Draft Layout, Containment and Performance of the Safety System of the European Supercritical Water-Cooled Reactor

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Abstract

In Europe, the research on Supercritical Water-Cooled Reactors is integrated in a project called "High Performance Light Water Reactor Phase 2" (HPLWR Phase 2), co-funded by the European Commission. Ten partners and three active supporters are working on critical scientific issues to determine the potential of this reactor concept in the electricity market. Close to the end of the project the technical results are translated into a draft layout of the HPLWR. The containment and safety system are being explained. Exemplarily, a depressurization event shows the capabilities of the safety system to sufficiently cool the reactor by means of a low pressure coolant injection system.

1. Introduction

The High Performance Light Water Reactor (HPLWR) is a pressure vessel type Light Water Reactor (LWR) with supercritical water at 25MPa as coolant and moderator. Co-funded by the European Commission, a consortium of 10 partners from 8 European countries and three so-called active supporters are working on critical scientific issues within the project "High Performance Light Water Reactor Phase 2" which lasts from 2006 until 2010. The objective of this project is to assess the feasibility of this reactor concept to determine the potential in the electricity market as described in more detail by Starflinger et al. [1]. This European project is part of research activities on Supercritical Water-Cooled Reactors (SCWR) within the Generation IV International Forum.

Inside the reactor core of a HPLWR, water at a pressure of 25MPa is heated up from 280°C to 500°C in three steps, thus gaining an enthalpy rise of 1936 kJ/kg according to the IAPWS steam table [2] which is approximately 10 times larger compared to a modern PWR, like EPR™. Consequently for the HPLWR concept in order to reach the same energy (in kJ), a 10 times lower mass flow rate is required. Due to the high steam parameters, a net cycle efficiency of 43.5% and, due to much lower mass flow rate, a reduction of component sizes are envisaged, which strongly contribute to reduce the electricity generation costs and capital costs of this nuclear power plant, as described by Bittermann et al. [3]. Hence, the HPLWR has the potential to serve as a further step in the 1000MWe class of Light Water Reactors (LWR).

The project structure and recent results on design of the reactor pressure vessel and internals, neutronics, materials and heat transfer were presented recently by Starflinger et al. [4]. This paper focuses on the remaining issues, i.e. plant layout, containment, and design and performance of the safety system.

2. Plant layout

The plant layout of the High Performance Light Water Reactor is very similar to modern Boiling Water Reactors, e.g. like KERENA™, with pressure suppression containment. Figure 1 depicts a section through the HPLWR reactor building (left) and through the turbine building (right) as designed by AREVA NP. Because of the small height of the reactor pressure vessel with 14.3m only, the height of the containment and consequently, the height of the reactor building could have been reduced significantly.

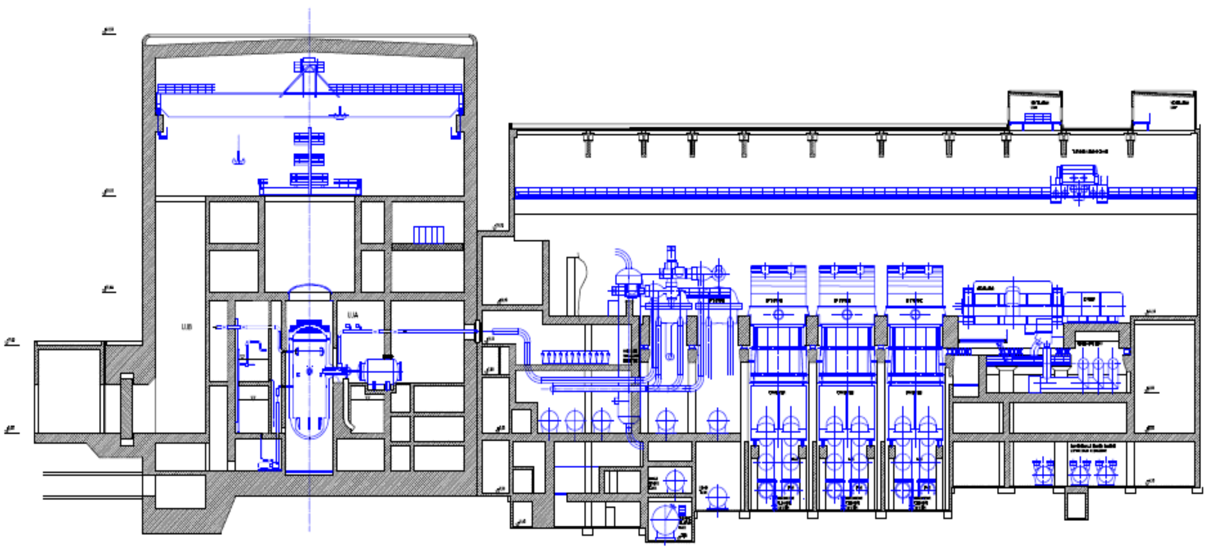


Figure 1 Section through the reactor building and through the turbine building of the HPLWR.

2.1 Reactor Building

The main dimensions of the reactor building can be determined as follows:

- Diameter: 45m
- Height: app 55m
- Volume: app 90,000m^3

The reactor building of the HPLWR houses the containment and internals, nuclear fuel storage facilities and handling equipment, shielding and storage pool, low-pressure section of reactor water and fuel pool cleanup system, fuel pool cooling system, main steam and feedwater lines including outboard containment isolation valves, and safety instrumentation and control equipment. Additionally, the reactor building crane and the fuel loading machine are located in the upper part. The containment itself is accessible by a hatch. Residual heat removal pumps and heat exchangers are installed underneath the containment in separate compartments.

The diameter of the reactor building is mainly determined by the containment diameter and by the arrangement of the reactor pool and the operating floor, whereas the total height is mainly determined by the containment height and by arrangement of the crane and fuel loading machine. As shown in Figure 2, a horizontal plan view at the elevation of the operating floor, set-down areas of different components have been specified. During outage, reactor internals like the steam plenum and control rod guide tubes are stored inside the reactor pool. Other components like control rod drives and closures of the reactor pressure vessel and of the containment can be stored besides the pool.

