Selected Aspects of the EPR Design in the Light of the Fukushima Accident

Report for Greenpeace International

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Scope of the study and main results

This study is investigating design aspects of the EPR – a nuclear power plant of Generation III – which are relevant in connection with the critical issues which became apparent at the Fukushima accident. The study focuses on the provisions against station blackout (emergency power supply), and spent fuel pool design and cooling.

Mostly, the German Konvoi plant has been selected as the standard against which the EPR's design is measured – a Generation II reactor type which has been in operation for more than 20 years.

Regarding emergency power supply with Diesel generators, the EPR's system is equipped with fewer generators and can support fewer functions than the emergency power supply system of the German Konvoi plants:

- EPR has 4 primary emergency diesel generators (EDGs), plus 2 additional DGs (the so-called station blackout diesel generators, SBO-DGs). A Konvoi plant also has 4 EDGs, as well as 4 additional D2 DGs, fulfilling similar functions as the SBO-DGs.
- The SBO-DGs have to be started up manually in case of need. The Konvoi D2 diesels are started automatically.
- The SBO-DGs can only support water injection into the secondary circuit, whereas the D2 diesels can be used to power water injection both into the primary and the secondary circuit.
- The SBO-DGs are not sufficient for achieving the cold shutdown state, as the D2 diesels are. The extra boration system which would be required in this case cannot be supplied with electricity from the SBO-DGs. It can be supplied from the D2 DGs at the Konvoi plants.
- In each case, DGs are installed in two physically separated buildings, which is the main internationally accepted measure against aircraft crashes. The DG buildings of the EPR are not designed against aircraft crash, whereas one of the Konvoi DG buildings is designed against this event.

The picture is different for the cooling of the spent fuel pool; with the European EPRs being roughly equivalent to the Konvoi, while the standard of the basic design and the US EPR is lower:

- The cooling of the pool is less redundant in the basic design and the US EPR, which have two cooling trains, than in the Konvoi plants with three cooling trains. These two cooling trains cannot be supplied with electricity from the SBO-DGs; the Konvoi trains can be partially supplied by the D2 DGs.
  The European EPRs, however, have three cooling trains, one of which can be supplied with electricity from the SBO-DGs. They are roughly equivalent, in this respect, to the Konvoi plants.
- The spent fuel pool is located in a separate building in case of the EPR, while it is inside the containment for the Konvoi plants. Thus, in Konvoi plants, interchange of core decay heat removal systems and fuel storage pool cooling systems is possible. In the EPR, on the other hand, the spent fuel pool cooling system has to be able to work independently in all cooling situations. This, however, could also be seen as advantageous since it makes failure propagation between core cooling and fuel pool cooling impossible.

Regarding the hydrogen problem, the containment of the EPR is equipped with recombiners / igniters with a capacity for severe accidents. As in the case of the Konvoi plants, there is no obvious deficit in this respect. It lies beyond the scope of this study to investigate whether there might be accident sequences for which the hydrogen mitigation measures in the containment are not sufficient.

The situation is different for the building of the spent fuel pool. As far as can be seen from the published material, there are no precautions against hydrogen in this building of the EPR. This is quite different from the situation in a Konvoi plant, where the spent fuel pool is located inside the containment and it can be expected that the hydrogen control measures in the containment can also deal with hydrogen generated in the spent fuel pool.

Loss of ultimate heat sink was not considered in this study since, according to the EPR’s Basic Design Report, it is less critical than failure of the EDGs /1/. The time constraints for this study necessitated a strong focusing on the most critical issues.

All in all, for the issues considered here, the standard of the EPR is generally lower or, at best, equal to that of the German Generation II Konvoi plants, which already have been in operation for more than 20 years[1].

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[1] This does not imply that the Konvoi type generally has a higher standard than EPR. The general protection against aircraft crash is roughly equivalent in both cases. Furthermore, it has to be noted that the EPR is equipped with a core catcher which has the purpose of controlling a core melt accident and protecting containment integrity in this case. This feature is absent at the Konvoi type.

There are further differences in the design of both types but it is beyond the scope of this study to discuss them.

I. A Brief Review of the Fukushima Daiichi Accident (Units 1 to 4)

Many details regarding the Fukushima accident are still under debate. Some relevant information about the situation in the units after the impact of the tsunami is still not available or confirmed.

Thus, the subsequent description has to be understood as preliminary. It is mainly based on a presentation of the German owners' group VGB /2/ if not otherwise stated. According to /2/ all operating reactor units (units 1 to 3) were successfully shut down within seconds after arrival of the ground waves. Because of the destruction of infrastructure due to the strong earthquake a long lasting loss of offsite power occurred. In order to supply the necessary power for water injection into the reactor core and for heat removal some of the emergency diesel generators started.

Around 55 minutes later Fukushima- Daiichi was struck by the tsunami, with a wave height of estimated 14 m, which was much higher than the design height (5.7 m) and also higher than the ground level at the plant site (10 m) which provided an additional safety margin. The tsunami wave resulted in a common cause failure (CCF) of all emergency diesel generators and of the Essential Service Water System (ESWS) which is needed to remove the residual heat and to cool nuclear installations like pumps.

The consequences of these multiple losses of safety relevant equipment were different, depending whether the unit was in operation (units 1 to 3) or in shutdown mode (unit 4).

In units 1 to 3 the residual heat production in the reactor core resulted in steam production within the reactor pressure vessel which was released to the pressure suppression pool (wetwell) via pressure relief valves.

For units 2 and 3, the water supply to the reactor pressure vessel (RPV) to compensate the vaporized coolant was achieved by steam-driven emergency pumps, referred to as "reactor core isolation pumps", at high RPV pressure. For successful operation of these pumps battery power was needed, for the control of the valves of the system, and of the turbine.

