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SUB-CHAPTER 17.3 - EPR DESIGN OPTIONEERING

1. INTRODUCTION

Sub-chapter 17.3 describes the optioneering process carried out in France and Germany between 1987 and 2006 to develop the EPR design, and the design review carried out by independent safety experts on behalf of the French and German safety authorities.

The present sub-chapter presents the outcome of the design optioneering process in terms of the principal design options that were selected and rejected to achieve a balanced design that minimised risk to workers and the public, while achieving practical constructability and a cost-effective design. The rationale for the evolution of the design, and the improvements from predecessor designs, are explained along with the reasons why certain features were selected and others rejected.

This sub-chapter is organised as follows:

- Section 2 describes the optioneering of safety systems and structures protecting against accidental release of radioactivity

- Sections 3 and 4 describe the optimisation of the design to minimise doses to workers and the general public due to plant operation

- Section 5 describes the role played by PSA in achieving a design which minimises risk

- Section 6 presents the conclusion that, although formal principles of As Low As Reasonably Practicable (ALARP) were not applied as an integral part of the EPR design process, the process of design optimisation to minimise risk due to accidents and to optimise operator dose in normal plant operation and accidents was closely analogous to the formal UK approach of ALARP.

2. OUTCOME OF OPTIONEERING PROCESS – SAFETY SYSTEMS/STRUCTURES

2.1. GENERAL DESIGN PRINCIPLES

International studies on the safety approach for the next generation of Nuclear Power Plants (NPPs) (for example, IAEA studies) have stressed the importance of strengthening the defence in depth concept, and achieving greater independence between the barriers preventing release of radioactivity to the environment. These measures require, amongst other aspects, explicit consideration of severe accidents in the design of the containment system.

The main elements of the defence-in-depth concept that have been used as a basis for the design of the EPR are:

- Balance between the different levels of protection,
- Level of independence between different levels of protection,
- Achieving an appropriate balance between the prevention and the mitigation of accident situations,
- Achieving an adequate level of conservatism in the design and in the protection of the barriers,
- Increased emphasis on shutdown states and on specific events that may result in potential containment bypass.

The above considerations have led to a number of design enhancements for the EPR compared with the previous generation of PWRs operating in France and Germany (particularly the N4 and Konvoi designs). Some of the significant enhancements are reviewed in the following sections.

Furthermore, the EPR has been developed to address all issues of safety, public perception and economic operation. Experience to date in both France and Germany on standardisation of plant design has been a major factor in the overall EPR design.

2.2. RESULTS OF DESIGN OPTIMISATION

2.2.1. Plant size

Like other new plant design processes, the EPR design process began by defining the intended plant size. Current experience in France, Germany, and the rest of the world indicated that the new plant sizes, at least for the foreseeable future, will be large (> 900 MWe).

The preference for larger plant sizes is based on proven operating experience; the economic advantage of an increased unit size based on available proven technology has also been a major influence.

2.2.2. Containment design

To meet the safety objectives for EPR, modifications to the containment design were required to improve protection against uncontrolled environmental releases in design scope conditions (see Sub-chapter 3.1). In such accident situations, the requirement was that the structural integrity of the containment and its leak-tightness must be preserved.

The initial concept chosen for the EPR containment building was a double-wall containment based on technology derived from the current French N4 containment design. The inner wall is a pre-stressed concrete shell. The outer wall is made of reinforced concrete and forms part of a global “aircraft shell” that protects most parts of the nuclear island from aircraft impact and other external hazards. The two walls are separated by an inter-wall annulus, which is maintained at a sub-atmospheric pressure so that leakages from the inner containment can be collected and filtered before being discharged to atmosphere via the stack. The double-wall containment building stands on a reinforced concrete basemat.

The main technological and design principles for the EPR containment chosen to satisfy the required specifications and their evolution are as described below:

- An internal containment volume of 75,000 m^3 was initially chosen to reduce the risk of a global hydrogen detonation. This resulted in the maximum concentration of hydrogen in dry air within the range 10 to 13%. Taking into account the 241 fuel assemblies in the core, passive hydrogen recombiners and a target maximum hydrogen concentration of 10%, optimisation studies resulted in the free volume being increased to 80,000 m^3,

- The containment outer wall, made of reinforced concrete, is designed to withstand loads resulting from external hazards (earthquake, explosion, airplane crash, etc) and for leak recovery. Compared to the loads used in the design of the French N4 plants, the loading combinations due to external hazards considered for the EPR are greatly increased. In particular, the seismic level considered corresponds to a zero period ground acceleration of 0.25 g, and the external explosion load corresponds to an incident pressure wave of 100 mbar. The design of the EPR to withstand aircraft crash initially considered only loads due to the impact of military jet fighters. However, after the 9/11 event, the design loads on the outer wall were considerably increased to embrace a wide range of potential terrorist attacks, including the deliberate crashing of a large commercial aircraft,

- To minimise the possibility of containment bypass events, specific design criteria have been implemented to prevent direct leakages from the Reactor Building to the environment. These include a requirement that all pipes carrying radioactive substances passing through the containment wall pass into sealed peripheral buildings so there is no direct release route from inside the containment to the environment. Therefore the peripheral buildings are considered to form part of the containment function.

