OVERVIEW OF THE JAPANESE SCWR CONCEPT DEVELOPED UNDER THE GIF COLLABORATION

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Abstract

A Supercritical Water-Cooled Reactor (SCWR) concept has been developed in Japan under the financial support of the Ministry of Economy, Trade and Industry since fiscal year 2000, and Japan has been a member of the SCWR development in the Generation IV International Forum (GIF). This paper overviews the Japanese SCWR concept, which is called JSCWR here. The basic design philosophy is to utilize proven light water reactor and supercritical fossil-fired power plant technologies as much as possible to minimize the R&D cost, time and risk. The JSCWR is a thermal neutron spectrum reactor using light water as moderator and coolant. The JSCWR plant consists of a pressure-vessel type, once-through reactor and a direct Rankine cycle turbine system. To assess the viability of the JSCWR, its technical feasibility and plant economics have been evaluated. The results show that the JSCWR concept is viable and there are some future work to be done such as accumulation of various data for design and manufacture and creation of regulatory standards.

1. Introduction

The Supercritical Water-Cooled Reactor (SCWR) is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374°C, 22.1 MPa), which enables combination of a once-through reactor and a direct cycle system. The SCWR has potential advantage of low capital cost thanks to its high thermal efficiency and plant system simplifications.

The development of the SCWR concept was started by the University of Tokyo in 1989, which acquired world wide interest and was selected as one of the six Generation IV nuclear energy systems by the Generation IV International Forum (GIF) in 2002 [1]. The international collaboration started then to plan and implement research and development (R&D) of key technologies such as materials selection and thermal-hydraulics of supercritical fluid. The System Arrangement was signed between Canada and Euratom in 2006, and acceded by Japan in 2007 [2-4], which gave a framework for the international R&D of the SCWR system and established the formal System Steering Committee (SSC) [5], and Project Arrangement for thermal-hydraulics and safety R&D was signed in 2009 [4], which is expected to be followed by another Project Arrangement for materials and chemistry R&D.

The SSC has set the target of the GIF collaboration to complete major R&D by 2020 to provide sufficient information to enable the design, licensing, and construction of a prototype reactor in 2020s. The objective of the GIF is to have the Generation IV nuclear energy systems available for international deployment around 2030 [5].

Several concepts are currently under consideration to seek various potentials of the SCWR [5]. For example, pressure vessel and pressure tube type reactors, thermal and fast neutron spectrum cores, and light-water, heavy water, and solid moderators have been considered. But the key technologies for these concepts are very similar, which gives the opportunities for the GIF collaboration.

In this paper, a SCWR concept developed under the financial support of the Ministry of Economy, Trade and Industry (METI) is described [6], which is called Japanese SCWR (JSCWR) here. A Japanese consortium consisting of the Institute of Applied Energy, the University of Tokyo, Kyushu University, Kyoto University, Japan Atomic Energy Agency, Hitachi-GE Nuclear Energy, Ltd., Hitachi, Ltd., and Toshiba Corporation has been working together to establish the concept and to implement key technology developments.

The basic philosophy of the JSCWR development is to utilize proven light water reactor and supercritical fossil-fired power plant technologies as much as possible to minimize the R&D cost, time and risks. So the JSCWR is designed as a thermal neutron spectrum reactor using light water as moderator and reactor coolant. The JSCWR plant consists of a pressure-vessel type, once-through reactor and a direct Rankine cycle system. Reactor coolant fed through inlet nozzles is heated up in the core and flows through outlet nozzles with no recirculation in the vessel. The core outlet coolant, which is customarily called ‘steam’ although there is no distinction between steam and water above the supercritical pressure, is directly delivered to the turbine system, and the feedwater comes back directly from the feedwater pumps. The balance of plant (BOP) consists of three-stage turbines, condensers, and condensate and feedwater system, and electricity is generated by a generator driven by the turbines, which is a well-matured technology and needs essentially no additional R&D.

Main technical data of the JSCWR are summarized in Table 1. The electrical output is assumed to range from 600 MWe to 1700 MWe class to fulfill user’s requirements as much as possible. In this document, the reference value is selected 1725 MWe, which corresponds to a reactor thermal output of 4039 MWth.