The operation of the reactor core isolation pumps allowed water injection from the wetwell into the reactor pressure vessel. Therefore a circulation >> suction of water from the wetwell ➔ injection into RPV ➔ evaporation of water ➔ release of steam into the wetwell << was established for some hours (at least in some of the units). Anyway, it was not possible to remove the heat from the containment (wetwell and drywell). As a consequence, the temperature of the water within the containment increased. After reaching saturation temperature, also the containment pressure increased.

At the sites no restoration of offsite power was possible and delays occurred in obtaining and connecting portable diesel generators. After exhaustion of the battery capacity injection of coolant into the RPV at high pressure was not possible anymore. The water level within the RPV decreased and the temperatures of the fuel elements increased. Eventually uncovering and overheating of the reactor cores occurred. High fuel element temperatures led to hydrogen production due to oxidation processes in the reactor cores, with main contributions from fuel cladding (Zircaloy) steam reactions at temperatures above ≈ 1000 °C (exothermal reaction).

(Unit 1 is not supplied with a reactor core isolation system. There is another system for high pressure coolant injection but it was not available because the batteries dedicated to this system were flooded. Specific details will not be discussed further here since they are not relevant for the purpose of this report.)

As soon as high pressure injection of coolant to the RPV was not possible anymore in a unit, the operators had to relieve RPV pressure to allow low pressure injection of seawater by auxiliary pumps. As the containment (wetwell) was the heat sink for the whole system, the relief of the RPV pressure caused additional increase of containment pressure. Additionally, hydrogen produced due to core heatup was trapped in the nitrogen-inertized containment.

As heat removal from the containment by regular heat removal systems due to lack of electric energy was not possible, the containment temperature and pressure increased beyond design values. Operators decided to vent the containment to prevent failure by overpressure. The venting was carried out to an elevated release point on the service (refuel) floor on top of the reactor building. Consequently the steam-nitrogen-hydrogen mixture was released into the non-inertized part of the reactor building. As the ventilation system was not working because of the station blackout the gas mixture remained inside the top hall in the reactor building. Eventually ignition of the mixture occurred after reaching flammable limits. It resulted in the observed explosions with the subsequent destructions of the reactor buildings[2].

Unit 4 was shut down at the time of the accident; the core had been transferred to the spent fuel pool. The cooling of this pool was lost. Heatup of the water within the fuel pool, subsequent evaporation and possibly (partial) uncovery of the fuel elements leading to major fuel damage occurred[3]. Water losses due to possible damages at the

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[2] This is not the only interpretation of the events. There are also indications that the venting lines ended outside the reactor building. According to alternative hypotheses, the release of hydrogen into the upper parts of the reactor buildings was caused by containment leakages due to high containment pressure.

[3] Some members of the expert community have severe doubts that this fuel uncovery with subsequent hydrogen production actually took place in unit 4 (or at least, that serious fuel damage occurred). According to them the explosion in unit 4 was not caused by hydrogen, but

reactor well and / or the spent fuel pool in course of the earthquake may have been a reason for the serious problems at unit 4.

Cooling was also lost at the spent fuel pools of units 1 to 3; the extent of fuel damage occurring there is not clear.

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by another unidentified source. One reason for this assumption is that also lower parts of the reactor building (beneath the spent fuel pool) have been seriously damaged by the explosion.

II. Main Lessons Learnt from the Fukushima Accident

In the meantime several organisations have drawn their specific conclusions based on the information about the Fukushima accident, see e.g. /3/. Switzerland has already issued several ad-hoc measures which have to be implemented by the utility owners: among others there are additional emergency power generators for external supply of safety relevant equipment like batteries and instrumentation systems, mobile pumps for coolant injection, a sufficient amount of cables and tubes, additional fuel for emergency diesel generators, a sufficient amount of boron for sustaining sub-criticality, tools for the installation of the equipment. All the equipment has to be transportable by helicopters, see e.g. /4/. Additional means for water injection into the spent fuel pools have also been demanded.

In the following, conclusions drawn at the end of March 2011 by the German Reactor Safety Commission (RSK) for German nuclear power plants (NPP) /5/ will be presented in some more detail.

RSK considers it necessary to examine

> “to what extent the general safety objectives of ‘reactivity control’, ‘cooling of fuel assemblies in the reactor pressure vessel as well as in the fuel pool’ and ‘limitation of the release of radioactive substances (preserve barrier integrity)’ are fulfilled in the event of impacts beyond the design requirements applied so far. For this purpose, the robustness (available design margins, diversity, redundancy, structural protection, physical separation) of the safety relevant systems, structures and components and the effectiveness of the defence-in-depth concept have to be assessed.”

Additionally RSK demanded an

> “examination to what extent the functions for fulfilling the safety objectives remain available for assumptions going beyond the scenarios postulated so far. In this context, postulates regarding the non-availability of safety and emergency systems have to be considered, like e.g. the longer-term loss of power supply incl. the emergency power supply, or the non-availability of the auxiliary service water supply.“

RSK here directly refers to the multiple tsunami induced failures of main safety functions in Fukushima. Fukushima also revealed serious difficulties with the application of accident management procedures and equipment in case of serious accident conditions. RSK deduced the necessity to review the scope of

> “accident management measures and their effectiveness. Here, the extent and the quality of preliminary planning for postulated event sequences, such as the

> non-availability of the cooling chain for cooling of the fuel assemblies in the reactor core as well as in the fuel pool, the non-availability of electricity supply, and any massive fuel assembly damage that may occur up to core meltdown, have to be assessed. Furthermore, a substantial destruction of the infrastructure and inaccessibility due to high local dose rates as well as the availability of personnel also have to be assessed. One focus of the review regarding the robustness of all installations and measures is on the identification of an abruptly occurring aggravation in the event sequence (cliff edges) and, if necessary, on the derivation of measures for its avoidance (example: exhaustion of the capacity of the batteries in the event of a station blackout)."