- In addition to this initial design requirement, an extensive study of all potential bypasses of the containment function due to the failure of equipment connected to pipework passing from the containment building to peripheral buildings, has been performed. This study resulted in changes to the design of some fluid circuits, including installation of complementary isolation methods (see below),

- In the initial design, the leak tightness of the containment was achieved using a partial composite liner on the inner face of the internal wall. Tests were conducted on a large scale mock-up (with and without the composite liner) to gain experience of the behaviour of such a system, using dry air and air/steam mixtures in pressurised conditions. On the basis of the results of these tests, and experience feedback from current French plants, it was decided to change to the use of a steel liner inside the containment in order to improve its leak tightness, particularly for the case of severe accidents conditions.

2.2.3. Design improvements to avoid containment bypass events

Consideration has been given to fault sequences in which radioactive materials might be released to the environment via fluid systems connected to the Reactor Coolant Circuit (e.g. the Safety Injection/Residual Heat Removal System, the Chemical and Volume Control System, the Extra Boration System etc.), thus effectively bypassing the containment function.

The risk of containment bypass via Steam Generator Tube Rupture (SGTR) has also been analysed in the containment design process. Design provisions adopted for EPR, particularly the requirement for the maximum head developed by the safety injection pumps to be below the set pressure of the safety relief valves on the secondary system, the automatic initiation of fast RCP [RCS] cooldown, and the requirement for automatic shutdown of Chemical and Volume Control System charging pumps on detection of a high water level in the Steam Generators, reduce the risk of primary coolant bypassing the containment through the secondary system.

Functional analysis and quantification of the potential initiators to evaluate the risk of bypass for each of the scenarios considered using PSA methods has suggested that the risk due to bypass is very low. The current PSA presented in Sub-chapter 15 is an update of this initial analysis and is reviewed in Sub-chapter 17.4.

2.2.4. Design for mitigation of severe accidents

A key design objective for EPR was to achieve a significant reduction in potential radioactive releases due to all conceivable accidents in comparison with current plants, including core melt accidents. In the framework of EPR design, this objective requires that:

- Accident situations involving core melt which lead to large early releases must be “practically eliminated” during the design process. This objective applies in particular to high pressure core melt sequences,

- Low pressure core melt sequences must be dealt with so that the maximum conceivable release would necessitate only very limited public protective measures in the vicinity of the plant.

As a result of these requirements, and considering the basis of the defence-in-depth concept that the core melt would have to be cooled outside the reactor pressure vessel, specific means have been designed and implemented to protect the containment building, and in particular its basemat, from the effects of core melt.

For the basemat protection, the original solution selected for the EPR was to allow spreading of the core melt debris over a large area outside the reactor pit. The overall aim of the concept was to stabilise the molten debris by water cooling inside the containment, thus avoiding a long-term release of fission products into the environment, due to excessive thermal loads or damage to structures causing loss of the containment function.

The spreading area which is maintained in dry conditions during normal operation is designed to avoid hydrogen production due to interaction between the basemat concrete and corium. It is connected to the in-containment refuelling water storage tank (IRWST) by pipes which flood the corium once it has spread into the compartment.

In addition, and in order to limit the pressure increase and to decrease this pressure inside the containment as rapidly as possible, a Containment Heat Removal System has been implemented to cool the water used to fill the spreading compartment. This system, which has no active components inside the containment, is a two train system cooled by an intermediate active system for which power is supplied by two specific diesel generators in the event of failure of other emergency power sources.

With regard to control of hydrogen concentration, several solutions were considered including recombiners and igniters to prevent global detonation or deflagration due to high hydrogen concentrations. Passive autocatalytic recombiners were ultimately selected for this purpose.

Design measures for mitigating the consequences of low pressure core melt scenarios evolved significantly during different phases of the EPR design process. Numerous studies and tests were performed which led to improvements in the design of specific elements or components such as:

- The capacity of the reactor pit to collect the corium that could be produced inside the vessel due to the fuel melting was enhanced by using sacrificial concrete in the reactor pit,
- The position and design of the gate used to discharge corium into the spreading area via the melt discharge channel (see Sub-chapter 6.2),
- The design of the components protecting the basemat, including replacing a proposed zirconia layer with an appropriate thickness of sacrificial concrete from which heat was extracted via cooling channels placed inside the basemat underneath the spreading area.

2.2.5. Safety systems design: Passive features investigated for the EPR

HSE guidance on the demonstration of ALARP in nuclear facilities [Ref-1] states that passive protection systems are preferred over active protection systems.

A major activity in the design of EPR protective features has involved assessing the comparative benefits of active and passive safety systems incorporating passive features to the greatest extent allowed within the stated design objectives of the EPR. The selection of passive design features is considered in the present sub-section.

2.2.5.1. Criteria used to assess passive systems

Potential passive design features and systems were subject to a systematic assessment with respect to the criteria of simplicity of design, impact on simplicity of plant operation, safety and cost.

