DRAFT LAYOUT OF THE HPLWR POWER PLANT

C. Koehly[1], J. Starflinger[2], T. Schulenberg[1], M. Brandauer[1], D. Lemasson[1], R. Velluet[1], H. Herbell[3]
[1] Karlsruhe Institute of Technology, Karlsruhe, Germany
[2] IKE, University of Stuttgart, Germany
[3] EnBW Kernkraft GmbH, Kernkraftwerk Philippsburg, Germany

Abstract

The High Performance Light Water Reactor (HPLWR) is a Supercritical Water Cooled Reactor designed by a consortium of European partners in the 6th European Framework Programme. This paper describes a potential layout of the reactor building including the containment with the reactor and with the required safety systems, the turbine building with turbines, condensers, feedwater pumps and preheaters, and the start-up system. Design details are given for selected key components to estimate their size. Compared with a conventional power plant of similar power output, the HPLWR power plant can be designed significantly smaller.

1. Introduction

The High Performance Light Water Reactor (HPLWR) is one of the six concepts being investigated in the Generation IV program of advanced nuclear systems. Schulenberg et al. [1] describe the design concept of the reactor, which features a three-pass core cooled with a single phase water flow at a core inlet pressure of 25MPa. The coolant is heated up from 280°C inlet temperature to 500°C core exit temperature in three steps with intermediate mixing, keeping the cladding temperature of the fuel below 630°C. A once through steam cycle converts the total thermal power of 2300MW at a mass flow rate of 1179kg/s to a net power output of 1000MW of the power plant. The latest design status of the reactor has been described by Koehly et al. [2].

A containment design and its safety systems have been proposed by de Marsac et al. [3] based on a safety concept of Bittermann et al. [4]. Like with boiling water reactors, the containment features a pressure suppression pool and 4 upper flooding pools with an automatic depressurization system, which enables a compact design and provides a large heat sink in case of accidents. Active low pressure injection systems are foreseen in the basement underneath the containment.

The steam cycle has been optimized by Brandauer et al. [5] with a reheater between the high pressure and the medium pressure turbines and with 7 stages of preheaters. Based on these studies, a layout of the entire HPLWR power plant is now proposed, comprising all components, which have been worked out in detail so far. The present layout of the HPLWR plant is based on the latest design concepts of boiling water reactors, which have been adapted to the requirements for the HPLWR.

2. Plant Layout

The plant layout of the HPLWR presented here is based in principle on an Advanced Boiling Water Reactor like NPP Gundremmigen in Germany. A first layout of the HPLWR plant has been designed by Bittermann et al. [6] which has further been extended here to include details of the start-up system, the reheaters and the feedwater tank, which have recently been designed, as well as major piping. The isometric view, Figure 1, shows the HPLWR reactor building on the left and the turbine building on the right, connected with 4 feedwater lines (blue) and 4 steam lines (pink).

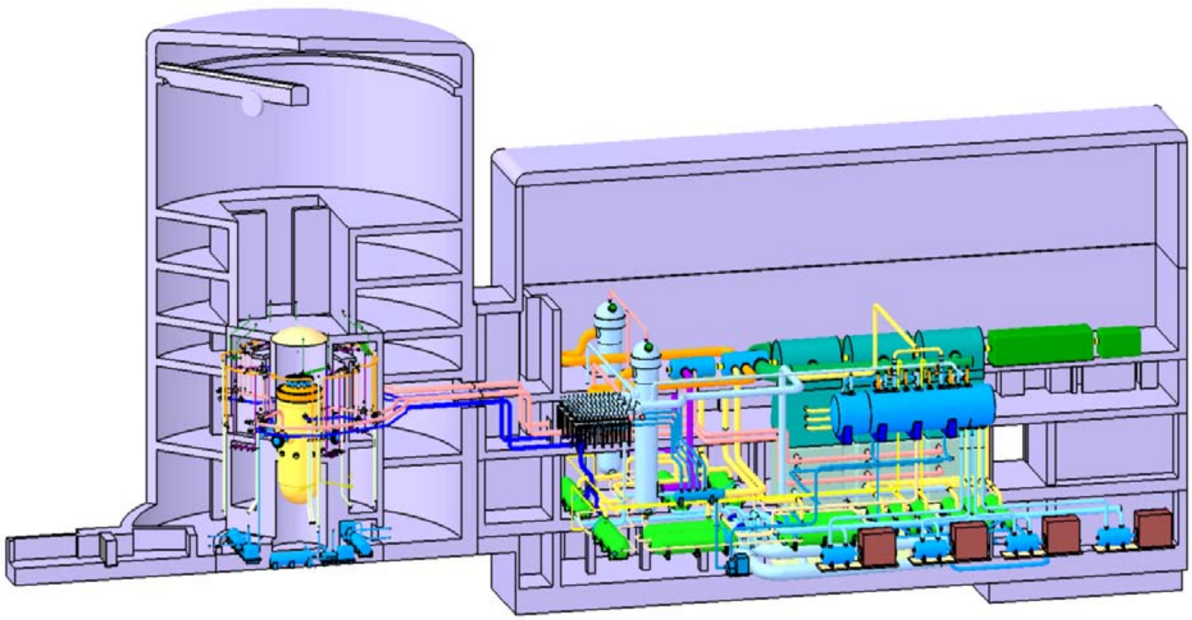

Figure 1 Cut away view of the reactor building (left) and the turbine building (right).

2.1 Containment and Reactor Building

The reactor building of the HPLWR includes the containment with the reactor pressure vessel, the safety systems and the residual heat removal systems, which have been worked out already in more detail. Additional compartments surrounding it containing safety-related mechanical, electrical and instrumentation & control (I&C) components and auxiliary systems, like the boron injection system, the reactor water and fuel pool cleanup system, the fuel pool cooling system and the radioactive liquid waste storage system. On top of the containment, the fuel handling area with the shielding and spent fuel storage pool can be found. The main function of the reactor building is to protect all safety-related equipment against the effects of natural and external man-made hazards. The reactor building also guarantees confinement of radioactivity as the last barrier preventing the release of radioactive materials to the outside atmosphere upon occurrence of a beyond-design event. Therefore, all components with a high radioactive inventory are placed within the reactor building. This includes also activated charcoal filters, the air recirculation system and the transport way for the spent fuel cask. Containment isolation valves prevent release of a significant radioactive inventory into the turbine building in case of a break. The main parameters of the reactor building are an outer diameter of 45m, an approximate height of 61m and an approximately volume of 95000m³. The total height is determined by the height of the containment, the height of the fuel pool on top, and the maximum required lift of the reactor building crane. Figure 2 shows a sectional view of the reactor building with containment, reactor pressure vessel and safety systems.

