The Preliminary Structural Design of SSBWR-200

Suyuan Yu[1], Yajun Zhang[1] and Wenxiang Zheng[1]

1) Institute of Nuclear Energy Technology, Tsinghua University, Beijing, 100084, China

ABSTRACT

Boiling Water Reactors have many possible applications worldwide, especially in China. INET has completed a conceptual design of a 200MWe simplified small BWR which eliminates the inner or outer pump in the primary loop and enhances the safety. The primary coolant flow is driven by natural circulation with the corresponding structural design based on NHR and BWR technology. The core is located at the bottom of the RPV with a long riser above the core outlet to increase the natural circulation capacity. The safety system is based on passive decay heat removal. The rather tall RPV has a large water inventory in the primary system with all penetrations located above the core top. Therefore, no exposed core and no fuel damage will occur after a pipe rupture or any other accident. The structural design of the core, RPV, internals and other related equipment is presented in this paper.

INTRODUCTION

Light water nuclear reactors including boiling water reactors (BWRs) and pressurized-water reactors (PWRs) account for the major part of nuclear power plant designs, of which 23% are BWRs[1]. Compared with PWRs, BWRs can have higher efficiency because the water temperature remains unchanged during boiling and more heat from the reactor core can be transferred to the water to generate steam[2]. BWRs have more than 40 years history[3]. EBWR-20 was the first experimental BWR in the world built at Argonne Natilonal Laboratory in 1957. Dresden 1 was the first BWR nuclear power plant in the world put into service in 1960. Since then, almost 100 BWR nuclear plants have been built, among which ABWR is the most advanced type. Both K6 and K7 at Kashiwazaki, Japan are successful typical ABWRs. However, these BWRs have an either inner pump or outer pump which means stricker safety requirements. The alternative is to use natural circulation for the primary coolant to eliminate pumps in the primary loop, which needs some innovate structural design. For this purpose, INET of Tsinghua University has prepared a plant concept known as the SSBWR-200, which is a small boiling water reactor for co-generation with a thermal output of 630 MW developed using the nuclear heating reactor (NHR) technology at INET.

The main purpose for the development of SSBWR-200 was to provide an independent energy source for an industrial complex and for multiple applications, such as industrial steam supply and seawater desalination as well as district heating and air conditioning. Of course, the SSBWR-200 can also serve as a power source for islands and remote areas isolated from the national power network. Therefore, the SSBWR-200 design was developed for non-electrical applications or, at most, co-generation of electricity and heat.

Since sensible heat is rather expensive to transport over a long distance, the SSBWR-200 for nuclear heating applications should be sited close to the populated area it serves. Therefore, its safety requirements should be even stricter than those for the APWR and ABWR power plants. The SSBWR-200 also has economic limits due to its size limitation.

To fulfill the economic goals, which are to compete with a conventional plant of the same scale and to compete with nuclear power plants in the range of 1000 MWe, the plant costs including reactor construction costs must be reduced.

PLANT STRUCTURAL CONCEPT

The SSBWR-200 will serve as an energy source for co-generation of electricity and heat. The design was developed using both NHR and BWR technology with an integral arrangement having all primary systems inside the reactor pressure vessel. Figure 1 shows a cross section of the SSBWR-200 reactor. The core is located at the bottom of the RPV. Reactor coolant circulates between the core region and downcomer due to natural convection. There is a long riser on the core outlet to increase the natural circulation capacity.

The rather tall RPV leads to a large water inventory in the primary system. All penetrations are located on the upper part about 10 meters above the core outlet. Therefore, no exposed core and no fuel damage will occur after a pipe rupture or any other accident. Therefore, the ECCS can be eliminated in the SSBWR-200.

The dynamical hydraulic control rod drives used in the SSBWR-200 are integrated into the reactor core, so there are no penetrations in the bottom closure of the RPV. Two independent cooling tube bundles are installed at the water surface level to remove the decay heat into a water pool and then into the atmosphere by natural circulation. The steam separator is eliminated and the steam drier can reduce the moisture content in the steam to 0.1% to assure normal operation of the steam turbine.

The main SSBWR-200 design parameters are shown in Table 1.