Firstly, it was required that the design should be simplified, or at least not made significantly more complex by the implementation of the passive feature. In this context, proven technology of the components used was required, in accordance with the HSE Guidance.

The degree of passiveness involved was investigated: to what extent did a proposed solution rely on active equipment like valves or on active auxiliary systems such as cooling or ventilation? Also, it was required that the overall system configuration should be simplified by implementation of the passive feature. An indicator of simplification could be a reduced requirement for system interconnections.

Secondly, the operation of the plant and of the passive system should be simple. Normal operational modes like power operation, start-up, shutdown, refuelling, and maintenance should not be affected by the passive system. Spurious actuation of passive systems should be detectable and recoverable by straightforward actions to avoid undue consequences on overall plant operation. The operation of the passive system itself should also be simple: initiation should be based on plant status and not on difficult diagnosis of an accident scenario: the system operational mode should not depend on plant status or reactor operating situation.

As a general rule, passive features chosen for implementation would need to be inspectable and capable of being tested in-service, with the testing mode being as close as possible to the operational mode of the system.

The final assessment criteria were related to safety and cost. To be implemented, a passive system should give clear safety and economic advantages.

Additionally it was important to establish that new accident scenarios would not be introduced by passive systems. The systems should fit in with the well-proven defence in-depth concepts and allow an extended time response to incidents or accidents. Accident consequences should not be aggravated by operation of the system. It was considered important that the multiple barrier concept (the integrity of the reactor coolant pressure boundary, control of containment leakages by double containment) used in French and German PWR designs, should not be weakened by the introduction of passive systems.

2.2.5.2. Passive Features adopted during the Design Optioneering Process

Following the review of passive safety features, the following additional passive features were included in the EPR design:

- larger Steam Generator (SG) and pressuriser volumes providing increased thermal inertia, thus slowing plant response to upset conditions,

- initial RIS [SIS] valve line-up (suction from the IRWST) meets long term cooling needs without realignment,

- lower core elevation relative to the cold leg cross-over piping which limits core uncovery during small break LOCAs,

- absence of lower head penetrations on the RPV for in-core instrumentation, thus eliminating one potential failure mechanism and failure location,

- passive pressuriser safety valves for both overpressure protection and prevention of spurious opening (passive opening under pressure increase, passive closing under pressure decrease),

- a large dedicated spreading area outside the reactor cavity to prevent the molten core-concrete interaction, by passive spreading and subsequent passive flooding of the corium,

- a large water source in the IRWST located inside the reactor building, draining by gravity into the reactor pit and the corium spreading area,

- a double wall containment with a reinforced concrete outer wall and a pre-stressed concrete inner wall and an intermediate space maintained passively under a small sub-atmospheric pressure during a limited period. A steel liner was integrated into the design of the inner containment to improve leak tightness under accident conditions. The aircraft proof shell surrounding the reactor building and other safety buildings was modified to withstand the impact of large commercial airliners,

- passive auto-catalytic hydrogen recombiners in the reactor building, to reduce risks due to hydrogen combustion in severe accident conditions.

2.2.5.3. Passive Features Rejected during the Design Optioneering Process

Some twenty passive features were evaluated in the conceptual design phase of the EPR which were not retained in the final design. Some of the principal passive features which were investigated for possible implementation in the EPR, but rejected, are described below.

2.2.5.3.1. Passive high pressure residual heat removal system

The objective of this system is to remove the residual heat by primary side cooling in events where existing designs rely on secondary side cooling, to avoid dependence on the emergency feedwater system (ASG [EFWS]).

The primary water flows by natural circulation through the Residual Heat Removal (RHR) heat exchanger located in an elevated water filled pool. The RHR heat exchanger is cooled by the pool water which evaporates into the containment. A containment cooling system becomes necessary or alternatively the pool must be cooled by an active cooling system. Active measures are required such as opening of valves for RHR system flow and start of heat removal from the pool or containment. The main results of the assessment of this system were the following:

- Flow rate through the RHR system depends (a) on the elevation between levels of the reactor coolant system (RCP [RCS]) loops and the RHR heat exchanger and (b) on diameter of RHR pipes.
- The concept would lead to a significant extension of class 1 equipment.
- Installation of a water pool including the RHR heat exchanger at about the same level as the operating floor and assuming that more than one train, including pool, would be necessary, would lead to a complex arrangement of the reactor building.
- An operational system would also be necessary to bring the plant to cold shutdown conditions for refuelling.

Although the passive RHR system has the potential advantage of easy operation, it was not retained for the EPR because it failed to meet the criteria of design simplicity or to achieve an adequate safety improvement.

2.2.5.3.2. Safety condenser

The objective of this concept is to implement an autonomous, self-fed secondary-side residual heat removal system.

The main element of the system is the safety condenser itself, located outside the containment and connected to the steam generator on the steam side and on the water side, and the demineralised water pool, which is connected to the shell side of the safety condenser.