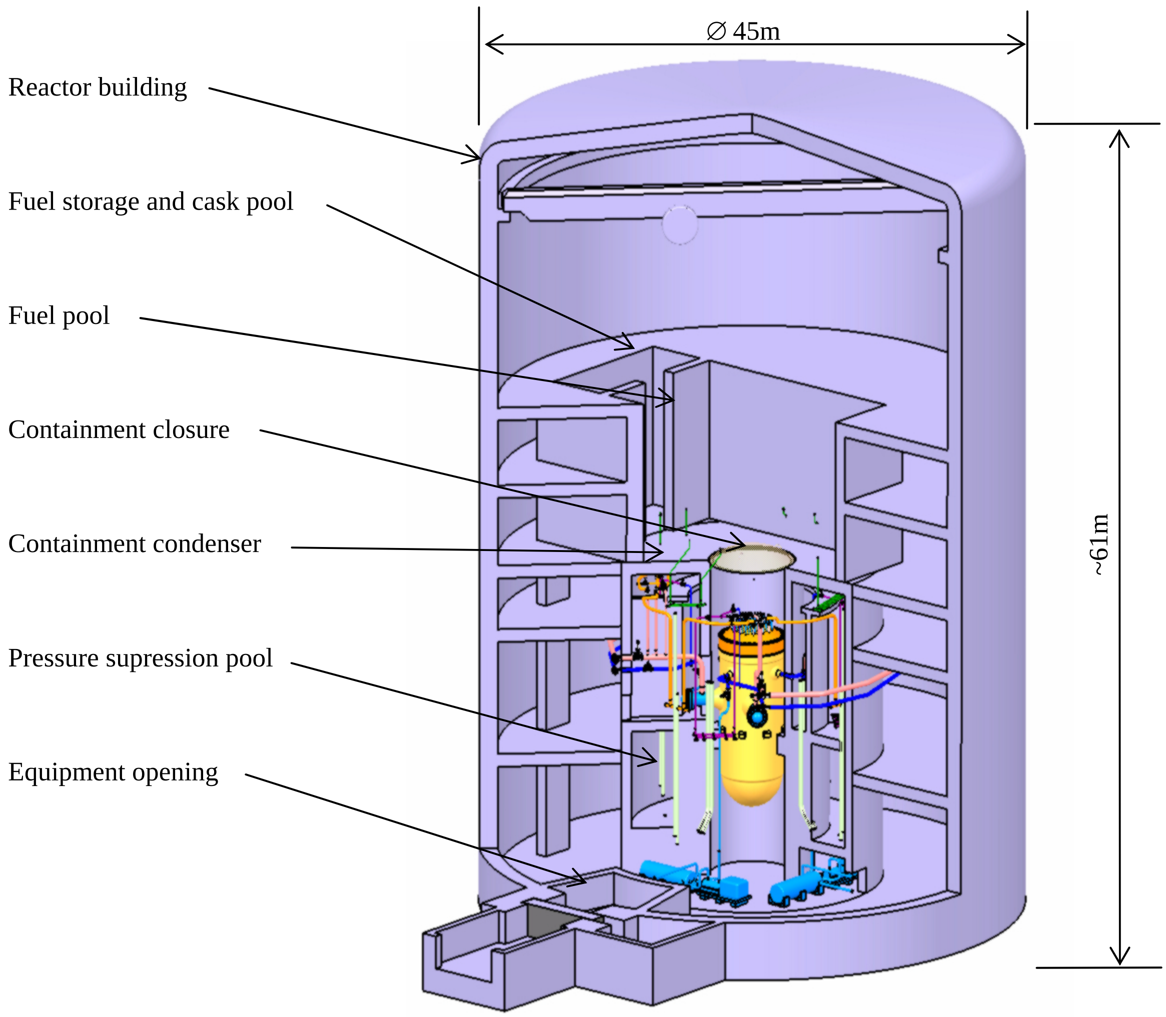

Figure 2 Cut away view of the reactor building.

The basis for the containment concept is taken from recent BWR plants and plants like SWR 1000 designed and developed by Siemens [7]. It becomes significantly smaller, however, as steam separators and dryers inside the reactor pressure vessel could be omitted, resulting in a total height of the pressure vessel of only 14.5m. The characteristic features are a cylindrical containment made from reinforced concrete, equipped with an inner steel liner and a pressure suppression system. Different from passive BWR concepts, the core flooding pools serve only as condensation pools for the safety relief system. The main parameters of the containment are an outer diameter of 21.6m, a height of 26.7m and a volume of approximately 9500m³. In total, more than 2000m^3 of water serve as a heat sink in case of accidents. In addition, the containment is thermally connected with the fuel pool above through containment condensers, providing further heat sink for passive residual heat removal.

As proposed by de Marsac et al. [3], the safety systems inside the containment include two redundant systems for maintaining the coolant flow and removing the residual heat from the reactor pressure vessel (RPV) after scram or shut down: a passive, high pressure coolant injection system (HPCI), and an active, low pressure coolant injection system (LPCI) with residual heat removal. Two four train systems, for active and passive systems each, are provided for this purpose. Figure 3 shows a sectional view of the containment with RPV and safety systems.