The scope of the review as proposed by the RSK has to include

> "natural events such as earthquakes, flooding, weather-related consequences as well as possible simultaneous occurrences. Postulates were presumed that are independent of concrete event sequences, such as failures affecting several redundant system trains, (common-cause failures, systematic failures), station blackout for longer than two hours, long-lasting loss of auxiliary service water supply".

Contrary to the approaches of regulatory authorities in several countries, human-induced events such as e.g. aircraft crash, blast pressure wave, and deliberate attack on safety-relevant installations are included into the scope of the examination. The reason is that these events can also lead to severe overall loads and destructions.

III. Brief EPR Overview

For the aspects discussed in detail in the following chapters some overall information is needed concerning the basic design of the EPR plant and of some safety relevant buildings. This is shortly described in /6/ as follows:

> “The layout of the safety systems and the design of the civil works structures minimize the risks from hazards such as earthquake, flooding, fire, airplane crash. The safety systems are designed on the basis of a quadruple redundancy, both for their mechanical and electrical parts and for of the supporting I&C. This means that each system consists of four subsystems, or ‘trains’, each one capable by itself of fulfilling then entire safety function. The four redundant trains are physically separated from each other and located in four independent divisions buildings.
>
> Each division includes one train of:
>
> - the safety injection system for injecting borated water into the reactor vessel in a loss of coolant accident. This consists of a low-head injection system and its cooling loop, and a medium-head injection system,
> - the steam generator emergency feedwater system,
> - the electrical and I&C systems supporting these systems.
>
> The building housing the reactor, the building in which the spent fuel is stored on an interim basis, and the four buildings corresponding to the four divisions of the safety system are provided with special protection against externally generated hazards such as earthquakes and explosions. Protection against an aircraft crash has been further strengthened. The reactor building is protected by a double concrete shell: an outer thick shell made of reinforced concrete and an inner thick shell made of pre-stressed concrete which is internally covered with a thick metallic liner. The thickness and the reinforcement of the outer shell provide sufficient strength to absorb the impact of a large commercial aircraft. The double concrete wall is extended to the fuel building, and to two of the four safeguard buildings containing the Main Control Room and the remote shutdown station which would be used in emergency conditions. The other two safeguard buildings which are not protected by the double wall are remote from each other and separated by the reactor building, which prevents them from being simultaneously damaged. In this way, if an aircraft crash were to occur, at least three of the four trains of the safety systems would be available.”

The arrangement of the main buildings is illustrated in the following figure.

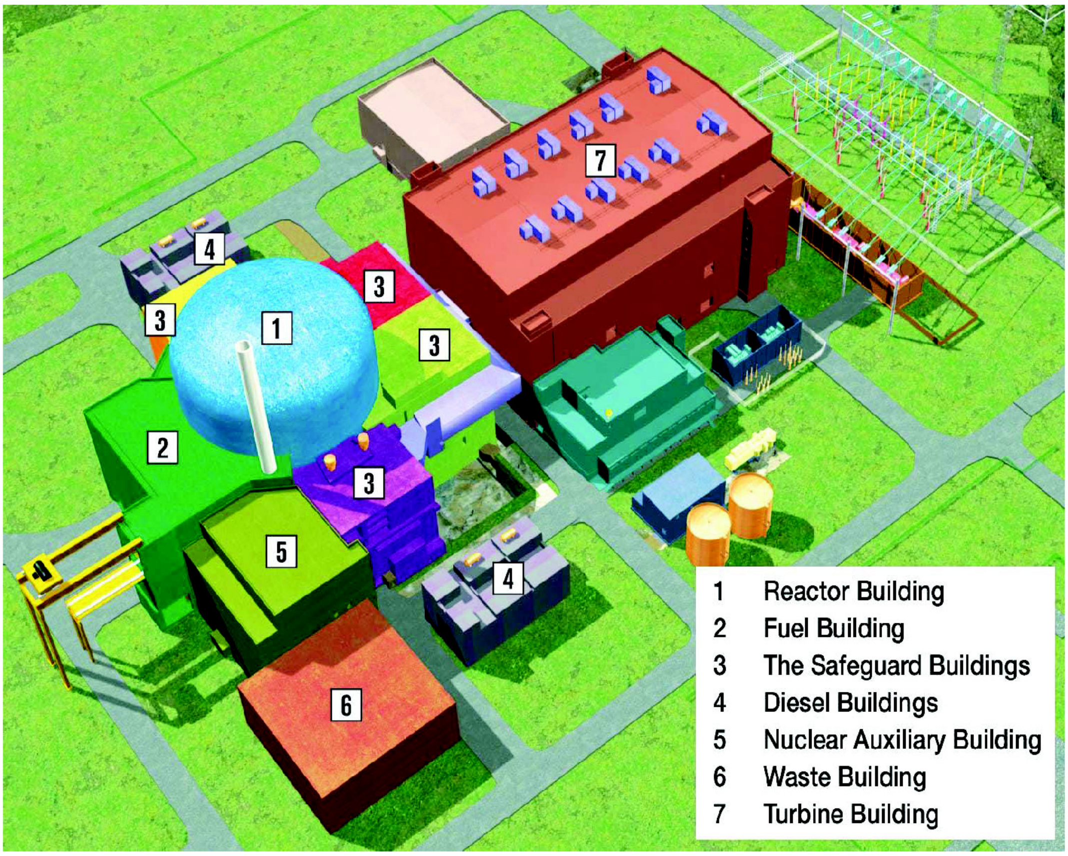

Figure 1: Main buildings of EPR (figure taken from /8/)