2. Nuclear system

2.1 Main characteristics of primary circuit

The primary circuit of the JSCWR constitutes a direct Rankine cycle consisting mainly of a reactor pressure vessel (RPV), main steam lines (MSLs), a turbine system, low-pressure and high-pressure condensate water pumps, feedwater heaters, feedwater pumps.

Main characteristics of the JSCWR primary circuit are:

1. The thermal efficiency is very high compared with those of current light water reactors (LWRs). It is estimated to be about 43%, which is 1.2 to 1.3 times higher than those of

LWRs, due to higher-temperature, higher-pressure steam at the turbine inlet.

2. The plant main system is much simpler than LWR systems. Steam generators and a pressurizer are eliminated when compared with a typical PWR system, and steam–water separation system and a recirculation system are eliminated when compared with a typical BWR system as shown in Figure 1.
3. Capacities of primary system components can be reduced because of a lower coolant mass flow rate per unit core thermal power resulting from the higher enthalpy content of the coolant.

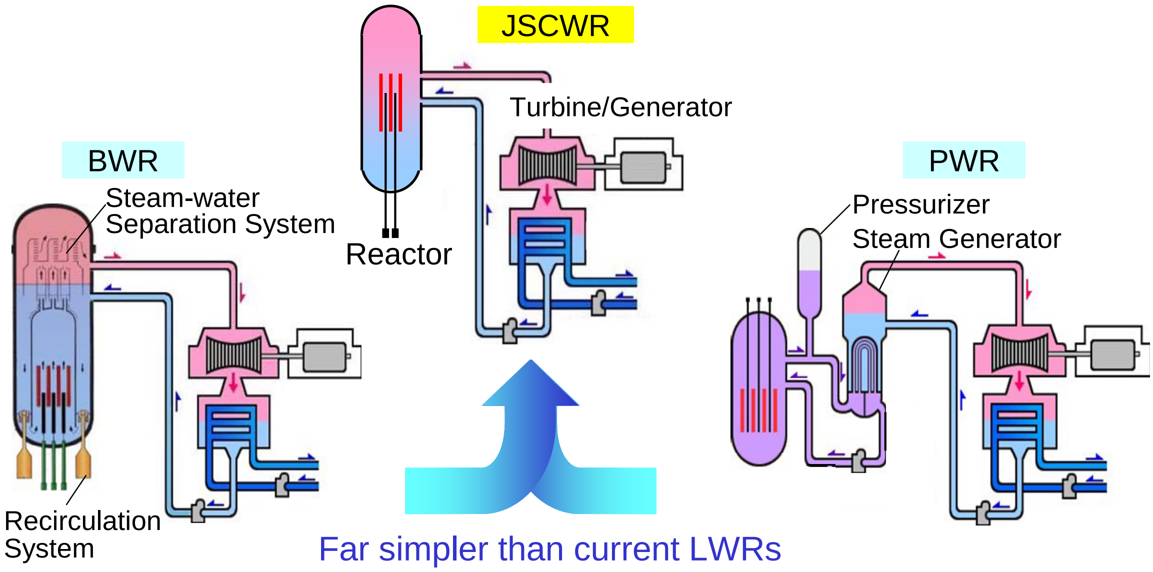


Fig. 1 Comparison of primary circuits between JSCWR, BWR and PWR

2.2 Reactor core and fuel design

The reactor core is operated at 25.0 MPa. The feedwater temperature is 290℃, and the average core outlet coolant temperature is 510℃. Both the pressure and temperature are much higher than those of current LWRs. They are compared in Figure 2.

Because the operating pressure is higher than the critical pressure of water (22.1 MPa), no phase change occurs in the core, which means the coolant changes continuously from low temperature, high density fluid at the inlet of the core to high temperature, low density fluid at the outlet. The coolant flow rate, 2105 kg/s, is significantly low since the enthalpy rise in the core is high compared with those of current LWRs.