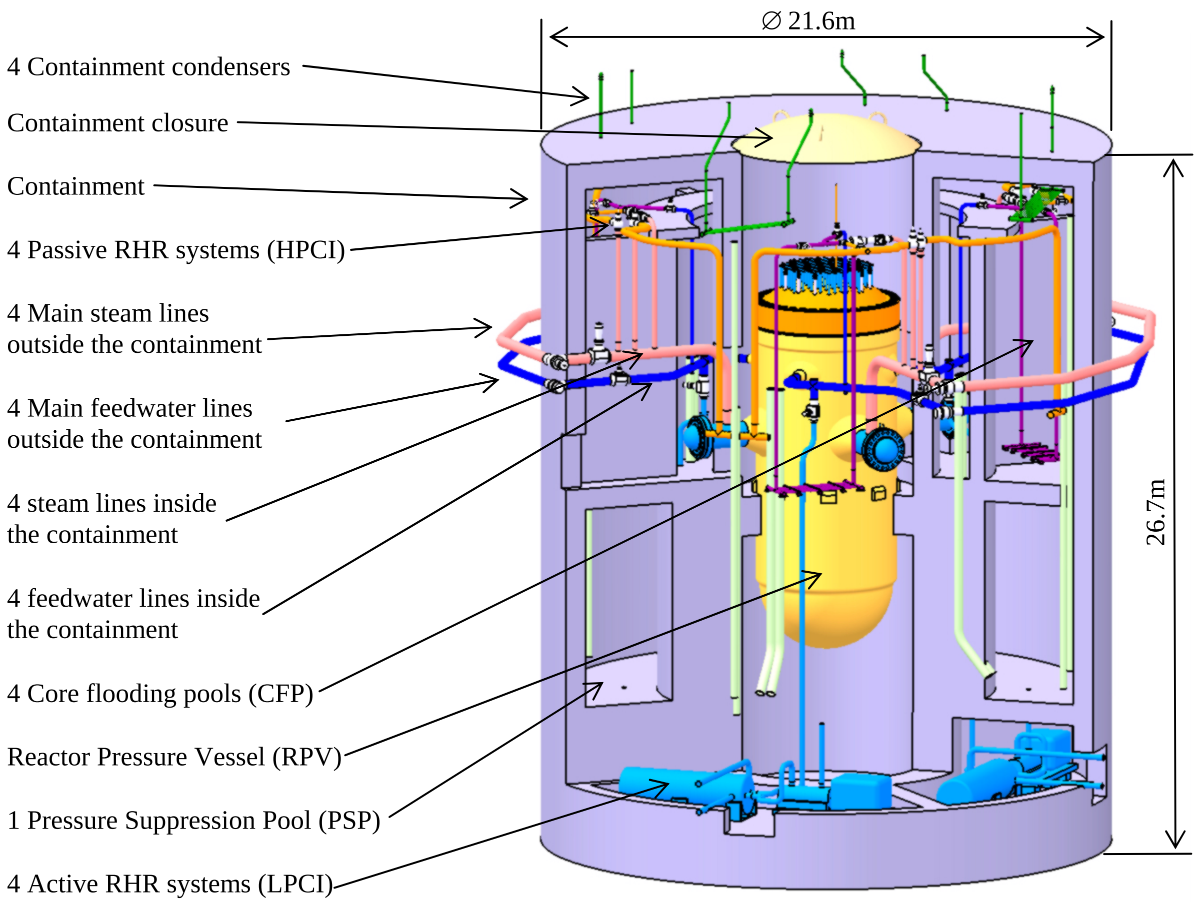

Figure 3   Cut away view of the containment.

In case of a break of the feedwater or steam lines outside of the containment, the containment isolation valves are closed and the reactor pressure vessel (RVP) will be depressurized through spargers. The passive, high pressure coolant injection system shown here is driven by steam injectors using the steam of the depressurization phase to refill the RPV with condensate in a closed loop, such that the core flooding pools provide the heat sink for residual heat removal (RHR) [3]. This system, however, has not been verified yet. As an alternative, it could be replaced by a condenser in the core flooding pool and a battery driven condensate pump, as proposed by Schlagenhaufer et al. [8].

The active low pressure coolant injection system contains 4 pumps and 4 heat exchangers, which are located in the basement of the containment. After depressurization, water from the pressure suppression pool is delivered to the feedwater line passing a cooler for RHR. A check valve protects the systems from reverse flow.

2.2 Turbine Building

The turbine building is located next to the reactor building. Figure 4 shows a cut away view through the turbine building with steam lines and turbine bypass lines in pink, feedwater lines in blue, and steam extraction lines in yellow. The turbine building contains all components of the steam cycle like turbines, condensers, feedwater pumps, preheaters, reheaters and the start up system. As the steam is activated, the turbine building is part of the controlled area of the plant. The main parameters of the reactor building are a length of app. 87m, a width of app. 49m, an app. height of 52m, resulting in a volume of approximately 222000m³. The length of the building is mainly determined by the turbine-generator set, while the width is determined by the workspace for the low pressure turbines including the condenser withdrawal length and the preheater pump arrangement.