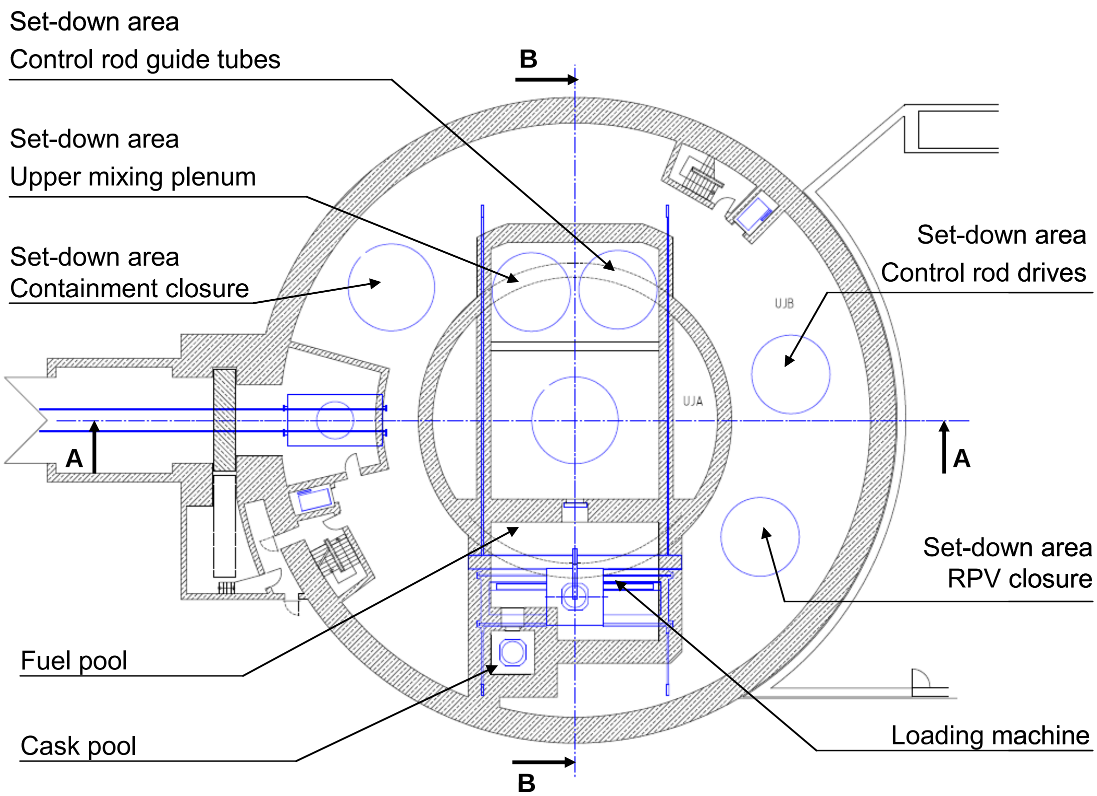


Figure 2 Plan view of the reactor building operating floor.

Two sections through the reactor building are shown in Figure 3 (section A-A) and Figure 4 (section B-B). The containment itself has a diameter of 21.6m and a height of 27.1m and is filled with nitrogen during operation of the reactor (red dashed lines) [6]. It contains the pressure suppression pool as well as the core flooding pools which serve as large heat sinks in emergency and accident cases. Figure 3 also shows compartments in which the electrical systems and the heating, ventilation and air conditioning system are located. The mechanical systems are placed on a level beneath the air lock to the containment. The walls of the reactor building are supposed to withstand airplane crashes.

In Figure 4, the fuel storage pool and the fuel loading machine are visible. Furthermore, parts of the safety system like the passively operating building condenser and the actively operation residual heat removal system can be seen.

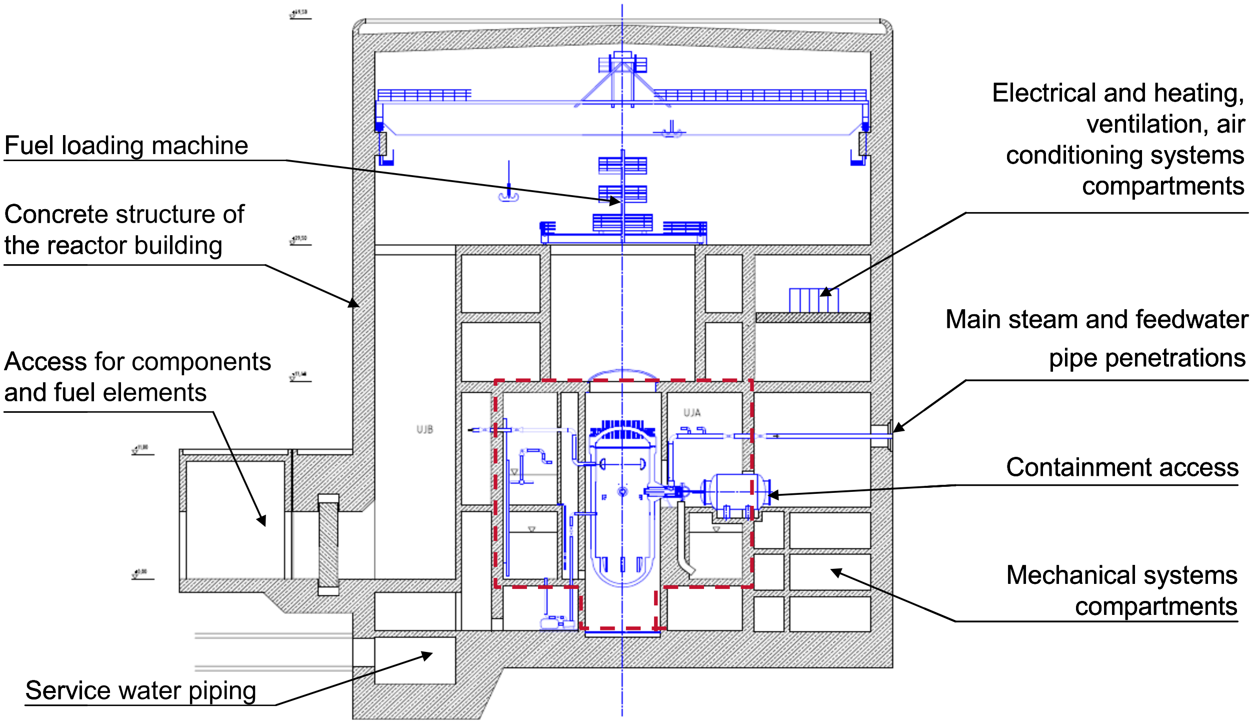


Figure 3 Section A-A.