The subsequent discussion of the station blackout refers not only to the emergency diesel generators but also to certain systems to remove residual heat and to borate the reactor coolant system. They are briefly described here:

- Extra Borating System: The Extra Borating System (EBS) provides a high pressure safety boration of primary coolant to compensate the reactivity resulting from the reactor coolant system cooldown. It is automatically actuated in case of an ATWS[4] to borate the primary coolant. Each of the EBS trains consists of a borated water tank, a positive displacement pump and two lines of injection into cold legs, via the safety injection penetrations. The EBS pumps and tanks are located in the two separated parts of the Fuel Building (the pumps being implemented at the lowest level). The boration function can be performed with a flow rate of 2.78 kg/s of 7000 ppm boric acid from a single train. The electrical power supply is provided by independent trains, backed up by the main

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[4] Anticipated transients without scram.

emergency diesel generators. Each pump may be supplied by two electrical power trains /8/, /11/, /12/.

- Emergency Feedwater system (EFWS): The main purpose of the EFWS is to guarantee water injection into the steam generators to remove the residual heat from the reactor coolant system in different plant conditions.[5] The EFWS consists of four independent trains, each supplying feedwater to a steam generator from an tank (useful water volume is 386 m³ for each of the division 2 and 3 tanks and 431 m³ for each of the division 1 and 4 tanks) by means of a pump. The EFWS tanks contain demineralised water. The EFWS tank capacity is adequate to maintain the plant in hot shutdown conditions for 24 hours. Re-supplying EFWS tanks from a 2600 m³ reserve supply, 800 m³ of which is shared with the firefighting water supply system, extends the capability to 100 hours. The headers installed between the four tanks, normally shut, enable reserve water from any EFWS tank to be supplied to any of the four trains. Headers installed between the injection lines, normally shut, enable the feed to be supplied to all the steam generators in the event of a failure of an EFWS pump. The electrical power supply to the EFWS pumps is provided by independent trains, backed up by the main emergency diesel generators (EDG). Also, in order to recover from situations of a total loss of electrical power supply by the EDGs, two of the four electrical trains are also backed up by a so-called SBO diesel generator, which is started manually/8/, /13/.

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[5] This type of heat removal is only possible in plant states with closed reactor coolant system and available steam generators.

IV. Provisions against Station Blackout

Specific Fukushima Background

After the tsunami struck the Fukushima NPP a total loss alternating current supply occurred as the emergency diesel generators failed (see chapter I.). Only battery power was available for a certain time, a plant condition subsequently called Station Blackout (SBO). Therefore a station blackout here is characterized as a total loss of three-phase alternating current[6]. Finally in Fukushima, the battery power also was exhausted after several hours.

Design of EPR

To provide the necessary electrical power for safety relevant systems in case of loss of offsite power (e.g. loss of grid due to earthquake as had happened in Fukushima, or due to extreme weather conditions) the EPR is equipped with four emergency diesel generators (EDG). These diesel generators contain all equipment “to produce the 10 kV emergency power for all consumers connected to the emergency power supply switchgear. The Diesel generators will be started automatically in case of simultaneous loss of main- and auxiliary grid connection and main generator or in case of failures in the 10 kV CI normal supply busbars. (…) Each train of the emergency power supply system is equipped with one 10 kV emergency Diesel generator set. All 10 kV Diesel generators are equipped with their own independent auxiliary systems.” /7/

The EDG are located in the two diesel buildings. Each diesel building houses two emergency diesel generators, each of which supplies a safety train within a division of the safeguard building. According to /8/ the diesel buildings “are constructed from reinforced concrete, and are built on an independent foundation raft. The two diesel buildings are geographically separated in order to meet the requirements for protection against aircraft crash. The two redundant generators (…) with their auxiliaries are protected against internal hazards by a separating wall. Both diesel buildings are designed to withstand earthquake and explosions” /8/.

A loss of offsite power combined with the failure of the 4 emergency diesel generators (EDGs) leads to a total loss of power on the emergency and non-emergency 10 kV busbars. This scenario is called Station Blackout (SBO) in the EPR Basic Design Report and is treated in chapter 19.2.1.3.8 of /9/. However, here it is called “Failure of the EDGs”, as we define the SBO as a total loss of three-phase alternating current. A failure of the EDGs would lead to the unavailability of various safety relevant systems (e.g.

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[6] This definition is important as the definition of SBO used by AREVA for the EPR is different. This will be explained subsequently.

safety injection system, Component Cooling Water System, Essential Service Water System, Ventilation systems, Battery chargers) and therefore of vital safety functions. The consequences of this scenario in case of failure of the EDG are described in /10/ as follows:

> "In case of a SBO [here: failure of the EDG] in power operation, the loss of the RCPs [Reactor Coolant pumps] triggers a reactor trip ('low RCP speed' signal). The SGs [Steam Generators] are no longer fed. Their level decreases due to the decay heat, the steam is released to the atmosphere through the SG relief valves (set point at 91.5 bar) as long as they are power supplied by the batteries and then by the spring loaded safety valves (set point at 101.5 bar) after battery depletion. At 100 % power the core power is 5100 MW and the SG water mass is 85 tons per SG. The SG dryout occurs about 1.5 h after the onset of the SBO. After SG dryout the core heats up. The decay heat leads to boiling in the RCS. The steam is released through the pressurizer safety valves into the containment. Core uncovery starts at about 2 h and core melt at about 3 h (see subsection 19.4.1). This is a high pressure core melt because the RCS [Reactor Coolant System] depressurization means are unavailable at this time, due to battery depletion. About 2 h after the onset of the SBO [here: failure of the EDG] the batteries are depleted. All the I&C [Instrumentation and Control] (safety and operational parts) become unavailable including the main control room. Preliminary probabilistic studies have shown that the core melt frequency target is not met for such a sequence."