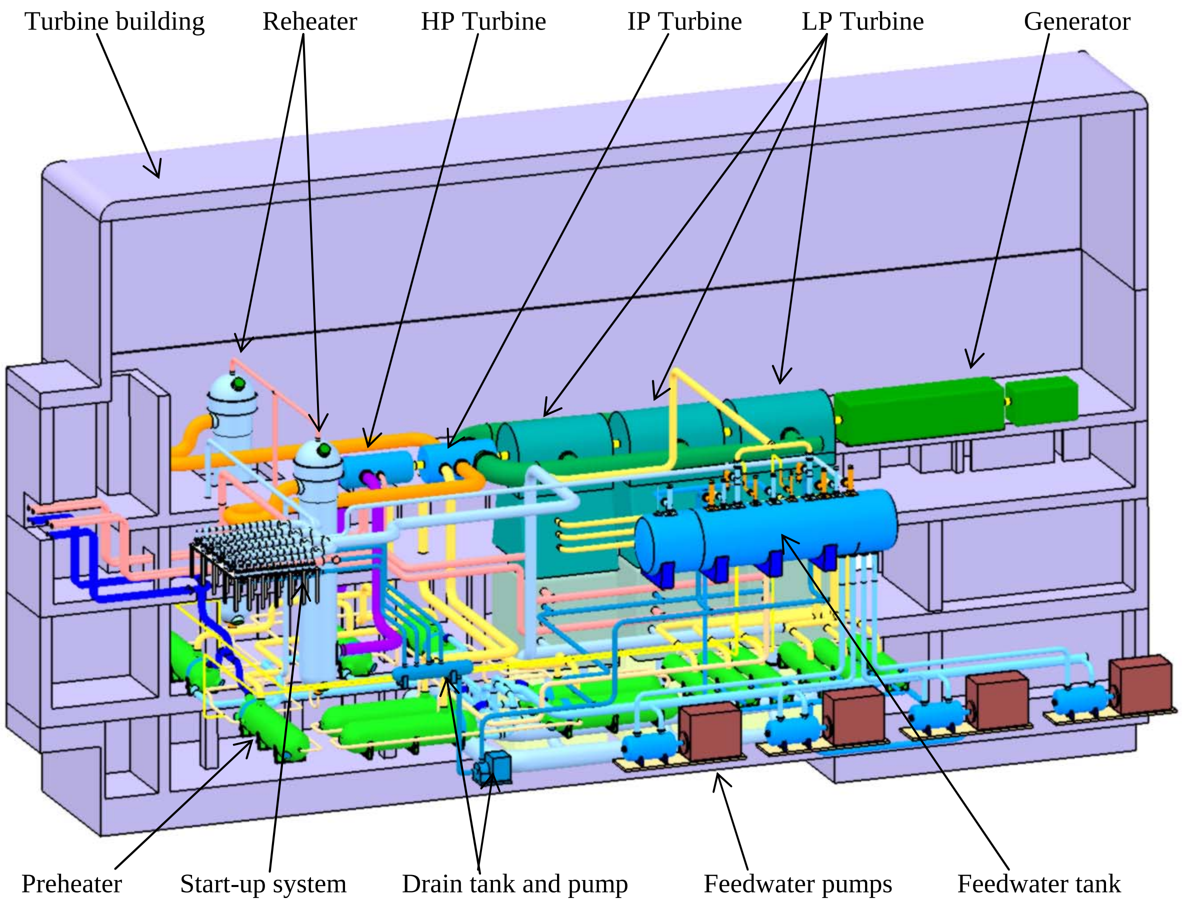

Figure 4 Cut away view of the turbine building with all steam cycle components.

Meanwhile, some of the main steam cycle components have been designed in more detail. They will be explained in the following chapters.

3. Steam Cycle Components

A once through supercritical steam cycle for the HPLWR with high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbines has been optimized by Brandauer et al. [5] for full load operation conditions.

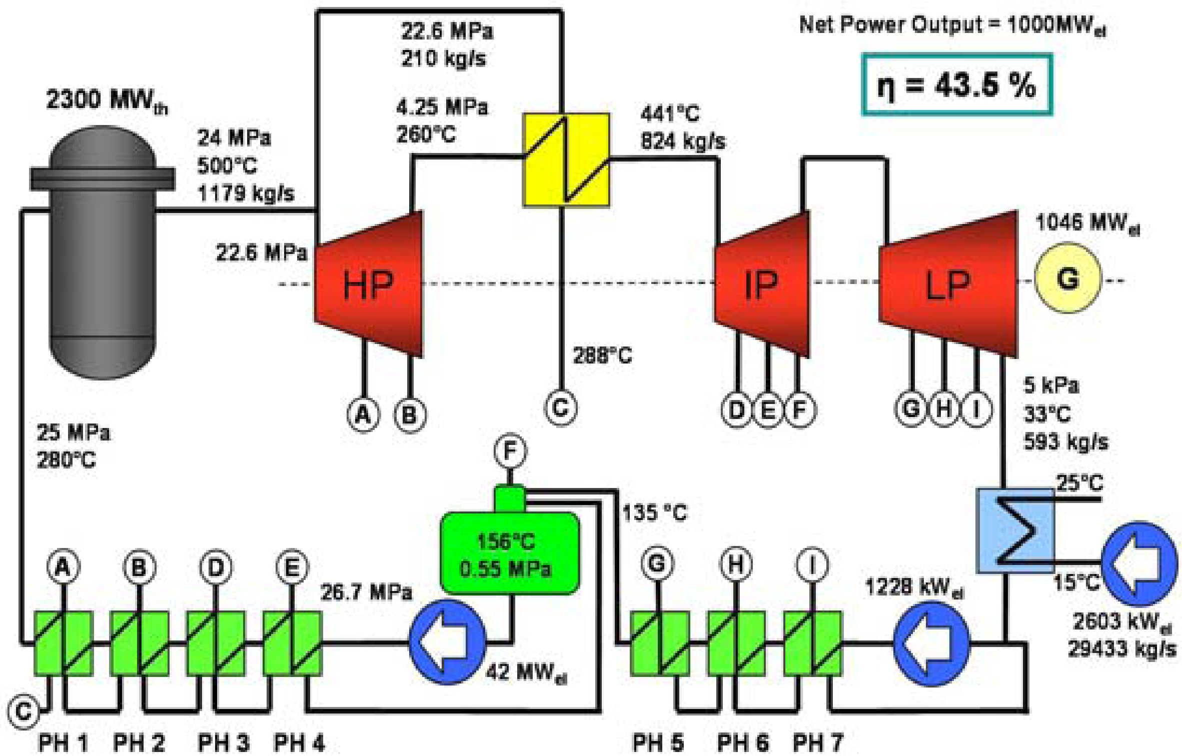

Figure 5 Heat flow diagram of the HPLWR steam cycle by Brandauer et al. [5].

Figure 5 shows a schematic illustration of the HPLWR steam cycle with parameters at full load. Superheated steam leaves the reactor with a temperature of 500°C at 24MPa pressure and 1179kg/s mass flow rate. Before it enters the HP turbine, steam is separated to reheat steam in the counter-current reheater. Most of the steam (82.2% of the total mass flow rate) is expanded through the HP turbine and reaches the counter-current reheater. There, it is reheated with steam from the reactor, before it is expanded in the IP and LP turbine. In the condenser, feedwater is slightly sub-cooled by the main heat sink, which is driven by the cooling circuit pump. From there, the feedwater leaves the condenser sump, where it is mixed with the condensate of the first LP preheater PH 7. Before it enters the LP preheaters, the pressure is levelled up by the condensate pump. In the three LP preheaters, which are fed by steam extractions from the LP turbine, the temperature is raised before it enters the feedwater tank. In four HP preheaters, the feedwater is finally heated up to 280°C core inlet temperature with the several steam extractions from the IP and HP turbines and the waste steam of the reheater, which is supplied as condensate into the preheater PH1. The feedwater pressure decreases from 26.7MPa at the outlet of the feedwater pumps to 25MPa at core inlet due to the pressure drop of piping and the four HP preheaters. With a thermal power of the reactor of 2300MW, a gross power output of 1046MW is obtained. The net efficiency amounts 43.5%.