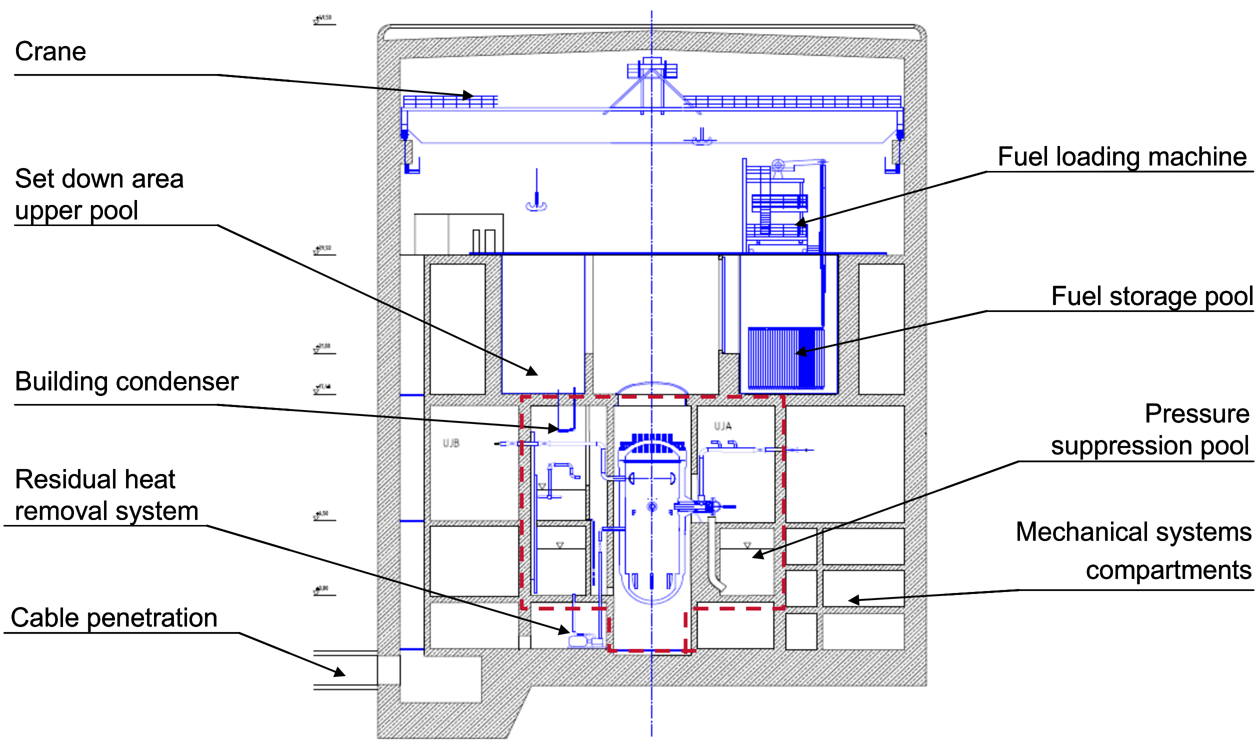


Figure 4 Section B-B.

2.2 Turbine Building

The turbine building is located adjacent to the reactor building. Figure 5 shows a longitudinal section through the turbine building containing the components of the supercritical steam cycle optimised by Brandauer et al. [7]. Its main parameters can be determined as follows:

- Length: app. 95m
- Width: app 56m
- Height: app 45m / 48m
- Volume: app. 250,000 m^3