During normal plant operation the system would be on standby and separated from the SG by closed isolation valves in the condensate line. The valve in the steam supply line is locked in the open position, so that the condenser is full of cold condensate on the tube side and is at main steam pressure. On the shell side, the condenser is partially filled: the closed control/isolation valve prevents the inflow of demineralised water from the demineralised water pool. To start up the system on a safety demand, the redundant, diverse condensate drain valves and the isolation valve in the demineralised water supply system are opened and the load controller activated. Draining of the secondary side of the condenser exposes heat transfer surface; heat transfer from the steam generator to the condenser takes place when the level on the tube side falls below that on the shell side. The cold condensate flowing from the condenser into the SG absorbs energy, before heat removal by the condenser begins. After the system run-up time, which is governed chiefly by the draining characteristic of the condenser, cooling begins. This is achieved by the admission, via the redundant, diverse control stations, of demineralised water from the demineralised water pool, which is at a higher static head. The result is evaporation to the atmosphere which acts as a heat sink.

The power for the valves required in normal operation and to ensure operation under emergency conditions is provided by a battery-backed supply. Since only a low electrical power is required, a grace period of several hours is available for restoring the function of any AC generators which may have failed.

Although the safety condenser concept presents potential reduction in activity release in the case of a SGTR, this concept was not retained for the EPR because it failed to pass all the selected criteria. In particular, the system does not meet simplicity and cost effectiveness.

2.2.5.3.3. Passive ASG [EFWS]

The objective of this system is the same as that of the safety condenser. The heat exchanger and the demineralised water pool are combined in a single component instead of two separated components.

In order to avoid elevated storage of large inventory of water, an emergency feedwater tank under nitrogen or compressed air over-pressure, located at ground level, allows replenishment of the passive condenser as and when required, to make up for water evaporation. This concept was not retained for EPR as it failed to meet the simplification and operational criteria.

2.2.5.3.4. Secondary side residual heat removal and passive feed

The objective of this system is to remove residual heat from the core for events such as station blackout and complete loss of feedwater, by providing a passive means to supply water to the steam generators (SG).

Elevated demineralised water pools, large enough to supply the SGs for several hours (station blackout duration), provide flow by gravity once the associated control valves have been opened and after closure of the SG main steam isolation valves. The cooldown is performed by steam release to the atmosphere through dedicated relief valves.

The main drawback of this concept is that the elevated pools must be protected against external events, particularly earthquakes. Movements of large inventories of water and the design of their supporting structures are major safety and cost challenges.

This concept was also not retained for EPR because it did not meet any of the four categories of evaluation criteria.

2.2.5.3.5. Medium-head safety injection by accumulators

The objective of this system is to simplify the safety injection system (RIS [SIS]) without reducing the safety level below that on existing plants. The idea was to remove the medium head safety injection (MHSI) pumps so as to reduce the SIS cost, reduce the maintenance requirements, and simplify operation of the system.

In order to fulfil the MHSI functions it is necessary to provide for an automatic depressurisation system and high pressure accumulators. Potential difficulties arose during the assessment of non-LOCA events with this concept. It was found that the management of steam generator tube rupture (SGTR) accidents would have to be reconsidered, and questionable operating modes were discovered.

The concept was dropped because it failed to meet the criteria of simplicity and failed to give clear safety benefit compared with a conventional active safety injection system.

2.2.5.3.6. Gravity-driven low-head safety injection from tank/sump by primary system depressurisation

The objective of this system is to provide an efficient ultimate back-up for injection of water at low pressure for long term reactor cooling. The RCP [RCS] is flooded with water above the loop level and water flows by gravity from sumps, through check valves, into the reactor vessel. Decay heat is removed to the containment atmosphere by evaporation of the flood water. Steam produced inside the containment condenses on surfaces cooled by a containment cooling system, and the condensate flows back to the RCP [RCS].

Active measures are required e.g. opening of isolation valves, opening of RCP [RCS] discharge and feed line from the sumps, start-up of the heat removal system in the containment.

The principal results of the assessment of this system were the following:

A large amount of water is necessary to flood the RCP [RCS], the amount depending on the reactor building layout. For typical cases, the volume varied between 4,700 m^3 and 10,000 m^3.

Large diameter of discharge line(s) and small flow resistance check valves are necessary to allow gravity flow to the reactor vessel. Spurious opening of valves in the discharge line(s) would have to be avoided. Additional connections to the RCP [RCS] are required for discharge line(s) and feed line(s). A full scale test to verify the concept would be difficult and extremely costly.

Although the passive low head safety injection system presents advantages, such as providing a back-up to low head safety injection pump and avoiding long term recirculation outside the containment, it was not retained for the EPR because it failed to meet the criteria of design simplicity and cost-effective safety improvement.