The reactor core is cylindrical in shape consisting of 372 fuel assemblies. Each fuel assembly stays in the core for three cycles. The cross sectional view of the core is shown in Figure 3 together with its loading pattern.

A fuel assembly consists of 192 fuel rods and a square water (moderator) rod in the center, surrounded by a square channel box (137 x 137 mm) as shown in Figure 4. The fuel rods contain UO_2 pellets like LWR fuels in the modified stainless-steel cladding. In the water rod, low temperature water flows downward to keep enough moderation in the core.

The active fuel length is 4.2 m, which is a little longer than typical LWR fuels, to reduce the linear heat generation rate. The total fuel length is about 5.8 m.

Control rods are used for primary reactivity control. The control rod drives are mounted on the bottom of the RPV. Cruciform control rods are vertically inserted into and withdrawn from the core by the control rod drives. To ensure adequate shut down margin and to minimize the local peaking during the entire operation cycle, gadolinia (burnable poison) is incorporated in the fuel.

The U^{235} enrichment for the equilibrium core exceeds 7% to achieve the similar discharge burnup as current LWR fuels. This high enrichment is mainly due to relatively high neutron captures of the structural materials especially fuel claddings and channel boxes.

An enrichment of 5% and more is currently not available on the market for commercial LWR fuels, but such technologies are under development in Japan for the next-generation LWRs and will be commercially available in the near future.