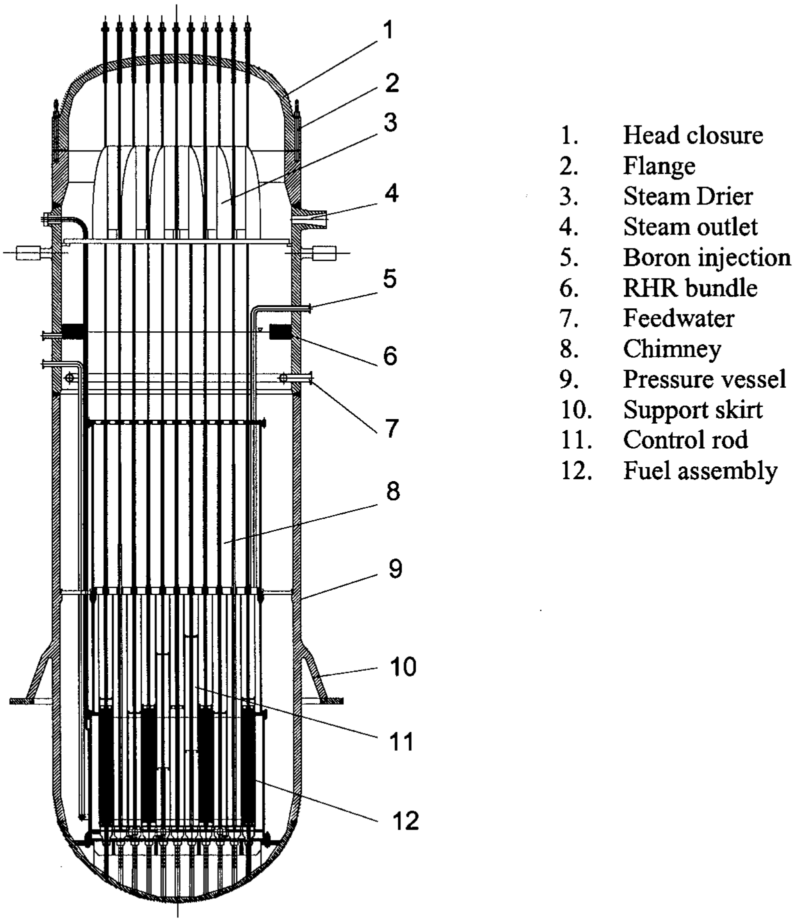


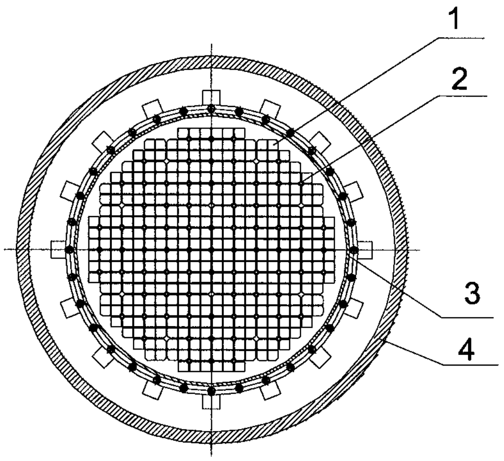
Fig. 1 The cross section of SSBWR-200

Table 1 Main SSBWR-200 Design Data

Thermal power	[MW]	630
Electricity output (min/max)	[MW]	30/200
Heat applications (min/max)	[MW]	0/~500
Plant life	[Year]	60
Steam conditions	[°C/MPa]	286/7.0
Active core height	[m]	2.2
Equivalent core diameter [m]		3.48
Volumetric power density [kW/L]		~30
Number of fuel assemblies		384
Number of control rods		89
RPV inside diameter/height	[m]	5/18

REACTOR CORE

The core active height is 2.20m. The core configuration is shown in Fig. 2. There are 384 fuel assemblies and 89 control rods in the core. The active equivalent diameter is 3.48 m. The height to diameter ratio is 0.63.