2.2.5.3.7. External cooling of metal containment

For metal containment structures, a concept in which heat removal is ensured by conduction through the containment wall is feasible in principle. Inside the containment, heat transfer would be by natural convection in the containment atmosphere and condensation on the containment wall inner surface. For external containment heat removal, several alternative cooling schemes can be envisaged. However a completely passive concept, using natural circulation air cooling, would only be possible for small unit sizes and in the long term, after decay heat is sufficiently reduced. Thus, additional means based on water spray on the outside containment surface are required at least in the short term. For the larger unit size of the EPR, water-circulation assisted external cooling would be required even in the long term. Use of water cooling on the containment outside surface, without evaporation and based on an active cooling circuit with a pump and heat exchanger, would allow retention of a double containment barrier, which would not be possible in case of a natural air circulation cooling mode. However, in such a containment heat removal concept, the passive means of heat removal is provided only on the inside of the containment. Furthermore, the heat transfer capacity by condensation on the inner containment surface in the presence of non-condensable gases is limited and, for the large thermal power of the EPR, could result in elevated containment pressures (several bar), in the medium term following an accident.

For these reasons, this option has not been retained for EPR.

2.2.5.3.8. External cooling of reactor vessel for melt retention

Some reactor types use flooding of the reactor pit as a means of maintaining the integrity of the reactor pressure boundary and preventing melt ejection into the containment in core melt scenarios. Heat is transferred from the melted core by conduction through the vessel walls and then by natural circulation to the water in the reactor pit. For the large unit thermal power of an EPR, natural circulation cooling on the outside of the pressure vessel would be insufficient to prevent failure of the reactor vessel wall. Therefore the option of in-vessel melt retention by passive external cooling of the outside of the RPV could not be used for EPR.

2.2.5.3.9. Sump cooler with passive cooling chain

The objective of this concept is to remove decay heat following a LOCA by natural circulation from the reactor building sump via submerged coolers and a secondary cooling system to the atmosphere.

Like many other passive concepts, opening of valves is necessary to start operation of this system.

Additional measures to transfer the heat from the containment sump were estimated to be necessary during the evaluation of this concept. A large heat transfer surface for sump cooler (a minimum of 1000 m^2) was found to be required.

The passive sump cooling feature was rejected because the large height difference required between the ultimate heat sink and the sump cooler to secure natural circulation (a minimum of 20 m) would result in unacceptable implementation costs.

2.2.5.3.10. Containment condenser coolers

The objective of this system is to provide a passive means, at least inside the reactor building, for removing decay heat in the long term after a severe accident, in order to avoid the internal pressure exceeding the containment design pressure.

Steam, driven by natural circulation, condenses on the outside surface of coolers. Cooling water circulates inside the coolers. The cooling system is active and located outside the containment.

The major drawbacks of this system, in comparison to the current EPR spray system, which uses the EVU [CHRS] to spray water into the upper volume of the containment, are the following:

- The heat transfer and containment pressure reduction capability are strongly dependent on the presence of non-condensable gas and on general convection flows inside the containment. The level of uncertainty in modelling these effects at full scale is such that it is not considered possible to predict the effectiveness of such systems with sufficient confidence,

- The condensers would have to be located in the upper part of the containment where they would promote hydrogen accumulation, reducing their heat transfer capability and potentially increasing the risk of detonation,

- A large amount of space would be required above the operating floor which is a congested area during maintenance and refuelling,

- A spray system is more effective than condensers in reducing pressure and removing fission products from the containment atmosphere.

However, this system offers several advantages over a containment spray system, the major one, being that it avoids recirculation of highly radioactive water outside the containment after a severe accident. Therefore, the containment condenser coolers provide a solution to one of the key severe accident challenges: how to remove heat from the containment building without circulating fluid through its walls and potentially impairing its leak tightness? Nonetheless, the conclusion was reached that this advantage was outweighed by the drawbacks of a condenser system.

2.2.5.4. Conclusions on adoption of Passive Safety Features in EPR Design

The EPR has been developed to address all issues of safety, public perception and economic operation. Experience to date in both France and Germany on standardisation of plant design has been a major factor in the overall EPR design.

In general, the majority of passive features proposed so far for Generation 3 reactors were considered to be largely unproven in testing and operation. Such features were considered to be economically unjustified and/or liable to lead to increases in plant complexity that may actually degrade rather than enhance safety. The EPR designers have selected only those passive features that meet the requirements of simplicity, operability/inspectability and cost-effective safety enhancement. At the same time they have sought to increase the reliability of active safety features (for example, by supplementing the emergency diesels supplying active safety systems with diverse diesels) in order to ensure that safety functions will be achieved with a very high level of reliability.

3. DOSES TO WORKERS IN ACCIDENTS

The safety design of the EPR has focussed on minimising the risk to members of the general public due to off-site radioactivity releases by minimising the frequency of initiating events and providing defence in depth against such events that could occur.

However, measures are also taken to minimise the radiation dose to workers in accidents.

For operators in the Main Control Room (MCR) who cannot be relocated, protection is provided by maintaining the control room at a positive pressure with respect to ambient and supplying air through a filtration system (safety classified).

Generally, worker protection from radiation doses in accidents is achieved through emergency procedures for evacuation and sheltering of workers to a safe area. The plant is designed with escape routes to allow workers to be evacuated from hazardous areas in case of emergencies. For example during refuelling operations, escape routes from the reactor buildings enable workers to escape to uncontaminated areas outside the building, while a negative pressure is maintained inside the building so that radioactive materials released will remain contained.