3.1.1 Turbine and generator set with condensers

The technology of the turbines and condensers is based on the turbines of supercritical fossil-fuelled power plants. Like there, full speed turbines and generator can be applied for the target power of 1046MW. A double flow HP turbine will be needed, which is usually not used in fossil fired power plants because of lower mass flow rates, but could easily be designed and manufactured; no further challenges are to be expected. A double flow IP turbine and three double flow LP turbines are needed at a condenser pressure of 5kPa; the total turbine train has a length of 41m. Details to the turbine design study for the HPLWR have been described by Herbell et al. [9]. Major dimensions of the complete turbine-generator set including condensers are shown in Figure 6.

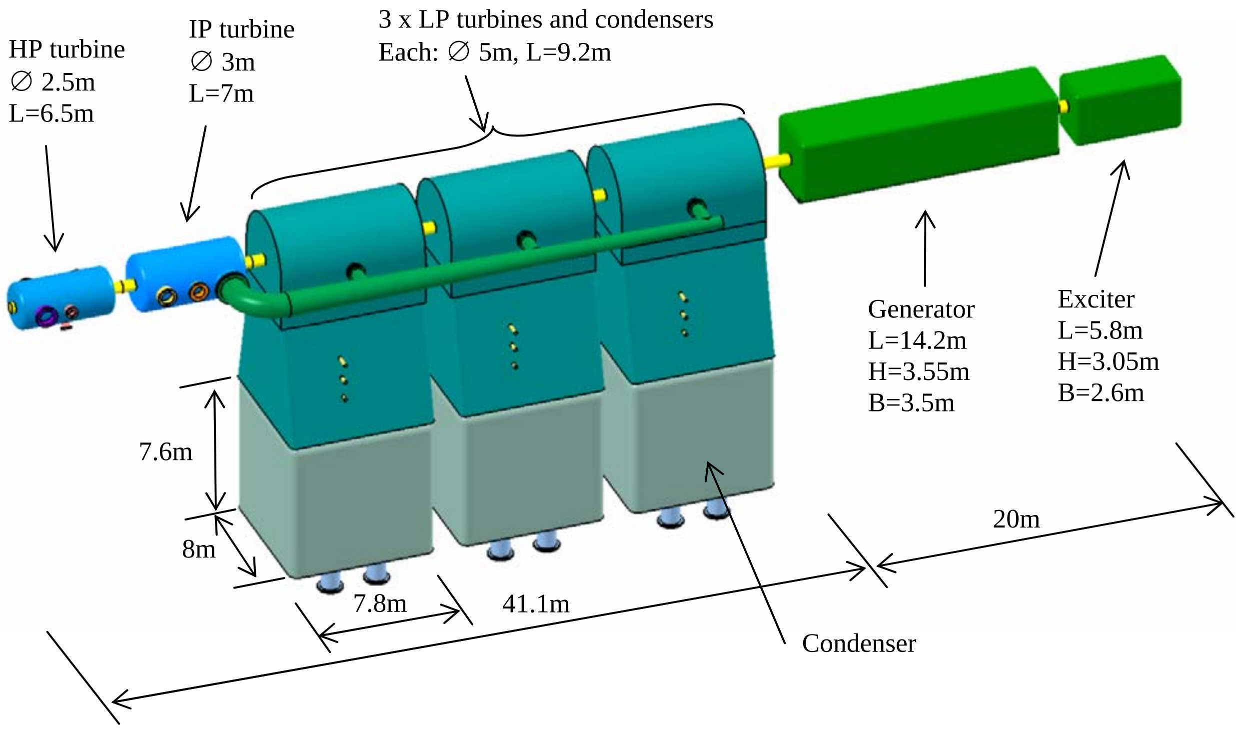

Figure 6 Dimensions of the turbine-generator set of the HPLWR.

3.1.2 Reheater

The reheater is designed as an ordinary shell and tube heat exchanger as proposed by Herbell et al. [10]. Even though the design is quite conventional, it is a new component in a nuclear power plant. Supercritical fluid is “pseudo” condensing inside the tubes and changing its density from steam like to liquid like properties. On the secondary side, saturated steam is superheated. Unlike conventional BWR plants, there is no need of a droplet separator before the reheater. The vertical reheater is sketched in Figure 7 (shown horizontally). The reheater has a height of 20m and an outer diameter of 3m. Two of these reheaters are needed, arranged on both sides of the turbine train.

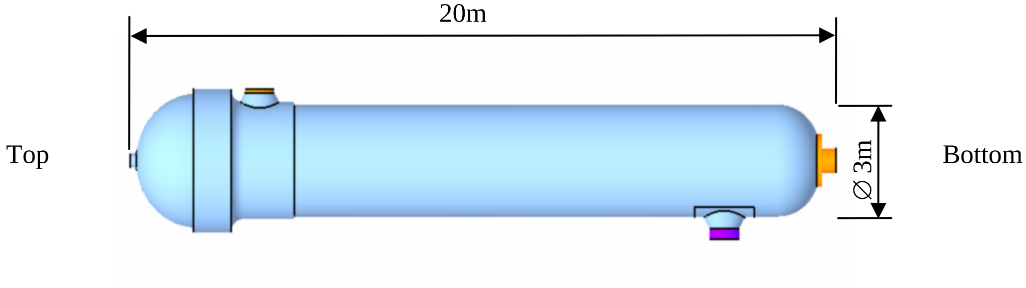

Figure 7 Reheater of the HPLWR (shown horizontally).

3.1.3 Preheaters

The preheaters have been designed and dimensioned by Brandauer [11]. He assumed 2 lines of 7 preheaters each, of which 4 high pressure preheaters (PH1 to PH4) are placed downstream the feedwater pumps and 3 low pressure preheaters (PH5 to PH7) are downstream the condensate pumps. PH7 may also be plugged into the condensers to minimize the low pressure steam extraction lines. A high pressure preheater, shown in Figure 8 (top) has an outer diameter of 2.5m with a total U-tube length of 12.3m. A low pressure preheater, shown in Figure 8 (bottom), has an outer diameter of 1.7m with a total U-tube length of 11.9m.