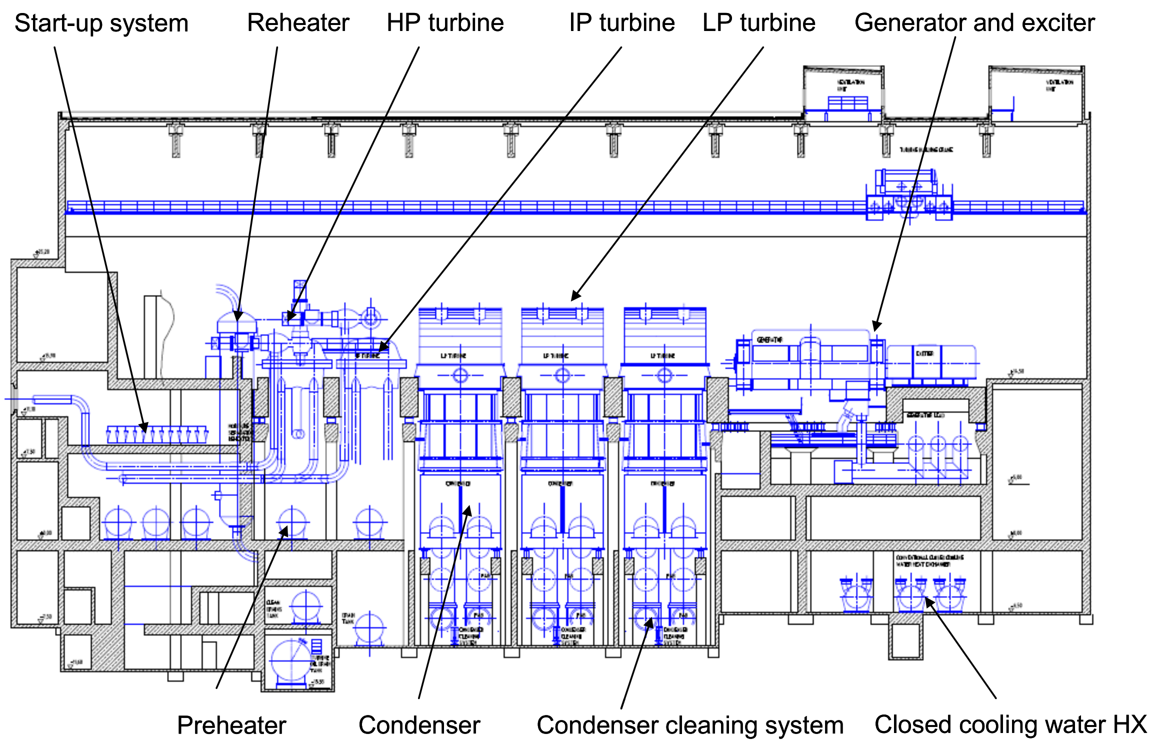


Figure 5 Longitudinal section turbine building.

The length is mainly determined by turbine / generator set. This set has been designed for supercritical water applications taking the knowledge of supercritical fossil boilers into account [8]. The width is determined by LP Turbine including condenser withdrawal length and preheater and pump arrangement.

As given in Figures 5 - 7, the following large components are located inside the turbine building: Turbine generator set consisting of three low pressure double-flooded turbines, one double flooded intermediate pressure and one double flooded high pressure turbine. Additionally, the generator and exciter are mounted on the same foundation. It also contains four feedwater pumps, four main condensate pumps, two vertically arranged reheaters, one feedwater tank and fourteen low pressure and high pressure preheaters horizontally arranged in two trains. The start-up system, designed by Schlagenhaufer et al. [5], is arranged on an intermediate platform between the high pressure turbine and the steam pipe penetrations of the reactor building. It operates between 0 and 50% load providing a closed loop between the RPV and the feedwater tank, which is large enough to deal with the excess water in the piping replaced by steam during heat-up.

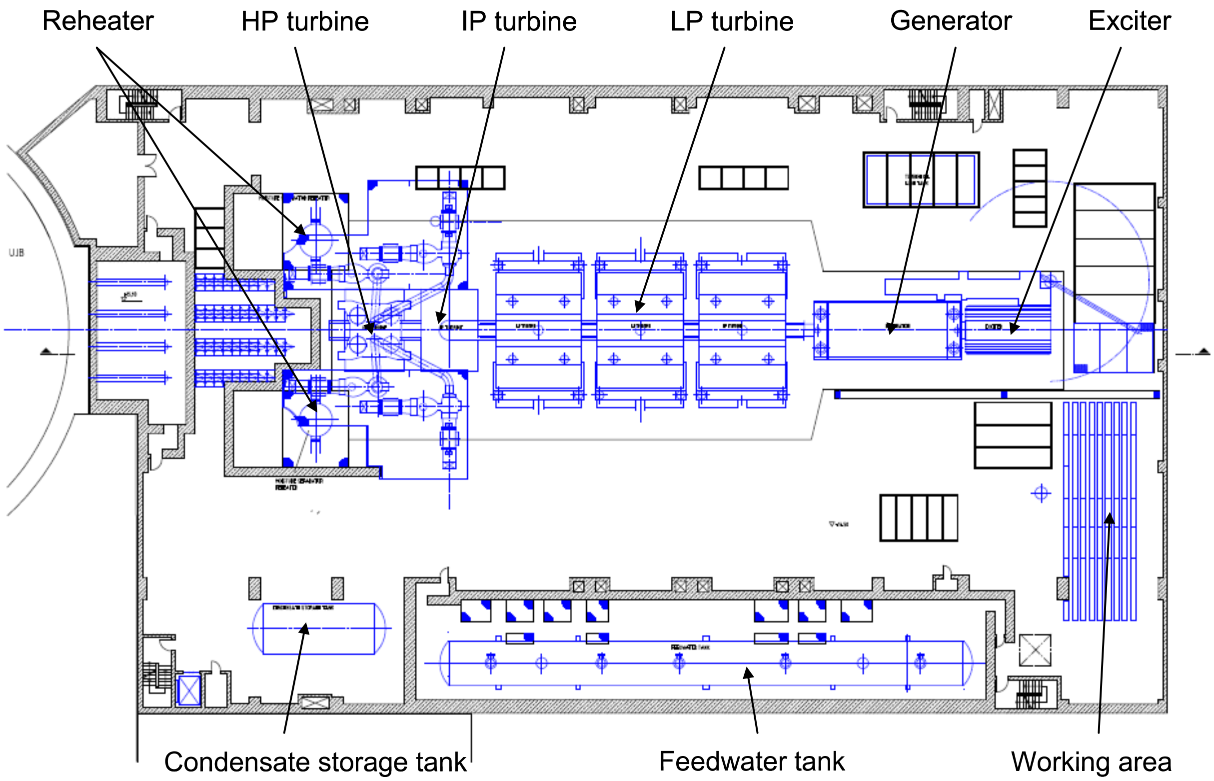


Figure 6 Plan view turbine building at turbine floor.