1. Fuel assembly
2. Control rod
3. Shroud
4. Pressure vessel

Fig. 2 Core configeration

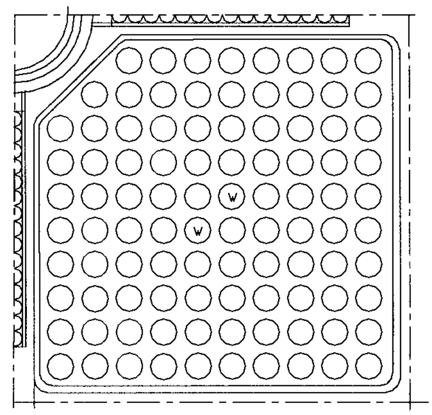


Fig. 3 Fuel Assembly

The fuel rod pellets consist of UO2 sintered with low enrichment. The cladding is made of Zircalloy 4. The pellet diameter is 8.43 mm. The outer cladding diameter is 10 mm. The sintered pellet density is $10.2g/cm^3$. The fuel box is also made of Zircalloy 4 with a length of twice that of the fuel assemblies. The distance between the box inner walls is 143 mm and the wall thickness is 2 mm. As shown in Figure 3, each assembly contains a 10×10 arrays with 3 fuel rods in one corner removed for the control rod channels. The fuel rod pitch is 14 mm.

REACTIR PRESSURE VESSEL (RPV)

The SSBWR-200 pressure vessel (Fig. 1) is a vertical, cylindrical pressure vessel made of welded low alloy steel forging sections. In view of the desired safety level the RPV for the SSBWR-200 is relatively large for an output of 630MWt. However, the vessel is designed, fabricated, tested, inspected and stamped in accordance with ASME code, Section III, Class 1 requirements [4]. The design of the RPV and its support system meets Seismic Category I equipment requirements.

SSBWR-200 RPV Parameters and Dimensions

The main design parameters and the main dimensions are listed in Table 2.

Table 2 Main Design Parameters of SSBWR-200 RPV

Design/Operating Pressure	9.0/7.0 MPa
Design/Operating Temperature	302/286 °C
Outer Diameter	5330 mm
Outer Height	18935 mm
Shell Thickness	165/200 mm

Reactor Pressure Vessel Materials

The materials used in the SSBWR-200 RPV comply with the provisions of ASME Boiler and Pressure Vessel Code Section III, Subsection NB and Appendix I[4,5] and also meet the requirements of 10CFR50, Appendix G[6]. The RPV is constructed primarily from low alloy, high strength steel plates and forgings. The plates are ASME SA-533, TYPE B, Class I and the forgings are ASME SA-508, Class 3. The materials for the bolts, nuts and washers for the main closure flange are ASME SA-540, Grade B23 or G24 having a minimum yield strength level of 893Mpa.

These materials provide adequate strength, fracture toughness, fabricability and compatibility with the SSBWR-200 environment. Their suitability has been demonstrated by long-term successful operating experience in reactor services.

Reactor Pressure Vessel Design

The upper and lower flanges are connected with 96 studs and are sealed with double metallic "O"-type rings. The vessel support skirt is constructed of low alloy or carbon steel such as ASME SA508, Class 3, SA-516, or SA-533. The top end of the support skirt is welded to the pressure vessel. The vessel support skirt flange is bolted to the steel support structure. The vessel support skirt is designed to meet the stress criteria of ASME code, Section III, Subsection NF.

There are no penetrations in the bottom closure because of downward control rod insertion. All the nozzles are in the vessel penetration section that is several meters higher than the top of the core to insure that the core can not be uncovered. The feedwater inlet nozzle has a thermal sleeve. Nozzles connected to the stainless steel piping have safe ends or extensions made of stainless steel.

All nozzle materials are low alloy steel forgings in accordance with ASME SA-508, Class 3. The safe end materials are compatible with the material of the mating pipes. The nozzles designs are in accordance with ASME Section III, Subsection NB.

The RPV stabilizer is designed as a safety-related type component support in accordance with the requirements of ASME Boiler and Pressure Vessel Code Section III, Subsection NF. The stabilizer provides a reaction point near the upper end of the RPV to resist horizontal loads caused by effects such as an earthquake or pipe rupture.

Reactor Pressure Vessel Fabrication

The RPV is a vertical cylindrical pressure vessel of welded construction fabricated in accordance with ASME Code, Section III, Class 1 requirements. The shell, RPV head, flanges and major nozzles are fabricated from low alloy steel forgings. The shell forgings are joined by circumferential welds. Welding performance to join these vessel components is in accordance with procedures qualified to ASME Section III and IX requirements. Weld test samples were required for each procedure for major vessel full penetration welds.