Therefore, in the design optioneering carried out between 1987 and 2006 it was considered, in an initial analysis, that doses to workers in accidents would generally be lower than those to exposed individuals off-site, who cannot be immediately protected by evacuation and sheltering.

4. OPTIMISATION OF DOSE TO WORKERS AND THE PUBLIC IN NORMAL OPERATION

To establish an ALARP position, under UK ALARP principles, the likely radiation doses to workers and members of the public from plant operation, are required to be as low as reasonably practicable. These aspects are discussed below.

4.1. MINIMISATION OF DOSE TO WORKERS

The EPR design process involved extensive optimisation studies to minimise worker dose. The objective was to apply an optimisation approach to radiological protection similar to that applied to safety. The optimisation was accomplished by improving the reactor design in relation to the best NPP units currently operating in France and Germany, with regard to worker collective dose. Details of the design optimisation are provided in Chapter 12, which is briefly summarised below.

The EPR approach to dose optimisation was to improve the design to both reduce the source term associated with plant operation and maintenance, and to reduce the amount of exposed work.

The EPR design source term has been reduced by the following design changes:

- optimising the use of stellite in the reactor vessel internals and valves,
- modifying the pressuriser layout by adding a floor separating the spray and discharge systems at the pressuriser-dome level. This significantly reduces the dose during maintenance activities on the safety valves, most of which is from the spray nozzles,
- inclusion in the reactor building of an area dedicated to storing the pressure vessel head (with appropriate shielding),

- removal of "hot spots" by eliminating pipe connections using socket welds on pipework carrying radioactive fluids, by chemistry optimisation, and by reducing the amount of antimony and chromium in primary system components.

The amount of exposed work (work subject to radiation) has been reduced by the following design choices:

- design changes to allow maintenance operations to be carried out in the reactor building during power operation, immediately before and immediately after outages. Provision of improved shielding and ventilation in the reactor building zone to which at-power access is permitted ensures a net reduction in the collective radiation doses associated with outages,
- increased use of bolted connections on key equipment (pressuriser heaters, control rod drive mechanisms etc),
- increased size of primary and secondary manways,
- modification to the steam generator waterbox layout to give easier access to peripheral tubes,
- reactor vessel head heat insulation removable as a single unit,
- absence of a forced ventilation device for the Control Rod Drive Mechanisms (RGL [CRDMs]) resulting in the elimination of opening and closing operations for the RGL [CRDM] ventilation system air duct,
- improvement to reactor vessel level instrumentation to reduce required maintenance operations,
- routing of the ex-core instrumentation into the reactor-vessel pit through the pool concrete wall to reduce operations associated with instrumentation system covers at the bottom of the pool,
- optimisation of the fuel handling operation duration,
- installation of improved shielding around active equipment,
- use of modular maintenance valves.

Optimisation studies have been carried out on the high dose activities by the designers for installation, materials and operation. Examples include:

- Optimisation of exposure associated with installation of thermal insulation, which is a high dose task in terms of collective and individual dose. Radiation protection modifications currently being studied include use of fast assembly-disassembly thermal insulation on primary and secondary circuit pipework, SGs, pressuriser, and at welds and sensitive tapping points.

- Optimisation of exposure associated with high dose work - site logistics activities such as equipment preparation and monitoring, scaffolding erection and removal, etc. Modifications being studied to optimise logistic operations include provision of shielding anchoring points for high dose activities, installation of fast assembly-disassembly scaffolding, installation of permanent platforms around SG openings etc.

- Optimisation of exposure associated with valve and component maintenance. Optimisation measures include replacement of gate valves with globe valves not requiring cobalt-based hard facing, elimination of pipe joints using socket welds on pipework carrying radioactive fluids, improvement of the water tightness of valves, use where possible of modular-maintenance globe valves to avoid activities such as packing replacement, in-situ grinding of the seat etc.

- Optimisation of doses associated with SG maintenance and inspection. The quantity of exposed work has been minimised by optimising location of pipes and equipment, as well as the size of the worksites. Access to the interior of the SGs has been improved by increasing the size of access openings compared with N4 NPPs. The frequency of tube bundle cleaning operations on the secondary side has been reduced by selecting materials that limit corrosion, and optimising secondary water chemistry. Additional improvements have been implemented to reduce damage to tubes and to the feedwater system.

- Optimisation of exposure associated with removal and replacement of the RPV head. Measures taken include optimising the transfer of upper and lower vessel internals underwater, provision of a dedicated storage area for the reactor vessel head, optimising the removal and replacement of the reactor vessel head thermal insulation (insulation removable as a single unit), etc.

Taking into account proven modifications and radiological protection modifications under consideration for EPR, the predicted value of the optimised dose is 0.345 man.Sv per year per unit (achievable over a 10 year operating period), confirming that the dose target level of 0.35 man.Sv per year per unit should be achievable (see Sub-chapter 12.4). This is a significant improvement on the collective dose for the best operating unit of the French fleet, GOLFECH 2, which has achieved 0.44 man.Sv per year over a full cycle of ten years. It represents only a small fraction of the design target for collective dose used in earlier PWR plants such as the Sizewell B PWR.