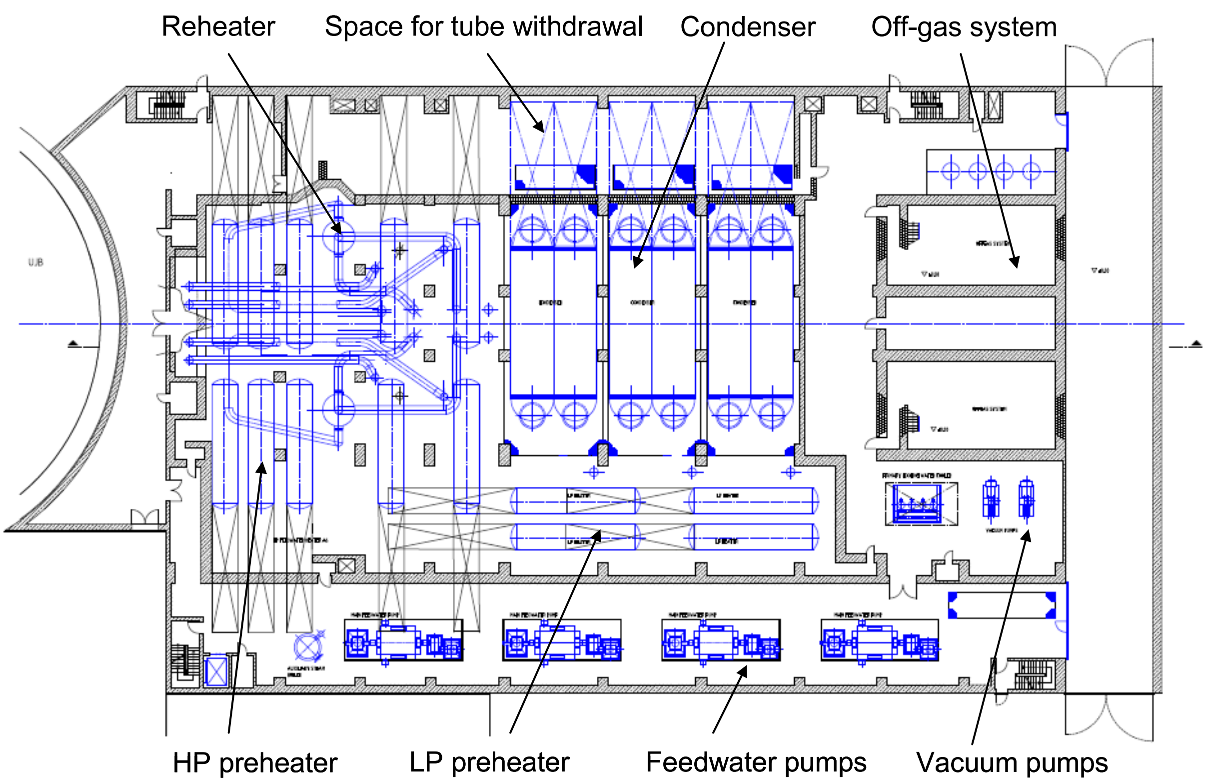


Figure 7 Plan view turbine building at preheater floor.

The volume of the HPLWR turbine building is comparable to the turbine buildings of conventional boiling water reactors. It should be mentioned that due to supercritical properties of the coolant, five turbines of the HPLWR turbine train (HP, IP, 3 LP) fit now into the same building like for a BWR turbine train of four turbines (HP, 3 LP).

3. Containment and Safety System

A first containment and safety proposal of the HPLWR was derived from the latest boiling water reactor containment concepts [6]. As shown in Figure 8, it includes the reactor scram system, the containment isolation, the depressurization system, four core flooding pools, a pressure suppression pool (wetwell), the dry well and the containment condenser. However, some passive safety systems, e.g. passive reflooding of the core, cannot be adapted directly to the HPLWR, since a natural convection flow is not possible in the three-pass-core. Consequently, the heat removal of the reactor pressure vessel (RPV) works only with systems that maintain the core coolant flow rate.

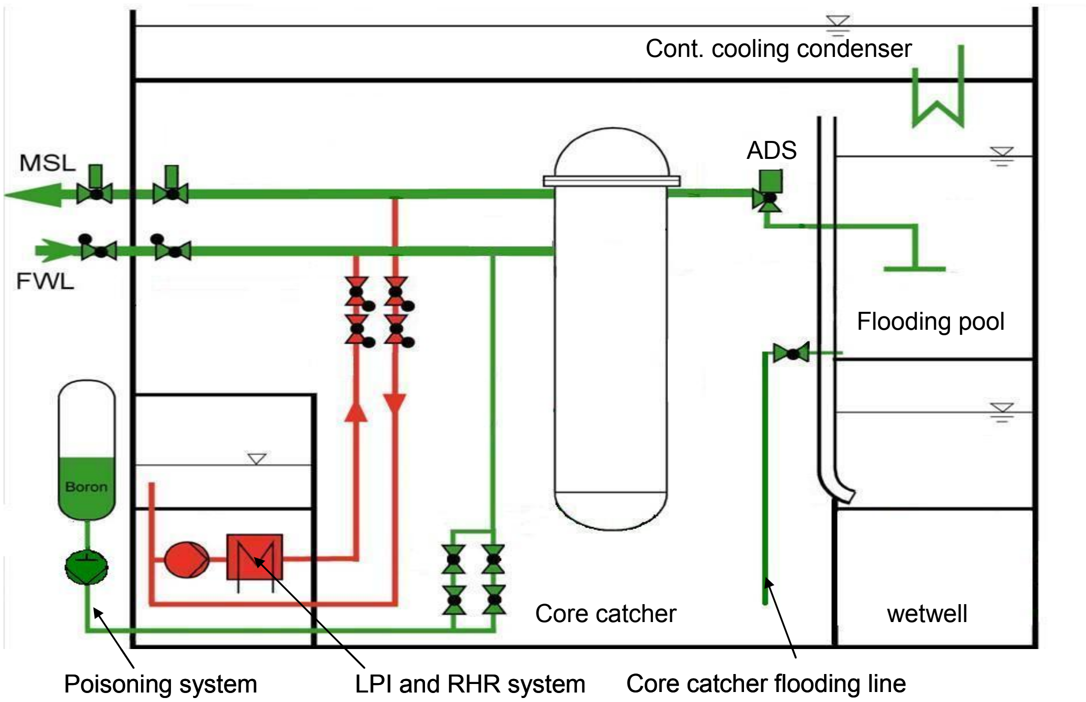


Figure 8 Schematic sketch of the safety system.