REACTOR INTERNALS

Core Support Structures

The core support structures include the shroud, shroud support, upper grid plate, lower grid plate and fuel assembly supports. These structures form the core partitions within the RPV, sustain the pressure differentials across partitions, direct the primary coolant water flow, and locate and support the fuel assemblies (see Fig. 1).

The shroud support, shroud and chimney make up a stainless steel cylindrical assembly that provides a partition to separate the upward coolant flow through the core from the downward recirculation flow. This partition separates the core region from the outer annulus. The shroud laterally supports and locates the fuel assemblies and is bounded with end rims at the top by the upper grid plate and at the bottom by the lower grid plate. A bolted-connection is used between the shroud and the shroud support brackets. The shroud provides horizontal support for the core by supporting the lower and upper grid plates.

The shroud support supports the shroud and the components connected to the shroud. It is a series of horizontal brackets welded to the vessel wall to provide support to the shroud and core.

The lower grid plate consists of a circular stainless steel plate with round openings stiffened with a beam structure. The lower grid plate provides lateral support for the fuel assemblies, fuel assembly supports, control rod guide tubes and the hydraulic control rod drive cylinders. The last two items are also supported vertically by the lower grid plate that is bolted to the shroud flange and shroud support.

The upper grid plate consists of a circular plate with some square openings for the fuel assemblies, cruciform openings for the control rods and some round openings for the in-core flux monitor guide tube. Each square opening provides lateral support and guidance for four fuel assemblies. The upper grid plate is bolted to the top rim of the shroud and the lower flange of the chimney.

The fuel assembly support is a series of vertical pipe structures under the lower grid plate to provide vertical supports to the fuel assemblies. There are enough holes in each support pipe to allow primary coolant flow into the core.

Chimney Section

The chimney consists of two stainless steel cylinders bolted together with internal stabilizers which give lateral support and rigidity to the chimney. The bottom chimney flange is bolted to the top surface of the upper grid plate. The chimney provides the driving head (>6.3m) necessary to sustain the natural circulation flow. The chimney separates the subcooled recirculation flow returning downward from the steam driers and the feedwater from the upward steam-water mixture flow exiting the core partition inside the chimney separate groups of 384 fuel assemblies. These partitions act to channel the mixed steam and water flow exiting the core into smaller chimneys, limiting cross flow and flow instabilities which could result from a much larger diameter open chimney. The partitions do not extend to the top of the chimney, thereby forming a plenum or mixing chamber for the steam/water prior to entering the steam driers.

The feedwater sparger is a stainless steel header located in the mixing plenum above the downcomer annulus. The feedwater sparger is connected to the feedwater line through a RPV nozzle. The sparger end brackets are pinned to the vessel brackets to support the sparger. Feedwater flow enters the center of the sparger and is discharged radially inward to mix the cooler feedwater with the downcomer flow from the chimney top. The feedwater also serves to condense steam in the region above the downcomer annulus and to subcool water flowing to the lower plenum in the vessel.

RELATED EQUIPMENT

Steam Drier

The steam drier assembly is a non-safety class component. It removes the moisture from the wet steam leaving the core through the chimney. The moisture concentration is much less than 0.1% after the steam drier which assures effectively operation of the steam turbine. The steam drier unites need to be carefully designed and made of stainless steel.

The height of SSBWR-200 steam driers is about 2.00m. Control rod position indicator tubes and the in-core flux monitor tube pass through gaps in the driers.

Residual Heat Removal Heat Exchanger

The residual heat removal heat exchanger is designed as two independent systems made of helical stainless steel pipe bundles (see Fig. 4 and Fig. 5) located at the water surface level (see Fig. 1).