To avoid this scenario the EPR is equipped with additional power sources, the so called SBO-diesel generators (SBO-DGs). Each of the two diesel buildings houses one SBO-diesel generator set. The two SBO-DGs have smaller power than the EDGs and are characterized as follows in /7/:

> "The SBO Diesel generators are started manually from the main control room in case of under voltage at the related busbar, the separation from the 10 kV emergency busbar and reloading of the motors according to the load sequence is also performed manually. The stored fuel capacity allows a continuous operation of 24 hours at design load. (…) Each of the SBO Diesel generator sets forms a complete autonomous unit with its own auxiliary systems. The Diesel engine is a four-stroke, water-cooled unit for compressed air starting with a power of 1400 kW at a speed of 1500 rpm. The cooling water of the Diesel engine is cooled through water/air heat exchanger with forced air fans. (…) The control voltage for the SBO Diesel generators and for the voltage for the starting valves is taken from the 400 V uninterrupted AC supply system via AC/DC converters. The equipment is installed in the Diesel buildings of division 1 and 4."

The SBO-DGs are diversified with regard to the EDGs and therefore, according to the opinion of AREVA, a Common Cause Failure of the SBO-DBs together with the EDGs has not to be considered.[7] The functional capabilities of the SBO-DGs are described in /10/:

> "They [the SBO-DGs] supply mainly the pumps of the emergency feedwater system of divisions 1 and 4, parts of the ventilation systems, the necessary I&C systems and the main control room (MCR) lighting. Functionally speaking, only one SBO-DG is sufficient to cope with a SBO, but 2 SBO-DGs are necessary in order to meet the core melt frequency target. The SBO-DGs are started and connected manually from the MCR. It is assumed that this action is performed at 30 min after occurrence of the SBO. As mentioned above the SG [steam generator] dryout would occur at about 1.5 h without SG feeding. Each EFWS train [emergency feedwater system] delivers more than 93.5 t/h at the SGRV [steam generator relief valve] setpoint (91.5 bar) which means that one train is sufficient to remove the decay heat at 1.5 h. If one SBO-DG and the related EFWS pump are started at 30 min, the secondary side water inventory will remain greater than 80 tons. The SBO is assumed to occur in any standard reactor state. (…) In order to be consistent with the probabilistic studies, the offsite power is assumed to be recovered within 24 h. The strategy in case of SBO is to maintain the plant at the initial temperature until the power recovery."

The strategy to cope with the failure of the EDG via the SBO-DGs depends on the reactor state. It is described in /10/. In all reactor states with closed reactor coolant system the heat removal takes place via water injection into the steam generators due to the emergency feedwater system:

> "This part deals with a SBO occurring in the reactor states A, B or C. (…) The SGs can be used for decay heat removal. The SGs are fed by the EFWS (emergency feedwater system) trains 1 and 4 which are power supplied by the SBO-DGs. These two trains can take water from any EFWS tank after a manual opening of the headers at the suction part of the pumps. The required amount of water to remove the decay heat during 24 h without plant cooling is less than the total available amount of water of the EFWS tanks, i.e. 1500 tons (see section 10.4.9).
> (…)
> In case of SBO there is no boron injection means but there is no need of boration to compensate a primary cooling because the strategy is to maintain the RCS at the initial temperature until the power supply recovery. In addition there is no control rod stuck in RRC-A [risk reduction category A] and therefore the control rods provide enough subcriticality to compensate the xenon depletion in the long term.

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[7] According to our definition above, failure of the 4 main EDGs and the two smaller SBO-DG would lead to a loss of the three-phase alternating current.

> The I&C [instrumentation and control] and the MCR [main control room] are supplied by the batteries with an autonomy of at least 2 h. After this duration, the necessary I&C and ventilations are supplied by the SBO-DGs so that the plant is controlled from the MCR."

In plant states with <u>open reactor coolant system</u> the use of the steam generators for heat removal is not possible. In case of failure of the EDG the low head safety injection and residual heat removal system becomes unavailable and the primary coolant starts heating up. The scenario is described in /10/ as follows:

> "Boiling in the RPV starts, within approximately 10 min in case of mid-loop operation. Core uncovery occurs within about 1.5 h. this applies to the state D before refuelling. For the state D after refuelling, these delays are about 4 times larger due to a lower decay heat. Water make-up would be necessary to compensate the steaming in the RPV [reactor pressure vessel]. However, the probabilistic studies show that the core melt frequency due to a LOOP [loss of offsite power] in shutdown state D with a duration longer than 2 h is 2.5 10^{-8}/reactor-year without water make-up (see section 19.3.2.2). This is considered as acceptable. A water make-up capability is therefore not provided for the case of SBO in state D (it is provided for the case of LOCC (loss of cooling chain): see section 19.2.1.3.9). In state E the reactor cavity is flooded for fuel assembly handling. There is about 2000 m^3 of water above the core, available for cooling. This water is contained (see subsection 9.1.3) in the reactor cavity, in the RPV internals storage cavity, in the instrumentation lances storage cavity and in the transfer tube cavity which are connected during fuel handling. A part of the water of the spent fuel pool could also participate to core cooling through the transfer tube but this amount of water is not considered here. This provides a conservative margin. With these assumptions steaming in the cavity starts at more than 4 h and less than 950 tons (to be confirmed) of water are vaporised before reaching 24 h. There is no need of water make-up in this case."