Figure 9 depicts a three dimensional drawing of the HPLWR containment and integrated safety systems. The grey structure represents the concrete walls, which were optimised with respect to loads on the wall due to the water inventory in the pools, weight of the reactor pressure vessel, and 0.5MPa internal overpressure in case of accidents. In the pump rooms in the basement of the containment, the pump, motor and heat exchanger of the residual heat removal system (low pressure coolant injection system, LPCI) are shown in blue. The light green pipes are the vent lines submerged in the pressure suppression pool, through which steam, being released into the containment atmosphere during an accident, is pushed into the pool water where it condenses. The orange lines are the pipes from the safety relief valves to the spargers which are located inside the core flooding pool. In case of a depressurisation, the steam is released into the core flooding pool where it condenses. The blue and the pink lines represent the four main steam lines and the main feedwater lines, respectively. The green pipes penetrating the concrete at the top of the containment belong to the four building condensers operating passively. The purple heat exchangers belong to an optional high pressure residual heat removal system.

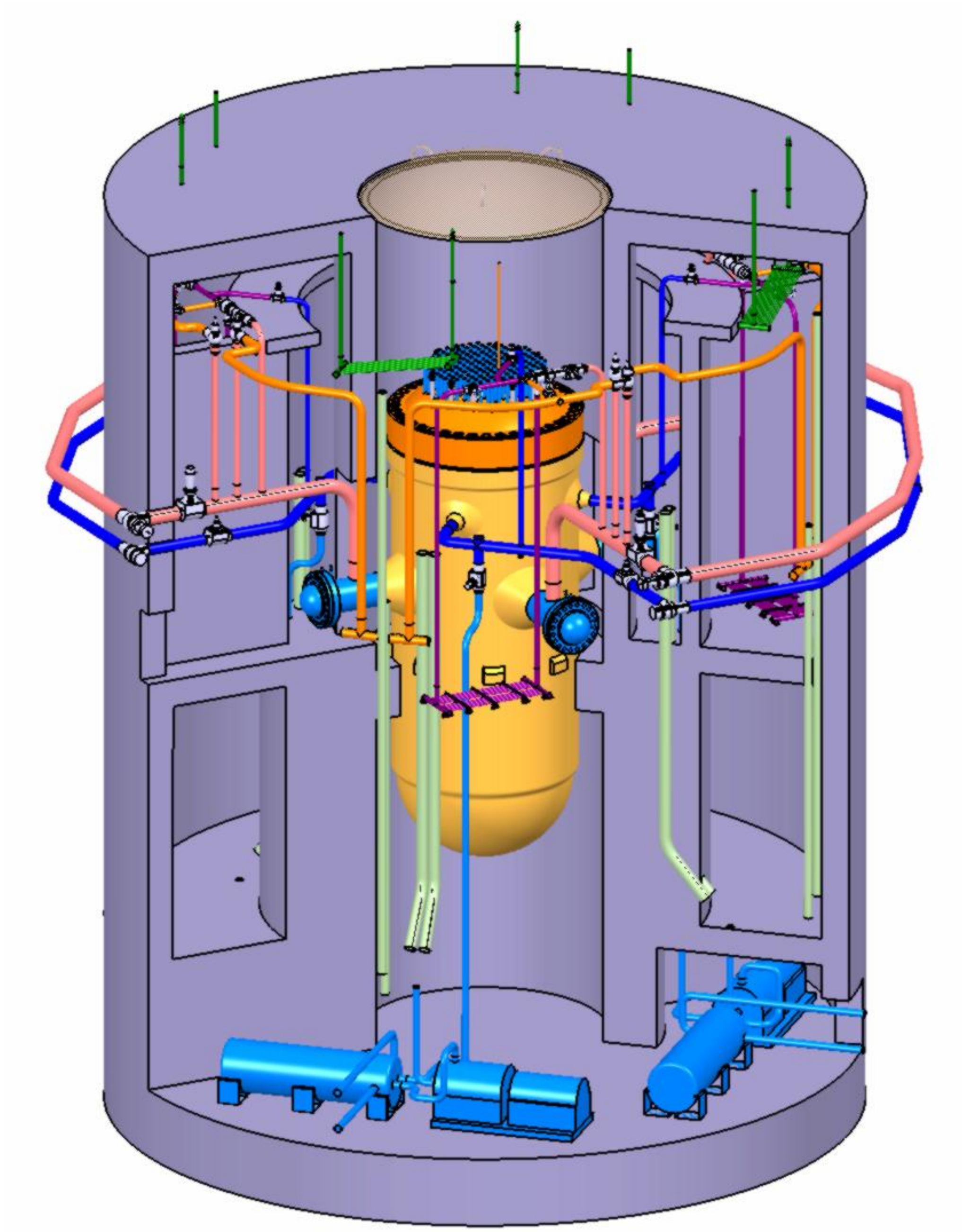


Figure 9 Three dimensional CAD drawing of the containment and safety systems.

Depressurization

In the case the pressure in the reactor pressure vessel exceeds the actuation pressure of the automatic depressurization system (ADS), the reactor is scrammed, eight safety relief valves are opened, and steam is fed into the core flooding pool through eight spargers. The long term cooling after depressurization is provided either by the residual heat removal system which is a low pressure coolant injection system. As an example for the ongoing safety analyses and performance of the safety system, a depressurisation event shall be exemplarily explained as follows.

A reactor trip with depressurization through the Automatic Depressurization System (ADS) is analysed in order to prove the capability of the APROS code [9] to go to subcritical pressures and to analyse the effectiveness of the ADS system. In APROS, the three-pass core of the HPLWR, as described by Schulenberg et al. [10], Figure 10, is modelled with heated structures, only, which means that no neutronic feedback is considered. In addition to the nominal channels for each section of the three-pass core, a hot channel is modelled in which the coolant is heated up to twice the heat-up of the nominal channel by adjusting the local power (Figure 11). This "hot channel factor" of 2 represents uncertainties in designing, manufacturing, analysing, and considers allowances under operation conditions.

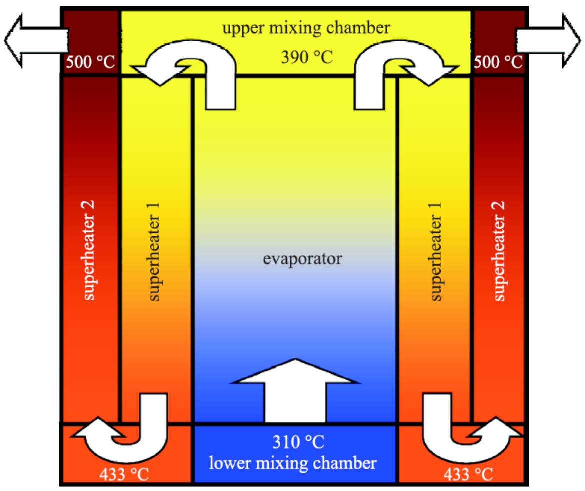


Figure 10 Three pass core of HPLWR.