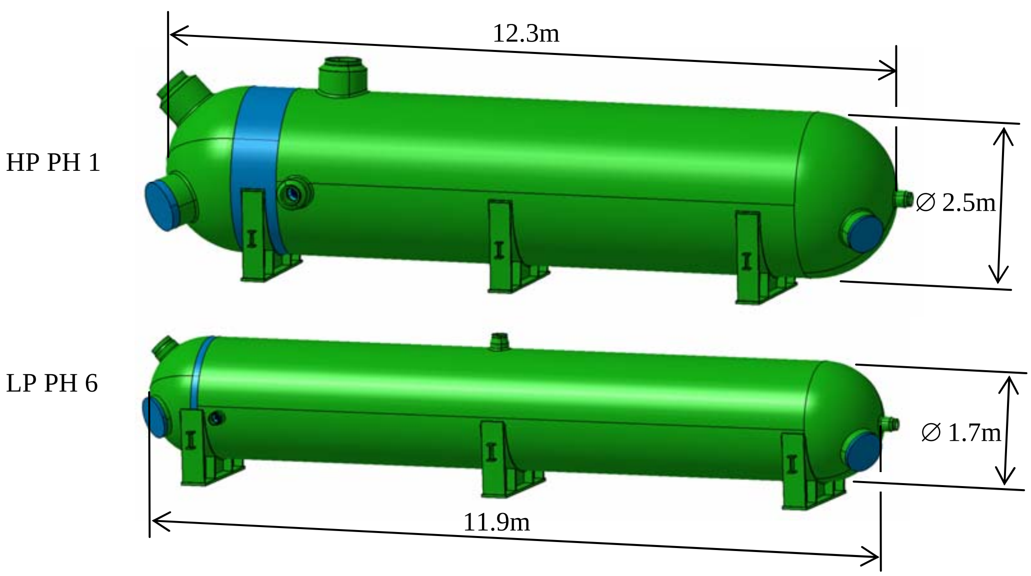

Figure 8 High pressure (top) and low pressure (bottom) preheater of the HPLWR.

Details of a high pressure preheater are shown in Figure 9. The feedwater enters the U-tubes from the lower shell on the left side. The extracted superheated steam is supplied from the top and condenses outside the tubes. It is sub-cooled in a separate compartment at the bottom and leaves the preheater as sub-cooled condensate at about mid height. From there, it is fed to the next preheater to be supplied from the right side. This way, all condensate of the high pressure preheaters is forwarded finally to the feedwater tank, and all condensate of the low pressure preheaters is forwarded to the inlet of the condensate pumps.

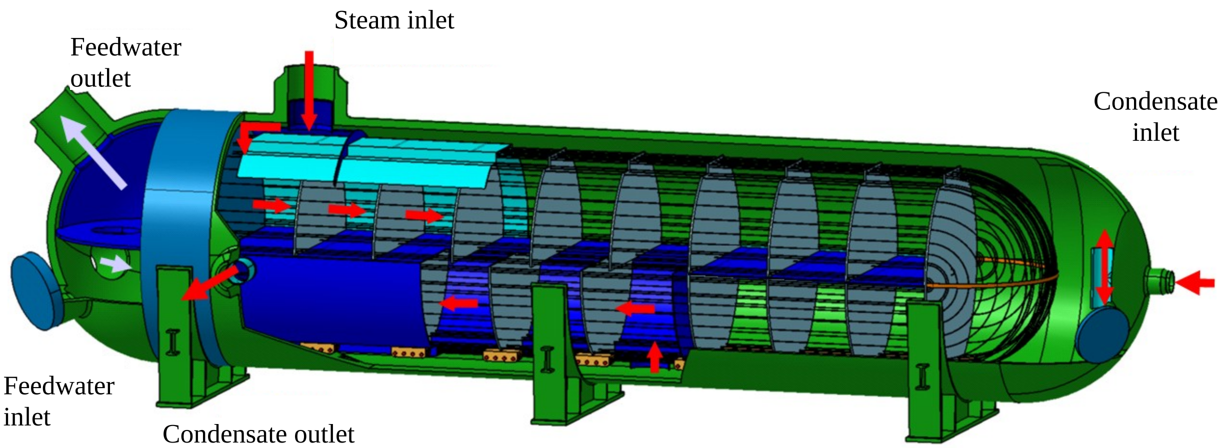

Figure 9 Design of a high pressure preheater of the HPLWR.

3.1.4 Feedwater Tank

The feedwater tank has been designed by Lemasson [12] to collect the condensate from preheater PH4, condensate from the drain tank of the start-up system, a steam extraction from the IP turbine as an additional preheater, and condensate from preheater PH1 during the start-up sequence. It has a length of 21.2m and an outer diameter of 4.8m (see Figure 10).

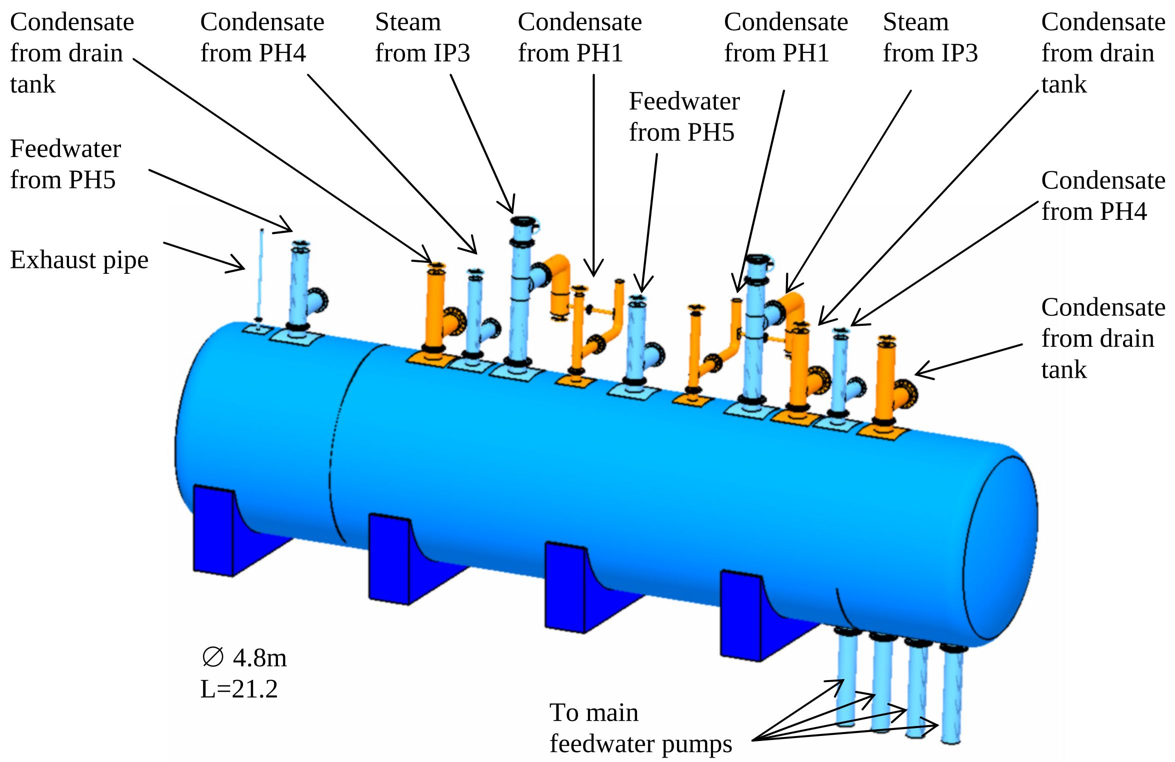

Figure 10 Feedwater tank for HPLWR.

