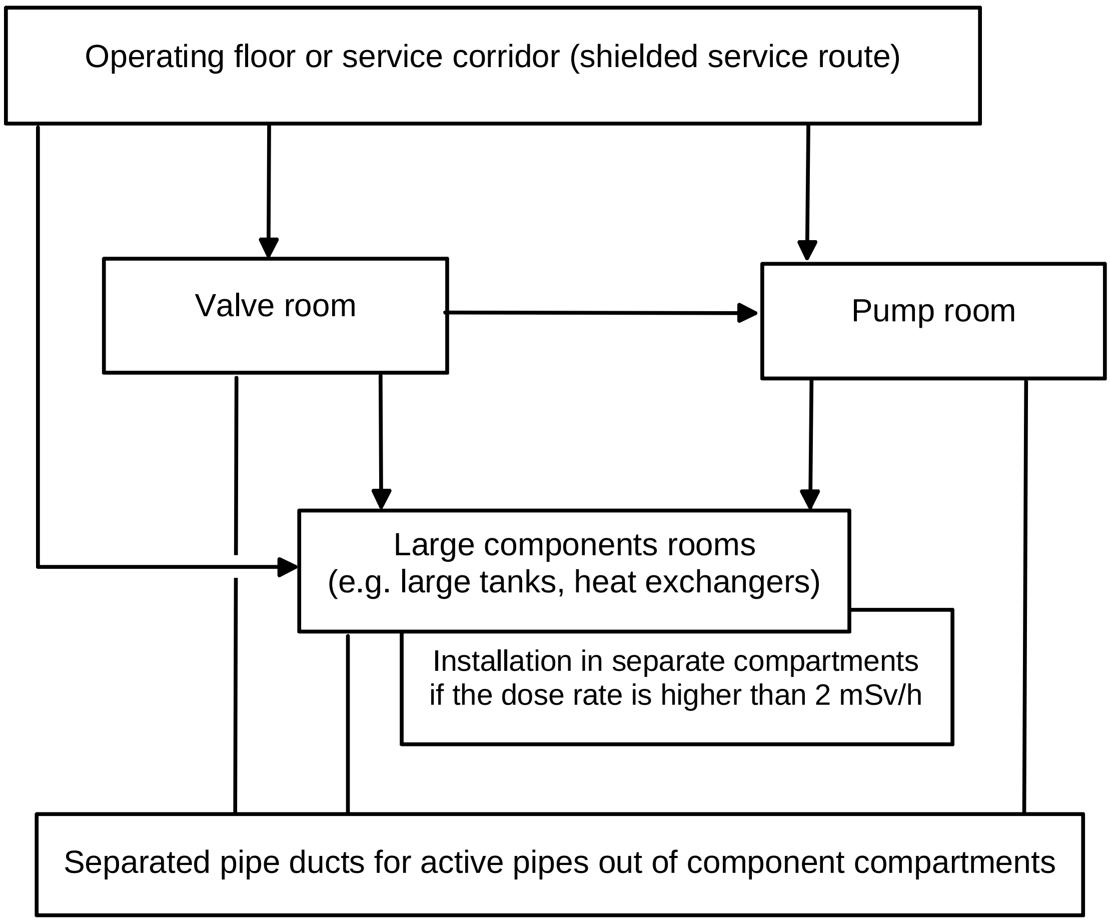

Figure 3: Principle scheme of compartment access

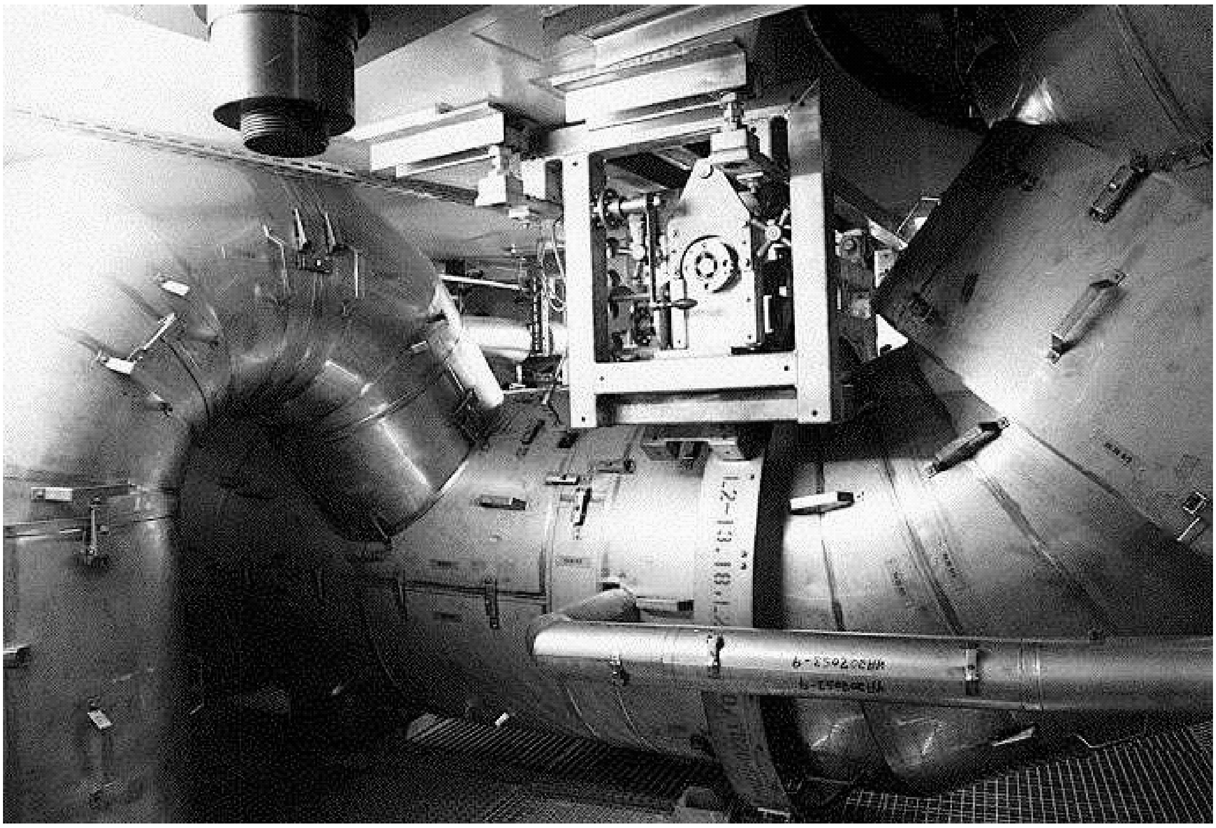