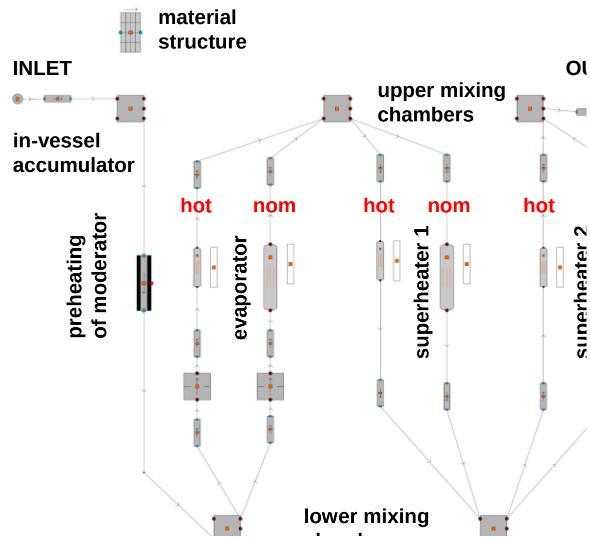


Figure 11 Hot and nominal channel nodalization of the three pass HPLWR core.

The opening times of ADV valves and cross sections of different components of the safety system like spargers were optimized in a parametric study by Schlagenhaufer et al. [11]. One example shall be taken here for explanation.

The event history for the depressurization event with start-up of the LPCI system is depicted in Figure 12. An inadverted isolation of all Main Feedwater line Isolation Valves (MFIV) and Main Steam Line Isolation Valves (MSIV) occurs after 5s of normal operation. The ADS valves open in 0.2s after the pressure in front of the ADS valves rises above the actuation pressure of 26MPa. A signal with a delay time of 0.6s is sent to the reactor SCRAM system and the control rods are inserted into the core within 3.5s, i.e. the power decreases linearly from full power to decay heat within these 3.5s. Another signal is sent to the LPCI pump, which is started within 1s, if the pressure at reactor inlet falls below 6MPa. For the measurement of the reactor inlet pressure, a delay time of 0.1s is assumed. The LPCI pump is assumed to launch within 1s from zero to 100% rpm.

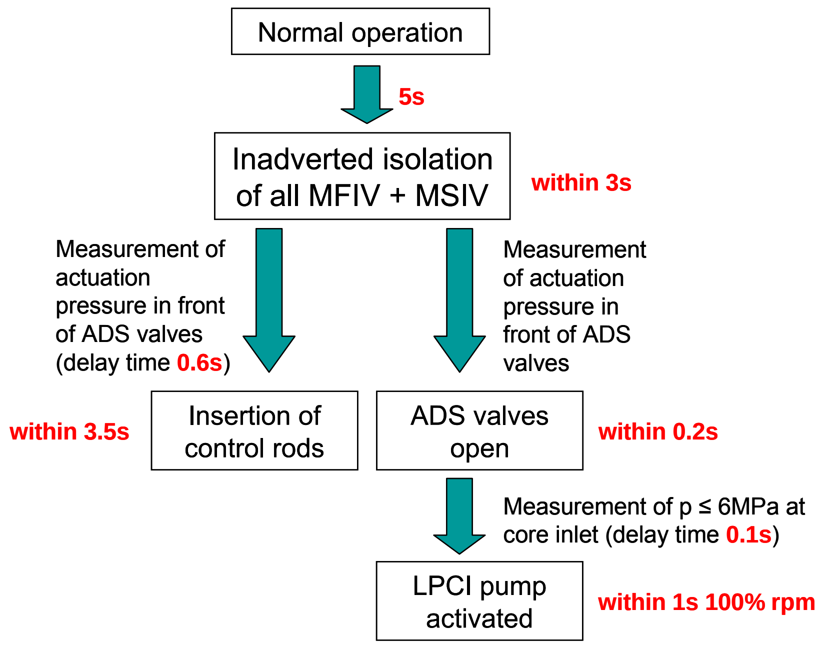
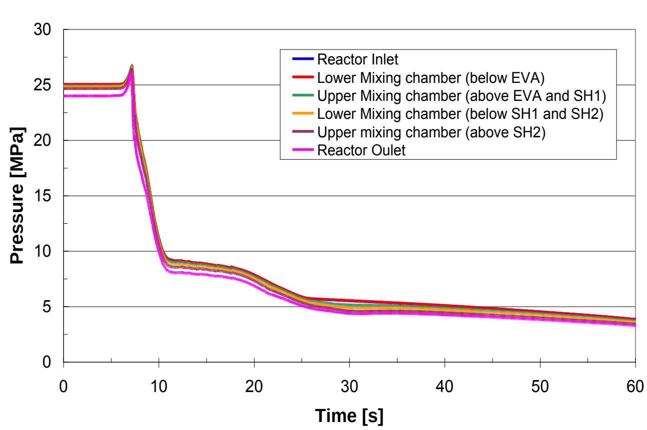


Figure 12 Event history for depressurization and start of the LPCI system.

The pressure evolution inside the RPV is depicted in Figure 13. On the left hand side, pressure recordings are given for different positions inside the RPV, which are indicated by means of different colours, illustrated on the right hand side of Figure 13. As given in Figure 12 the MSIV and MFIV close after 5s of normal operation causing a pressure peak. The resulting maximum pressure inside the RPV of 26.7MPa can be found at the inlet. It is slightly higher than the actuation pressure of 26MPa, because of the delay and opening times assumed for this event. However, the design pressure of the RPV of 28.75MPa [12] has not been reached. The pressure decreases quickly to about 7MPa within 3s, from where it is slowly decreasing to lower values (about 4MPa after 60s). With an actuation pressure of 6MPa, the LPCI system is delivering water to the RPV about 20s after closure of the isolation valves.