The feedwater tank was downscaled from existing feedwater tanks in BWRs with the thermal power of the HPLWR. Thus the tank volume is about 375m^3 of which 175m^3 is filled with water. Separate injection valves are installed for the different cases of nominal operation and shut-down/ start-up sequences. The valves expand the high pressure fluid directly into the feedwater tank. The feedwater will be pumped from the feedwater tank with 4 feedwater pumps, of which 3 are providing the total mass flow rate and a 4th pump is kept on stand-by.

3.1.5 Start-up system

A start-up system has been proposed by Schlagenhaufer et al. [13], which is operated below 50% thermal power, when the turbines are disconnected. While the pressure inside the RPV is always kept at supercritical conditions, the pressure control valve is producing a two-phase flow downstream which needs to be separated in a liquid and a steam phase. The separators have been designed by Velluet [14] as 4 batteries of 24 small cyclones each to minimize the total steel mass, as shown in Figure 11 (left). The liquid phase is collected afterwards in a drain tank, shown in Figure 11 on the right hand side. The separated steam is used to preheat the feedwater while the turbines are disconnected, and the water from the drain tank is supplied to the feedwater tank to heat up the stored volume. During the shut down phase, steam and liquid can also be supplied to the condensers instead.

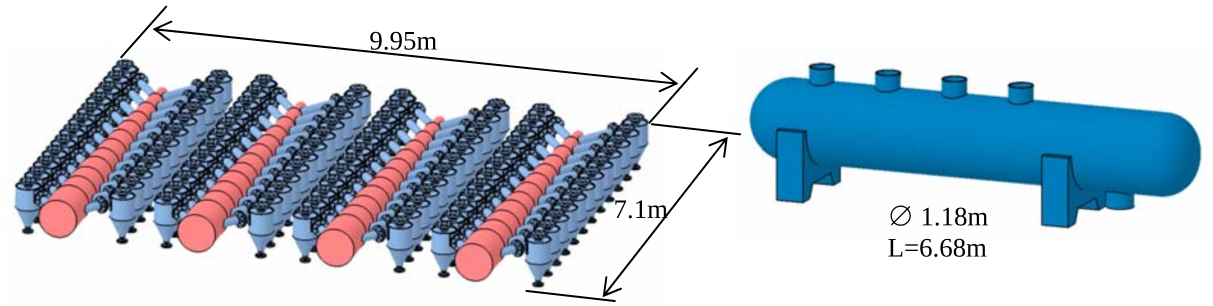

Figure 11 Separator batteries (left) and drain tank (right) for the HPLWR.

4. Assembly of the steam cycle components

The arrangement of all steam cycle components for the HPLWR is shown in Figure 12. The components are placed on different levels of the turbine building and interconnected with pipes. Figure 12 shows a top view on the steam cycle components without pipes for better visibility. Because of the different levels of the components, some parts are displayed over each other. The feedwater pumps and the preheaters are installed on the lowest floor, and the turbines, separator batteries and the feedwater tank are on 2 floors above to provide enough pressure head for the drain tank and the feedwater pumps, respectively. A drain pump might be required to pump the liquid from the drain tank to the feedwater tank.

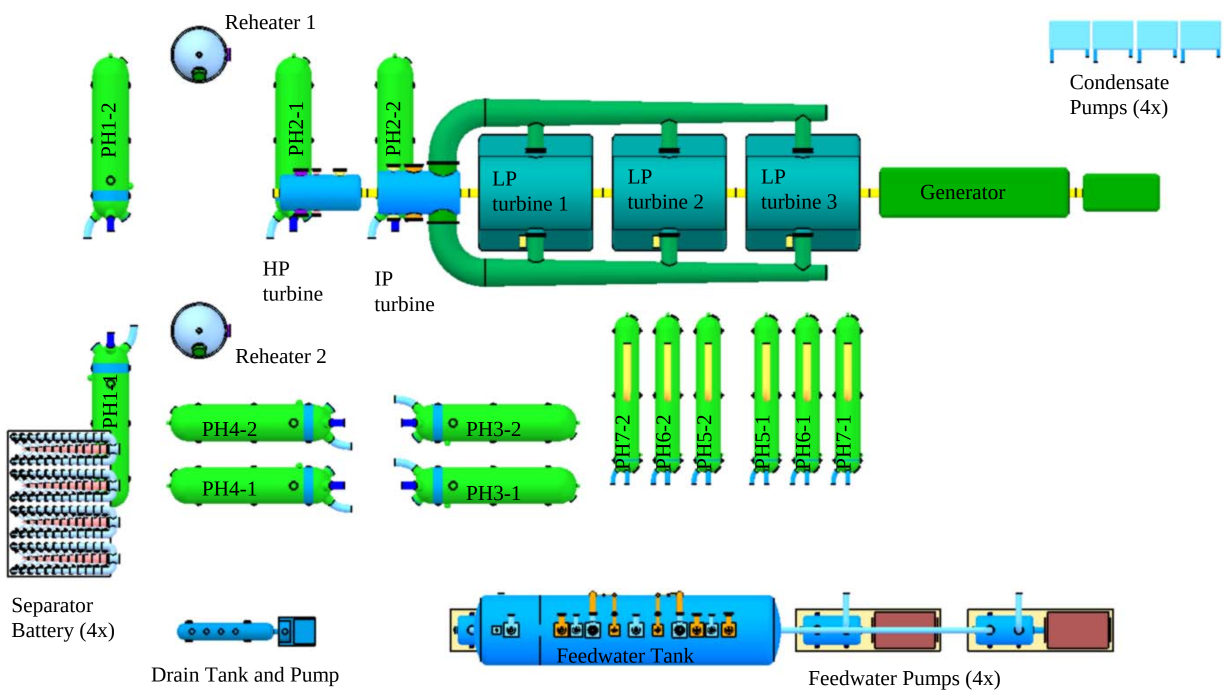

Figure 12 Top view on the arrangement of the HPLWR main steam cycle components and start-up system.