<u>Conclusions</u>

In the light of the Fukushima accident the following points should be further discussed with respect to potential SBO:

- Long term loss of offsite power – duration of several days or weeks – cannot and should not be excluded from the design basis. I. e. the onsite power supply has to be ready to cope with such a situation.
- With the help of the SBO-DGs and the EFWS the EPR can be kept in a controlled state for 24 hours, in all plant states with closed reactor pressure vessel and available steam generators. In case of high pressure and temperature of the reactor coolant system (e. g. loss of offsite power and failure of the EDG immediately after power operation) it is not possible to bring the plant into safe

cold shutdown conditions with the help of the SBO-DGs and the EFWS. Moreover the reactor coolant system cannot be borated in case of a failure of the EDG as there is no supply of electrical power to the extra boration system (EBS) by the SBO-DGs.

In this respect the situation is different in the German Konvoi plants. The Konvoi is equipped with two emergency residual heat removal (ERHR) trains (i.e. additional chains for decay heat removal from the primary circuit). The electrical power supply of the pumps is provided by the D2 diesel generators. The four D2 diesel generators in Konvoi basically fulfil the same function as the two SBO-DGs in EPR but their number is two times higher. They are diverse to the four main EDGs as in EPR and they are housed in a separate building which is protected against an airplane crash[8]. Each of the two ERHR pumps can be connected to one specific D2 diesel generator. As the power of the D2 diesel generators is significantly lower than the power of the EDGs (as in EPR for the SBO-DGs) the respective two diesel generators can either supply the assigned pump of the emergency residual heat removal trains or the assigned pump of the emergency feedwater system.

Additionally in the Konvoi plant the 4 pumps of the EBS are also connected to the D2 diesel generators. Therefore boration of the reactor coolant system, especially during cooldown of the system, is possible in case of a failure of the EDGs.

- Concerning the extra borating system (the EBS can inject highly borated water into the reactor coolant system for sub-criticality) there are two independent trains in EPR, whereas there are four independent trains in Konvoi. Automatic actuation in EPR happens only in case of an ATWS, in all other cases the system has to be started manually. Automatic actuation in Konvoi happens by low level in pressurizer or in case of ATWS. In Konvoi plants the system can either inject medium borated water from the large borated water storage tanks (part of the emergency core cooling system) to compensate small leakages at high pressure or highly borated water from the small boration system tanks. In EPR only injection of highly borated water from the small EBS tanks is foreseen.
- The capacity of the emergency feedwater pumps is smaller in EPR than in Konvoi despite the higher thermal power of the EPR (EPR: 26 kg/s, Konvoi: 36 kg/s). The EFWS pumps are driven by electro motors in EPR. In the Konvoi plants the EFWS pumps can be driven electrically and additionally they can mechanically be

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[8] The main reason for this protective measure is that the building also houses some safety relevant I&C systems. The main concept for the protection of the on-site emergency power supply (D1 and D2 DGs) is physical separation (“räumliche Trennung”) of the D1 and D2 buildings (as in EPR the separation of the two diesel buildings).

linked to the D2 diesel generators. Therefore two diverse means for driving the EFWS pumps are available in the Konvoi plants.

- The SBO-DGs have to be started manually in EPR. In the Konvoi plants the D2 diesel generators are started automatically to deliver the necessary electrical power to the emergency feedwater system.
- According to the Basic Design Report of the EPR, during mid-loop operation a loss of offsite power combined with a failure of the 4 main EDGs will always lead to a low pressure core melt scenario.
- The concept for housing the 6 diesel generators in EPR (4 EDGs, 2 SBO-DGs) and the 8 diesel generators in Konvoi (4 D1-EDGs, 4 D2 diesel generators) is different:
    - EPR: Two physically separated diesel buildings on different sides of the reactor building, each housing two EDGs and one SBO-DG. Diesel buildings withstand earthquakes and explosions. Protection measure against an aircraft crash is the physical separation.
    - Konvoi: Two physically separated diesel buildings. The building housing the 4 D1 EDGs is protected against earthquake. The building housing the 4 D2 diesel generators additionally is protected against airplane crash.
    - Physical separation is the internationally accepted standard protection measure against failure of all EDGs at a site in case of an aircraft crash (taking into account the mechanical impact, but also the consequences of a possible long-lasting and hot fire due to fuel burning). In this respect, there is no major difference between EPR and Konvoi. However, the EPR diesel buildings' protection against aircraft crash is provided exclusively by the different position of the buildings on the site, which are separated by the reactor building. A physical protection of the buildings is not implemented for the EPR. This is different to the Konvoi plants where all D2 diesel generators are installed in a building protected against aircraft crash. The design of this building provides additional protection (at least concerning the mechanical impact).
    - The main EDG and the smaller SBO-DG are diverse but they are installed in the same two buildings in EPR.
- The documents evaluated in the course of this study contain no detailed information about preventive accident management measures and procedures applicable in case of a station blackout. E. g. additional provisions should be provided for situations with available steam generators as are secondary pressure relief in combination with mobile low pressure water injection equipment which could be flexibly applied. Enhanced battery capacity could also advantageous in this respect. The Swiss ad-hoc requirements /4/ provide a

reasonable guidance for additional measures on the base of the Fukushima experiences.

V. Spent Fuel Storage Pool Design and Cooling

Specific Fukushima Background

The accident course in Fukushima has shown drastically how vulnerable the spent fuel storage can be, if coolability is not available for a longer period of time. In case of boiling of the water in the spent fuel pool and subsequent dry out of the fuel elements or parts of them the danger of overheating of the fuel elements arises. Consequences could be an exothermic chemical reaction of the fuel pin cladding, which is made of zirconium alloy, and eventually melting of fuel.

Beyond temperatures of ca. 1200 °C the cladding reacts with air exothermically so as to even accelerate this process and promoting the melting of the fuel. With water or steam, zirconium reacts generating large amounts of hydrogen, thus creating an explosive hazard for the integrity of the building.