These measures give confidence that the operator dose due to plant operation has been reduced to the minimum practicable level by optimisation of the plant design, and therefore that ALARP principles have been met in respect of worker risk from normal operation of the plant.

4.2. DOSE TO MEMBERS OF THE PUBLIC IN NORMAL OPERATION

Achievement of an ALARP situation requires that radiation doses to the general public due to normal plant operation are minimised and are as low as reasonably practicable.

Technical Guidelines paragraph A.2.7.2 (see Sub-chapter 3.1) requires that the EPR design achieves a reduction in volume of radioactive materials produced by the unit as waste, and that doses to members of the public due to wastes and discharges are minimised. This has resulted in the EPR design being optimised to reduce off-site doses to a minimum, showing significant improvements compared with existing French and German NPPs.

Sub-chapter 8.2 (sections 3 and 4) of the PCER describes the main design measures implemented in the EPR to reduce the production of radioactive waste, and improve the effectiveness of the containment function, in order to reduce off-site radioactive discharges in normal operation. The following gives a summary of key design improvements [Ref-1] [Ref-2]:

- Reduction of the liquid effluent source term by reducing the use of stellites, the cobalt content of materials and alloys, and the optimised manufacturing of steam generator tubes.
- Optimisation of the EPR chemical parameters to minimise the liquid effluent source term during all periods of operation at power, shutdown and start-up.
- Improvements in the segregation of floor/chemical drains resulting in significant reductions in the activities and volumes of liquids discharged from the effluent treatment systems.
- Improved filtration, demineralisation and evaporation techniques for treatment of radioactive liquid effluents.
- Use of hold-up tanks to increase radioactive decay of short lived nuclides before discharge of liquid effluents
- Reduction in the gaseous effluent term by optimisation of the design of the Gaseous Waste Processing System (TEG [GWPS]). Improvements include sharing of tank ullages; continuous nitrogen flushing of tank ullages and head spaces; recombination of hydrogen released in off-gassing from tanks which helps retain tritium and iodines in the aqueous phase; increased decay of short-lived gases (mainly xenon and krypton) released from the TEG [GWPS] on absorbent charcoal delay beds.
- Avoidance of pneumatic valves in the Reactor Building, resulting in reduced gaseous discharges from this building.
- Improved design of the ventilation/filtration system, particularly increased use of iodine traps in the ventilation system of the Nuclear Island buildings.

Tables 1 and 2 in PCER Sub-chapter 8.2 show that gaseous and liquid radioactive discharges, and solid waste and spent fuel volumes, predicted for the EPR, are significantly improved compared to existing NPPs in France and Germany and the Sizewell B PWR, with the exception of carbon-14 which cannot be readily contained, and tritium where there is a slight increase in the liquid phase discharge.

Based on the efforts made to reduce the radiation doses to the general public in normal operation, the EPR design is considered to meet the ALARP principle.

Chapter 11 of the PCER describes an assessment of the off-site collective dose due to normal operation of an EPR, performed using the Initial Radiological Assessment (IRA) methodology developed by the UK Environment Agency. The purpose of the IRA methodology is to provide an initial cautious assessment of the dose arising from radioactive waste discharges to the environment, and to identify those discharges for which a more detailed assessment should be undertaken. Application of the IRA methodology to the UK EPR gives an annual total dose for the critical group of 25.8 µSv/y. This value is well below the limit for a single installation of 300 µSv/y set by the UK 2000 Radioactive Substances Direction [Ref-3], and is close to the level of 20 µSv/y defined as a Basic Safety Objective (BSO) target in the HSE SAPs [Ref-4], supporting the view that the risk due to off-site radioactivity emissions is at a very low level, which corresponds to the Broadly Acceptable risk level.

5. USE OF PSA STUDIES IN THE EPR DESIGN

A general objective for the EPR design has been to reinforce the main elements providing defence in depth. To achieve this objective, the design has been made on deterministic bases supplemented by the use of probabilistic methods. Reactor operating experience and in–depth studies such as Probabilistic Safety Assessment analyses, as well as improvements in knowledge of physical phenomena occurring in accident situations such as core melt scenarios have been taken into account.

PSA can be used to quantitatively demonstrate implementation of the defence-in-depth concept as well as to show that a balance has been achieved between the different levels of protection and that the levels of protection are independent from one another.

Different PSA studies have been performed at the design stage of the EPR to support the choice of design options, including redundancy and diversity of the safety systems. PSA has also been used to select or reject changes to the main EPR options during the Basic Design Optimisation Phase.

As an example, with regard to the availability and reliability of the emergency electrical power supply, PSA was used to determine the number of diesel generators (four main diesel generators, backed up by two smaller diesels of diverse design) and to demonstrate that sufficient independence and diversity exists amongst the two types of diesel generators.

PSA studies have also been used to reduce the impact of common cause failure of redundant systems. This is the case of the Containment Heat Removal System for which several cooling system designs were compared, leading to a final design that includes a dedicated cooling chain, independent of the Component Cooling Water System, which is cooled by a diverse ultimate heat sink.