5. Conclusions

Compared with a BWR of similar net power, the containment is obviously significantly smaller, so that most of the cost savings are expected there. The entire reactor building, on the other hand, is only smaller by ~10m in height and by ~8m in diameter than the BWR reactor building of NPP Gundremmingen with its 1300MW net power (see Figure 13). An ambitious optimization of the entire reactor building with all its components is recommended, therefore, to reach a convincing low cost design.

Most size reduction and thus potential cost reduction in the turbine building is obviously gained by the full speed turbine train and by the compact reheaters, whereas the 7 stage preheaters and the high pressure feedwater pumps are compensating these savings to some extend. The start-up system, which is not required for BWR, does not contribute a significant steel mass, but is certainly an additional component as well. The entire turbine building, as designed here, is smaller by ~5m in length and ~1m in width than the NPP Gundremmingen.

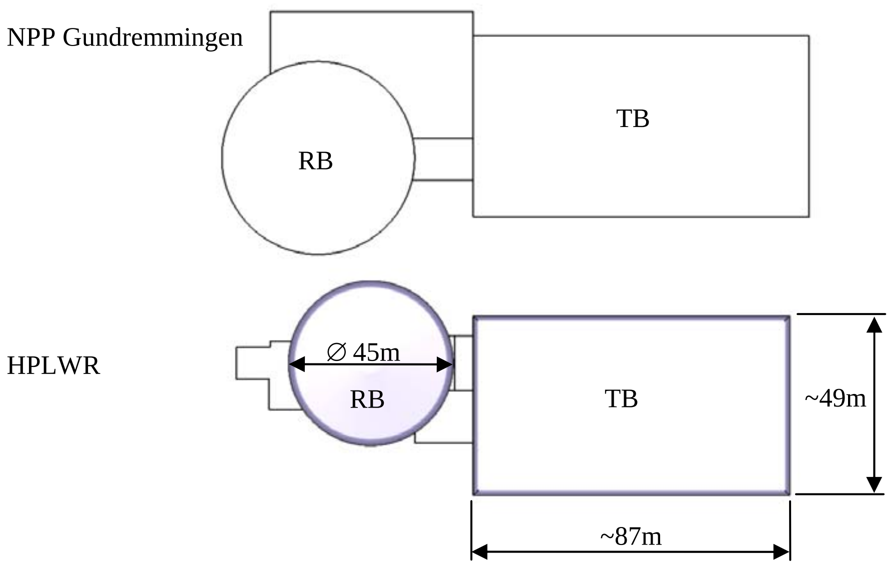

Figure 13 Top view on the size comparison between NPP Gundremmingen (top) and HPLWR (bottom).

6. Acknowledgments

This work has been funded by the European Commission as part of their project HPLWR-Phase 2, contract number 036230.

7. References

[1] T. Schulenberg, C. Maráczy, J. Heinecke, W. Bernnat, "Design and analysis of a thermal core for a HPLWR – a state of the art review", Proc. NURETH-13, Paper N13P1039, Kanazawa, Japan, Sept. 27 –Oct. 2, 2009

[2] C. Koehly, T. Schulenberg, J. Starflinger, "HPLWR Design Concept", 4th Int. Symposium on SCWC, Paper No. 37, Heidelberg, Germany, March 8-11, 2009

[3] B. de Marsac, D. Bittermann,, J. Starflinger, T. Schulenberg, "Containment design proposal with active and passive safety systems for a High Performance Light Water Reactor", 4th Int. Symposium on SCWR, Paper No. 10, Heidelberg, Germany, March 8-11, 2009

[4] D. Bittermann, T. Schulenberg, M. Andreani, "The Safety Concept of the HPLWR", 4th Int. Symposium on SCWR, Paper No. 11, Heidelberg, Germany, March 8-11, 2009

[5] M. Brandauer, M. Schlagenhaufer, T. Schulenberg, "Steam cycle optimization for the HPLWR", 4th Int. Symposium on SCWR, Paper No. 36, Heidelberg, Germany, March 8-11, 2009

[6] D. Bittermann, S. Rothschmitt, J. Starflinger, T. Schulenberg, "Reactor and turbine building layout of the High Performance Light Water Reactor", Annual Meeting on Nuclear Technology, Paper No. 1216, Berlin, Germany, Mai 4-6, 2010

[7] Zoran V. Stosic, Werner Brettschuh, Uwe Stoll, "Boiling water reactor with innovative safety concept: The Generation III+ SWR-1000", Nuclear Engineering and Design, Vol. 238, pp. 1863–1901, 2008

[8] M. Schlagenhaufer, T. Schulenberg, J. Starflinger, D. Bittermann, M. Andreani, "Design proposal and parametric study of the HPLWR safety system", Proc. ICAPP '10, Paper 10152, San Diego, CA, USA, June 13-1, 2010

[9] H. Herbell, M. Wechsung, T. Schulenberg, "A turbine design concept for the High Performance Light Water Reactor", 4th Int. Symposium on SCWR, Paper No. 76, Heidelberg, Germany, March 8-11, 2009

[10] H. Herbell, T. Schulenberg, "Reheater design concept for the High Performance Light Water Reactor", GLOBAL 2009, Paper 9345, Paris, France, September 6-11, 2009

[11] M. Brandauer, "HPLWR Wasser-Dampf-Kreislauf-Optimierung und mechanische Auslegung der Speisewasservorwärmung", Studienarbeit IKET, KIT, 2009

[12] D. Lemasson, "Design of a feedwater tank for the High Performance Light Water Reactor", IKET internship, KIT, 2009

[13] M. Schlagenhaufer, J. Starflinger, T. Schulenberg, "Plant control of the High Performance Light Water Reactor", GLOBAL 2009, Paper 9339, Paris, France, September 6-11, 2009

[14] R. Velluet, "Design of the water separator for the combined shut-down/start-up system of the High Performance Light Water Reactor", IKET internship, KIT, 2009