The lessons to be learned from Fukushima is, that the spent fuel storage installation necessarily has to be equipped with

- redundant and diverse cooling possibilities for the spent fuel elements and
- diverse mechanisms for energy supply

to prevent fuel pin damage reliably even in case of long term loss of power (offsite and emergency diesel generators) combined with loss of ultimate heat sink.

Furthermore concerning the spent fuel storage installation, independent of whether it is inside the containment or in a separate building, there have to be mitigating measures to cope with emergency cases as there are

- depressurization device for venting of the respective building
- reliable and effective filters for reducing the release of airborne radioactive materials
- non igniting measures to reduce the concentration of hydrogen such that no explosion danger arises when steam is condensed in the atmosphere or overpressure is released via venting.

Design of EPR

In EPR Basic Design the spent fuel storage pool (SFP) is located not within the reactor building but in a separate building /9/. The building is constructed according to the same safety principles as the containment as far as external events are concerned, i.e. there is protection against design earthquake as well as airplane crash following the according specification /14/.

In EPR Basic Design sub-criticality of the Spent Fuel Storage Pool is achieved by the geometry of the storage grid and by use of borated steel for separating the fuel elements /15/.

The basic design of the fuel pool cooling system (FPCS) and the fuel pool purification system (FPPS) to cope with loads due to earthquake, airplane crash, explosion pressure wave and internal hazards is described in /15/ as follows:

- Earthquake: "The FPCS is designed to withstand the Design Earthquake. The Fuel Pool Purification System (FPPS) is designed against DE up to the isolation valve of the draining pipes of the different RB and FB pool compartments, including the isolation valves. The purification function is not required in case of an earthquake. The containment isolation valves are designed against Design Earthquake."
- Airplane Crash: "The FPCS is designed to withstand the Airplane Crash according to the protection of the fuel building. The two FPCS trains are assigned to safeguard buildings 1 and 4. The capacity of one train is sufficient, therefore the impairment of one train by Airplane Crash is admissible also during safe shut-down and refuelling. The FPPS is partly located in the nuclear auxiliary building which is not designed for this purpose."
- Explosion Pressure Wave: "The FPCS is designed to withstand the Explosion Pressure Wave according to the protection of the fuel building. The FPPS does not withstand an explosion pressure wave, considering that the nuclear auxiliary building is not designed for this purpose."
- Internal Hazards: "The FPCS is designed to withstand following internal hazards : pipe failure (flooding, pipe whip, jet impingement forces, pressure wave forces, increased ambient conditions like temperature, humidity, radiation), fire, missile, fuel handling accident."

In the basic design, the cooling system has two trains, each of them capable for the basic task of keeping the temperature of the spent fuel pool within the allowed limits for all relevant scenarios of loading, thus being single failure resistant /15/. Each train has one pump and one heat exchanger. The heat is transferred to the component cooling water system (CCWS). The highest points of the suction pipes (penetrations in the spent fuel pool) are located below the normal water level to permit pump priming. To prevent water losses due to pipe breaks siphon vacuum breakers are installed /15/:

> "Siphon vacuum breakers are installed on the pipes, located into the spent fuel pool, in order to prevent pool siphoning in case of an accidental pipe break. During normal operation the siphon valves are opened. After detection of a leakage the affected train has to be cut out. Then the level in the fuel pool has to be made up again if necessary and the unaffected train can be taken in operation manually. The suction pipe head is located above the stored elements in order to allow the cooling

> of the pool even after a lowering of the water level and to prevent fuel uncovery in case of siphoning."

According to /15/ the cooling system shall be capable to ensure the following design requirements:

- "keeping a fuel pool temperature to less than 50°C during normal operation and refuelling outages;
- keeping a fuel pool temperature to less than 80°C during normal operation and refuelling outages under PCC2-4 conditions;
- the system and the fuel pool should withstand a temperature of 100°C during RRC-A or RCC-B conditions (…);
- restarting and operation of the system when the fuel pool is at 100°C."

The electrical power for the fuel pool cooling system is supplied by the four independent trains which are backed up by the main emergency diesel generators. The electrical back-up is performed manually considering the grace periods associated to the fuel pool heat up /15/.

In the light of Fukushima a main weakness of the basic design is the performance under the conditions of station blackout and loss of ultimate heat sink. In both cases the CCWS is not working, therefore the residual heat cannot be removed. The answer which was foreseen in the basic design seems to be the injection of water into the pool /15/:

> "In cases of total loss of the CCWS, the normal cooling function is also lost. Water makeup of the spent fuel pool can be performed, after connection of hoses, with means of the demineralized water distribution system the reactor boron and water make-up system, or the fuel pool purification system."

However it is not clear at all whether the water make-up system works in case of SBO (electrical power supply to the pumps of the water makeup system).

Concerning the US EPR the basic design has been changed insofar as each cooling train of the FPCS is equipped with two pump instead of one pump /16/ thus considerably reducing the probability of failure of the whole system in case of single failure of the pumps.

Compensation for water losses due to evaporation is done by the water make-up system /16/:

> "Normal make-up water to the SFP is supplied by the demineralized water system. The safety-related and Seismic Category I SFP make-up capability is provided with sufficient inventory and capacity to compensate for normal evaporation losses from the SFP for up to 7 days with the FPCS in operation and maintaining SFP temperature at 140°F. SFP leakage associated with a dropped fuel assembly has not been considered, as an assembly drop will not result in perforation of the SFP liner.