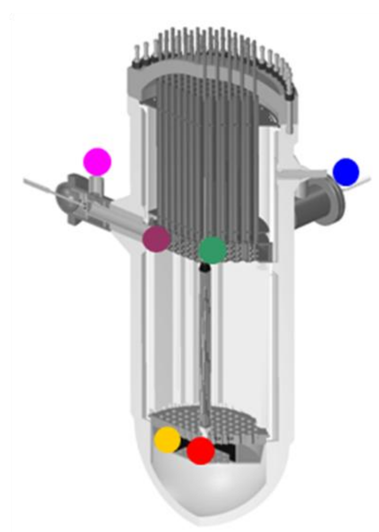


Figure 13 Pressure at different locations inside the RPV during depressurization.

The behaviour of the cladding temperature during this depressurization event is shown in Figure 14. The peak cladding temperatures of nominal channels (thick lines) are not of concern, because they are still under 630°C (materials limit for normal operation conditions), but the peak cladding temperature of evaporator hot channel (light blue line) rises by about 370°C for about 10s, whereas a smaller increase in other hot channels can be observed. A material limit of 850°C has been selected for transients. This temperature is assumed to be tolerable for a few seconds duration, because the mechanisms of oxidation or creep usually require a longer time period for a significant contribution. However, the materials limits in general must be confirmed experimentally in a later stage of the development of the concept.

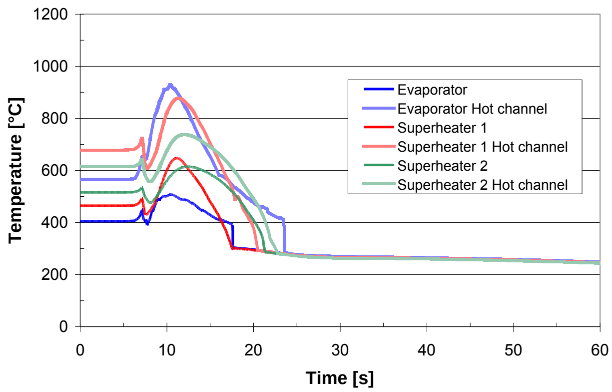


Figure 14 Cladding temperature of nominal and hot channels during depressurization.

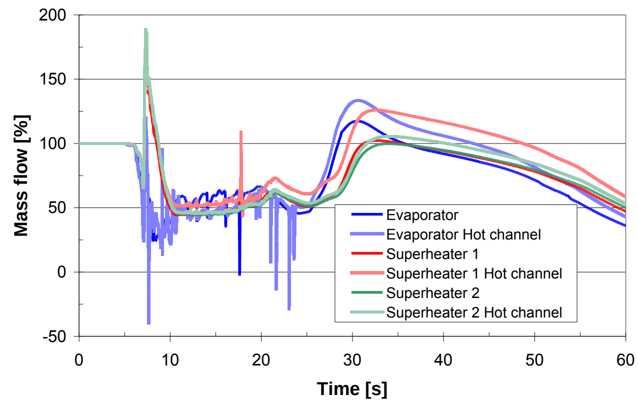


Figure 15 Mass flow rate of nominal and hot channels during depressurization.

In principle, two temperature peaks arise during the depressurization, the first smaller one at about 8s and a second larger one at around 11s. This behaviour can be explained by means of Figure 15, in which the mass flow rate of nominal and hot channels during depressurization is depicted. The reactor inlet mass flow rate drops rapidly to almost zero, because of the closure of the main feedwater isolation valves, whereas the thermal power is still high, since the reactor SCRAM has not been initiated by now. This results in a short insufficient cooling of the cladding material, causing the first smaller peak.

As seen in Figure 15, the reactor outlet mass flow rate rises significantly to a twice the nominal mass flow rate once the ADS system opens and the depressurization of the reactor pressure vessel starts, leading to a decrease of the cladding temperature. After 5s of depressurization, the reactor outlet mass flow is limited by the critical mass flow of a subcritical two-phase mixture in the ADS-valves. The limited mass flow rate and the still high power are causing the second peak in the cladding temperature. The temperature decreases because the power is reaching a certain level at which the mass flow rate removes the heat sufficiently. The stabilization of cladding temperatures at about 280°C occurs after 15s of depressurization, when the thermal power has been decreased to decay heat and the mass flow rate through the ADS valves is still high.

Although the mass flow rates of the nominal channels decrease significantly in the first 20s during the depressurization, the mass flow rate is still high enough to enable a cooling of the cladding material. However, the hot channel mass flow rates, which equal almost the value of the nominal channels, cannot prevent the cladding temperatures to rise significantly, since the hot channels face a higher thermal power. It can be seen further that the hot channels show a more unstable behaviour in respect to mass flow rate oscillations, especially the evaporator hot channel, which was identified as the most crucial one for peak cladding temperatures. Actuating the automatic depressurisation system with subsequent initiation of the LPCI system ensures a long-term cooling of the reactor. It is foreseen with 4 x 100% capacity in the HPLWR reactor concept.

4. Summary

The concept of a High Performance Light Water Reactor, representing the European version of the Supercritical Water-Cooled Reactor, has been developed so far that a plant layout could be drafted. The reactor building turned out to be smaller compared to existing boiling water reactor concepts, whereas the turbine building has a comparable size. The containment located inside the reactor building was improved to withstand the load of the water inventory of the emergency pools, weight of large components and internal overpressure. The layout of the safety system was adjusted accordingly. An example calculation of a depressurization event was selected to show the capability of the safety concept to sufficiently cool the reactor with an automatic depressurization system and actuation of an active low pressure safety injection system. More transient and accident calculations are currently being performed.

The draft layout of the HPLWR will be used to estimate plant erection costs. A first assessment of the entire concept with respect to the technology goals of the Generation IV International Forum shall be carried out next.

5. Acknowledgements

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6. References

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