Figure 4: Main coolant pipe inspection rails

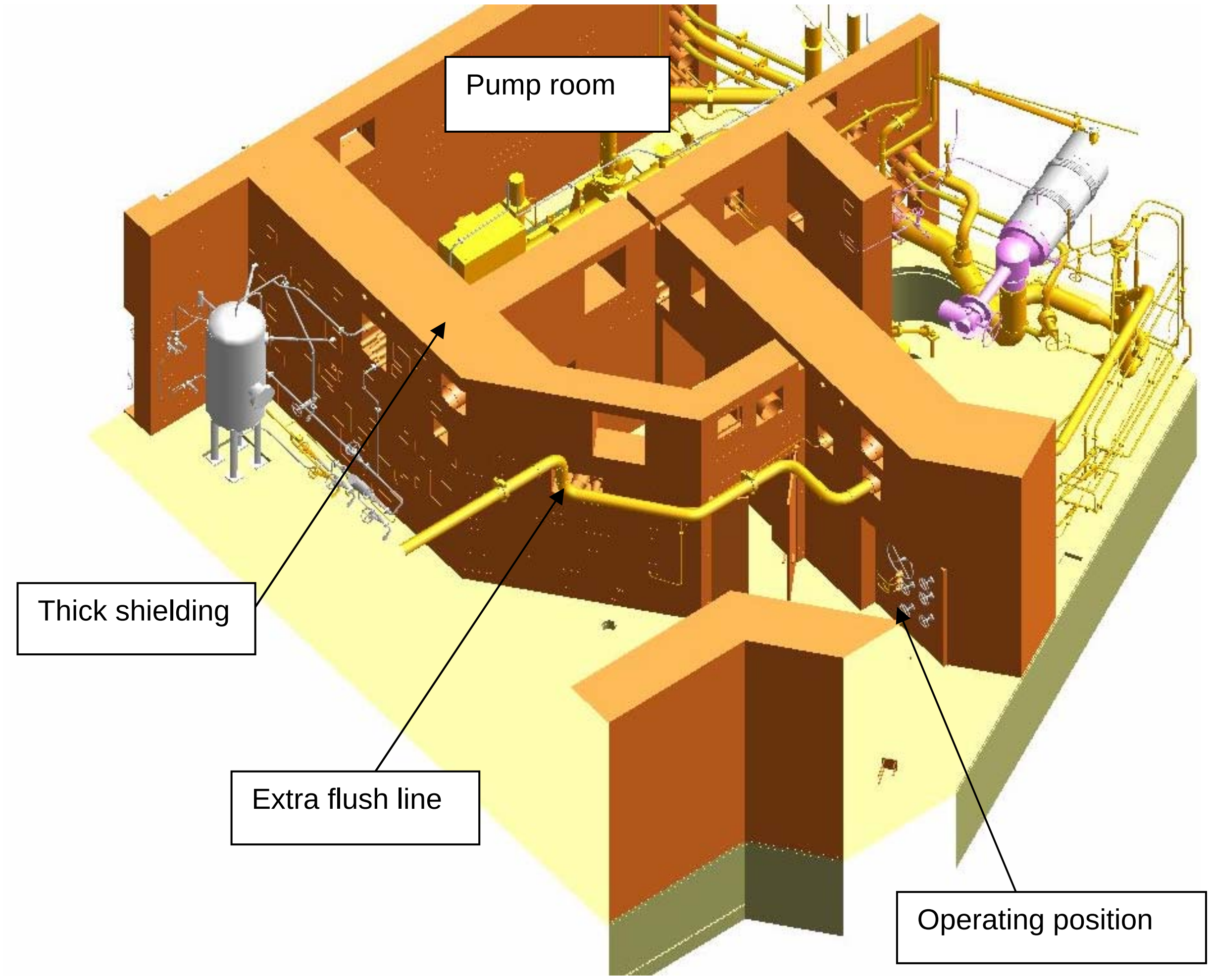

Figure 5. Design features in the Safeguards Building for post-accident management