> The SFP make-up water, approximately 29,000 gallons, is maintained in the cask loading pit or the transfer compartment (or both) which are both Seismic Category I structures adjacent to the SFP. A Quality Group C and Seismic Category I submersible pump and piping to the SFP is installed in both compartments. (…) The SFP make-up pumps are provided with emergency power and are operated from the main control room (MCR). Other independent on-site Seismic Category I water supplies are available to provide the back-up SFP make-up capability, including the IRWST with at least 500,000 gallons available during plant operation. The piping and pump used to deliver the back-up water to the SFP are not designed to Seismic Category I."

Fukushima has shown that melting of fuel in the spent fuel pool can be serious problem, especially if the spent fuel pool is located outside the containment as in Fukushima. "Technical guidelines for the design and construction of the next generation of nuclear power plants with pressurized water reactors" /17/ already contain the following requirement with respect to the prevention of fuel melt in fuel pool:

> "As far as the fuel pool is not situated in the containment building, it has to be demonstrated that spent fuel melt conditions in the pool are 'practically eliminated'. This demonstration has to take into consideration the case of earthquake."

This requirement has been accounted for in the concept of European EPRs, which, in this respect, has been developed further considerably from the basic design. The spent fuel pool is equipped with a third cooling train with one pump and one heat exchanger diverse from the principal trains; the heat exchanger is cooled by a completely separate cooling system /18/, /19/. According to /18/ the third cooling train has been specially designed to meet the two following objectives: to significantly reduce the risk of boiling in the spent fuel pool and to help in the "practical elimination" of the risk of fuel damage in the spent fuel pool. It should also be available in case of a failure of the four main EDGs and a loss of ultimate heat sink:

> "In addition, the third fuel pool cooling system PTR [FPCS] train is completely independent with respect to electrical supply and cooling system. Following a LOOP [loss of offsite power], the third train can be supplied by either the Emergency Diesel Generators (EDGs) or the Station Blackout (SBO) Diesel Generators. This independence provides a reduction of the risk of water boiling in the event of the loss of the two principal trains. To reduce the risk of accidental draining of the spent fuel pool, design features such as the automatic isolation of the lines connected to the bottom of the pool have been implemented. In order to study the design of the PTR [FPCS] in probabilistic terms, the following events have been considered:
>
> - Incidents or accidents affecting the principal PTR [FPCS] trains and/or their support systems.

  - Loss of the PTR [FPCS], corresponding to the simultaneous unavailability of the two principal trains, with a risk of losing the third train.
  - Degradation of the fuel assemblies in the spent fuel pool because of water depletion resulting either from evaporation due to the total loss of cooling or following accidental draining of the pond.

> The probabilistic assessments shown in sections 3 and 4 of Sub-chapter 15.3 confirm that the design allows:
>
> - The risk of boiling occurring in the spent fuel pool to be significantly reduced.
> - The risk of fuel assembly damage following a total loss of cooling or an accidental draining of the spent fuel pool to be considered as 'practically eliminated'. The risk of damage is evaluated at 6.27E-11/reactor year for loss of cooling and 2.3E-09/reactor year for accidental draining." /18/

In /18/ it is concluded that on the basis of the design features for the mitigation of accidents likely to affect the spent fuel pool (loss of cooling and accidental draining) and probabilistic assessments it is deemed that the risk of fuel assembly damage in the spent fuel pool can be considered as practically eliminated. Within the scope of this report, it is not possible to assess whether this ambitious goal really has been achieved. However, it is clear that the installation of a third diverse cooling train for the spent fuel pool in the European EPRs represents a considerable improvement, as compared to the EPR basic design.

As far as can be seen from the available documents there are no further emergency measures neither to prevent nor to mitigate events surpassing the design basis.

Conclusions

In current German PWR plants of type Konvoi the spent fuel storage pool is located inside the containment, thus allowing interchange use of core decay heat removal systems and fuel storage pool cooling systems. In addition containment systems provide protection against external events and emergency measures in case of beyond design basis accidents.

The Design of EPR in which the spent fuel storage pool is within a separate building is not necessarily a disadvantage. The fuel building is constructed according to the same principles of protection against external events as is the containment. Necessary switching operations for isolation of the system should in principle induce no additional safety problem.

However, auxiliary systems like the cooling system of the spent fuel pool have to be designed and dimensioned so as to be able to cope with all cooling situations in full autarky from core related safety systems.

In EPR basic design the systems of the spent fuel pool are designed according to the Single Failure Principle. Events like those happened in Fukushima without any additional diverse systems would easily lead to complete loss of cooling of the Spent Fuel Storage Pool. This is also a major weakness in the basic design of the EPR as cooling is lost in case of a loss of ultimate heat sink, a loss of offsite power in combination with a failure of the four main EDGs and in case of SBO. According to /15/ boiling temperatures might then be reached in the pool within 5 hours in refuelling situation and within 31 to 59 hours during the power cycle in case of UO2-fuel elements stored in the pool. With MOX elements stored in the pool the respective time scales are 4 hours (refuelling situation) and 14 to 36 hours (power cycle).

However, this weakness has been accounted for in the design of European EPR. There is a third cooling train with one pump and one heat exchanger diverse from the principal trains; the heat exchanger is cooled by a completely separate cooling system. In case of failure of the EDGs, it can be supplied with electricity from the SBO-DGs.

In the Konvoi design, there are three cooling trains, two of which can be supplied with electricity from the D2 DGs. Also, two residual heat removal pumps can be switched over from core cooling to pool cooling.

No information is available concerning additional accident management measures and procedures in the case that the spent fuel cooling systems are not available for a longer time in EPR. In particular, there is no indication in the documents evaluated that hydrogen recombiners and/or igniters are to be installed at the spent fuel pool.

Since there are no mitigating accident management systems for the spent fuel storage pool in case of total loss of cooling, hazardous situations might arise from dry out of the fuel pins and their possible damage afterwards and from hydrogen generation by steam/water – fuel cladding interaction.

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