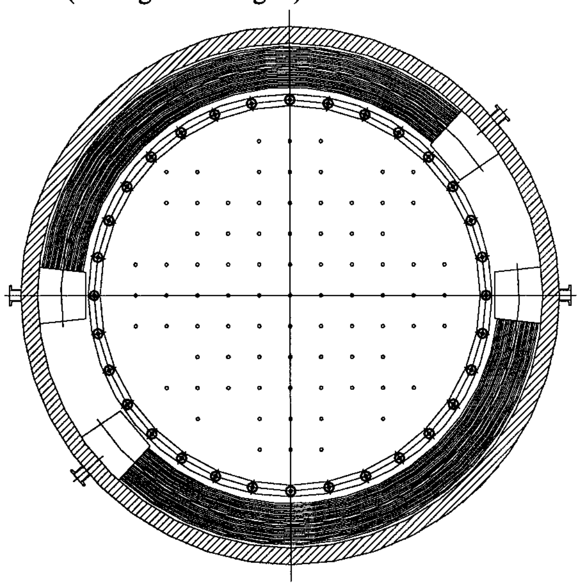


Fig. 4 Two sets of RHR bundles

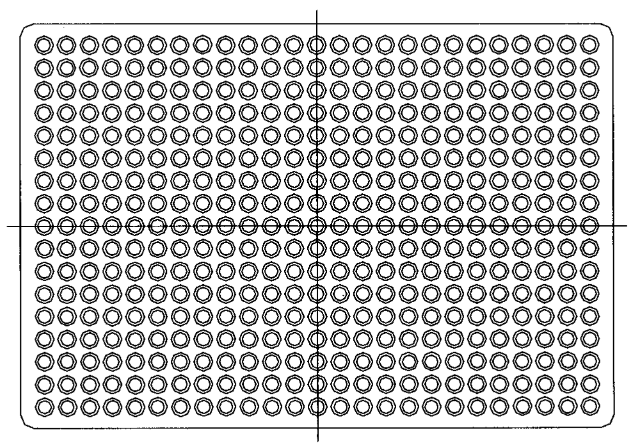


Fig. 5 Cross section of RHR bóundles

The safety function of the residual heat removal system is to ensure that the decay heat will be removed at a certain flux from the core after reactor shutdown so that the integrity of the fuel cladding and the reactor coolant pressure boundary will be guaranteed. There are two independent sets of residual heat removal heat exchangers. The required heat removal capability will be satisfied if either one of the two systems is put into operation. The two systems stand by each other. The passive residual heat removal is completely achieved by natural circulation.

Control Rods and Their Hydraulic Drive System

As shown in Fig. 1 and Fig. 6, there are 89 cruciform control rods located in the gaps between fuel assemblies. Each control rod has its own drive system. Each control rod channel is in the crossing of the wide water gaps of four fuel assemblies.

Tontrol rod hydraulic drive system was developed by INET in the 1980's. It has been successfully operated on NHR-5 since 1989[7]. It is also used in the preliminary design of Shenyang NHR-200, the First Chinese Nuclear Heating Demonstration Plant. SSBWR-200 also employs the system to use the experience on NHRs.

The system uses coolant water from the reactor pressure vessel. The coolant from the RPV is be pressured by a circulation pump and filtered by a filter located at the pump outlet. Then, the water is distributed by the control units to drive the stepping cylinders, which connect to the control rods. Therefore, the control rod is driven by the hydraulic force using the control system.

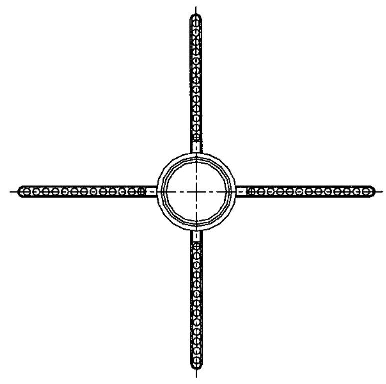


Fig. 6 Control rod unit

This design meets the requirements of a "fail-safe" design. The control rods will automatically drop into the core by gravity in case of loss of power supply, depressurization of the RPV, pipe break or pump shut down events. It also eliminates the accident of rapid rod ejection.

CONCLUDING REMARKS

This preliminary study of the SSBWR-200 plant concept has shown that the SSBWR-200 is a promising design with a very simplified design and a number of advanced and innovative features, which satisfy its safety and economic goals. There are no pipelines below the core top in the RPV, which means that the reactor core will always be flooded by water during a LOCA accident without an emergency injection system. Therefore, transient boiling does not occur for 99.9% of the clad fuel elements clad. The passive decay heat removal system can directly transfer heat from the reactor pressure vessel to the environment.

Further study of the plant concept is needed to develop the SSBWR-200 design into a commonly accepted plant.

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