In addition to supporting the choice of design options, PSA has been used to validate the list of events considered in the EPR design basis and to define the list of design extension conditions (RRC-A sequences) considered in the framework of core melt prevention.

The systematic use of PSA to develop an optimised design, which minimises risks, subject to practical considerations of cost and constructability, has similarities to the UK process of design optimisation to achieve an ALARP position. It is important to note that use of PSA during the EPR design development phase (1987 to 2006) was based on the application of Level 1/Level 2 PSA only. The primary objective of the studies was to confirm that design targets for frequency of core damage and large early release of radioactivity had been achieved.

For the UK EPR the PSA was extended to a Level 3 analysis in which the off-site consequences of radiological releases due to accidents were considered. An initial comparison of individual and societal risk levels from the UK EPR Off-site Consequence Risk Assessment (Level 3 PSA) with numerical risk targets from HSE SAPs showed that UK Basic Safety Objectives for risk were met. HSE Guidance on the application of ALARP to new nuclear build confirms that well supported numerical risk figures that show the BSO targets are met can be an important element in an ALARP demonstration.

The current Level 3 PSA presented in Sub-chapter 15.5 is an update of this initial analysis which is reviewed in comparison with numerical risk targets from HSE SAPs in Sub-chapter 17.4.

6. CONCLUSIONS ON EPR DESIGN OPTIONEERING RELATIVE TO ALARP REQUIREMENTS

It has been shown that the EPR design process has resulted in the addition of enhanced protection to prevent and mitigate the consequences of severe accidents, to protect against external hazards, to improve the capability of the containment function, including reducing the likelihood of radiological releases due to containment bypass sequences, and to increase the use of passive safety measures. The safety improvements have been backed by use of PSA to develop an optimised design that minimises risk. Additionally considerable effort has been expended to reduce the risk to operators and the public due to radiation doses during normal plant operation.

The EPR optioneering process has involved a 20 year study to optimise the design, maximising the safety of the plant within the constraints of economic operations and practical constructability. This process is closely analogous to the process of optimisation of design to achieve an ALARP position envisaged in HSE guidance documents on application of ALARP [Ref-1].

Although UK principles of ALARP were not formally applied as an integral part of the EPR design process, arguments have been made that the process of design optimisation to minimise risk from accidents and to optimise operator dose in normal plant operation is closely analogous to the formal UK approach of ALARP. In particular:

- the design has been developed by a comprehensive and systematic process to reduce risk to workers and the public,
- extensive design optioneering has been carried out in consultation with French and German safety authorities and international experts to optimise plant safety,
- design decisions and their rationale have been documented,
- risks due to normal operation and accidents have been extensively considered,
- PSA methods have been used to show that the risk of a significant environmental radiological release due to accidents meets the Basic Safety Objectives (BSOs) defined in HSE Safety Assessment Principles. HSE Guidance on the application of ALARP to new nuclear build confirms that well supported numerical risk figures that show the BSO targets are met can be an important element in an ALARP demonstration. The current Level 3 PSA presented in Sub-chapter 15.5 is an update of this initial analysis and is reviewed in comparison with numerical risk targets from HSE SAPs in Sub-chapter 17.4.

SUB-CHAPTER 17.3 – REFERENCES

External references are identified within this sub-chapter by the text [Ref-1], [Ref-2], etc at the appropriate point within the sub-chapter. These references are listed here under the heading of the section or sub-section in which they are quoted.

2. OUTCOME OF OPTIONEERING PROCESS – SAFETY SYSTEMS/STRUCTURES

2.2. RESULTS OF DESIGN OPTIMISATION

2.2.5. Safety systems design: Passive features investigated for the EPR

[Ref-1] UK Health and Safety Executive (HSE). Technical Assessment Guide, ND Guidance on the Demonstration of ALARP (As Low As is Reasonably Practicable). T/AST/005 Issue 4 Revision 1. January 2009. (E)

4. OPTIMISATION OF DOSE TO WORKERS AND THE PUBLIC IN NORMAL OPERATION

4.2. DOSE TO MEMBERS OF THE PUBLIC IN NORMAL OPERATION

[Ref-1] Flamanville 3 EPR - Summary report: specific design provisions related to EPR chemistry. ECEF072084 Revision A1. EDF. February 2008. (E)

[Ref-2] D. Tersigny. Analysis of environmental performance in the EPR France project. ECEP050315 Revision A1. EDF. March 2012. (E)

ECEP050315 Revision A1 is the English translation of ECEP050315 Revision A.

[Ref-3] Radioactive Substances (Basic Safety Standards) (England and Wales) Direction 2000. Defra, UK. (E)

[Ref-4] UK Health and Safety Executive (HSE). Safety Assessment Principles for Nuclear Facilities. 2006 Edition Revision 1. January 2008. (E)

6. CONCLUSIONS ON EPR DESIGN OPTIONEERING RELATIVE TO ALARP REQUIREMENTS

[Ref-1] UK Health and Safety Executive (HSE). The Tolerability of Risk from Nuclear Power Stations. ISBN 0118863681. The Stationery Office Ltd. 1992. (E)