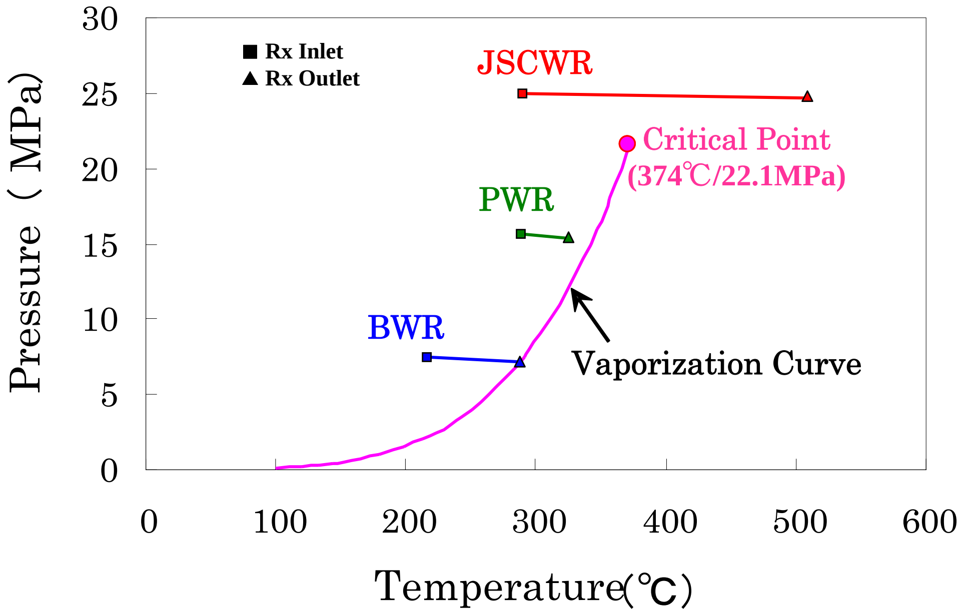


Fig. 2 Operating Pressure and Temperature Ranges of SCWR, PWR and BWR

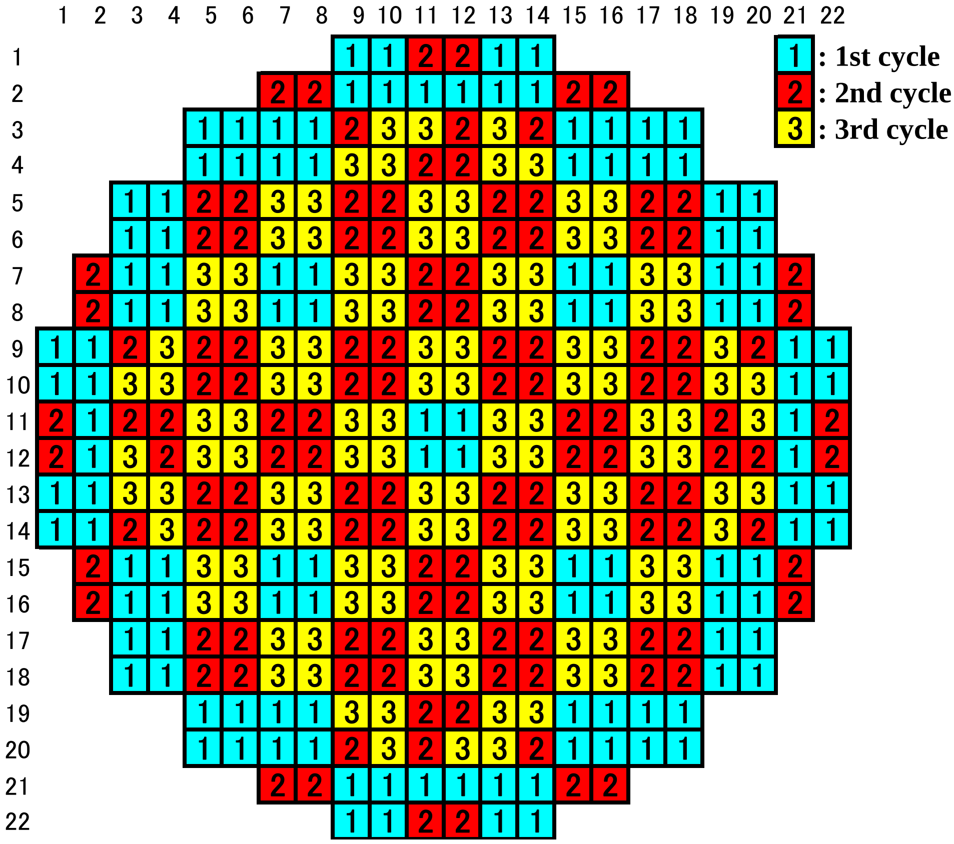


Fig. 3 Cross sectional view of the JSCWR core and its loading pattern

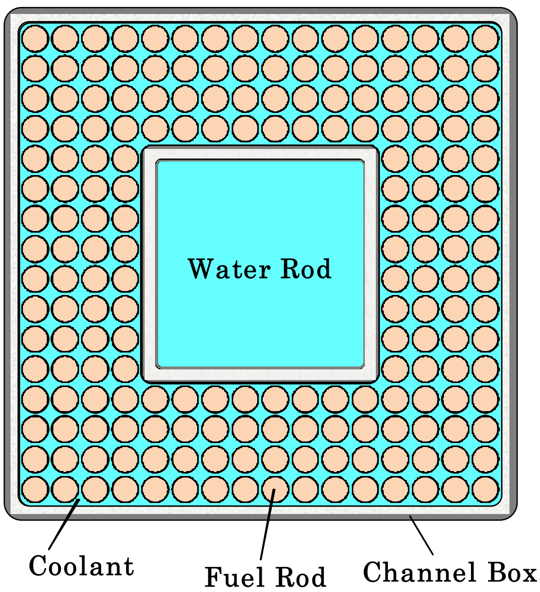


Fig. 4 Cross sectional view of the JSCWR fuel assembly

2.3 Reactor internals

The structure of the JSCWR RPV is similar to that of PWR. The inner diameter is about 4.8 m; the total inside height is 16.5 m.

The flow in the RPV is depicted in Figure 5. The coolant is provided through cold legs (inlet nozzles) and flows out through hot legs (outlet nozzles). Most of the coolant flows downward through the annulus region between the RPV wall and the shroud (downcomer), and flows into the lower plenum. A part of coolant is directed to the upper dome to remove heat from the shroud head and flows into the bypass line. The coolant from the downcomer mixes with the coolant from the bypass line in the lower plenum and flows upward through the core.

The inner surface of RPV wall is cooled by the inlet coolant as in PWRs to keep the temperature low enough to use the same materials used for PWRs.

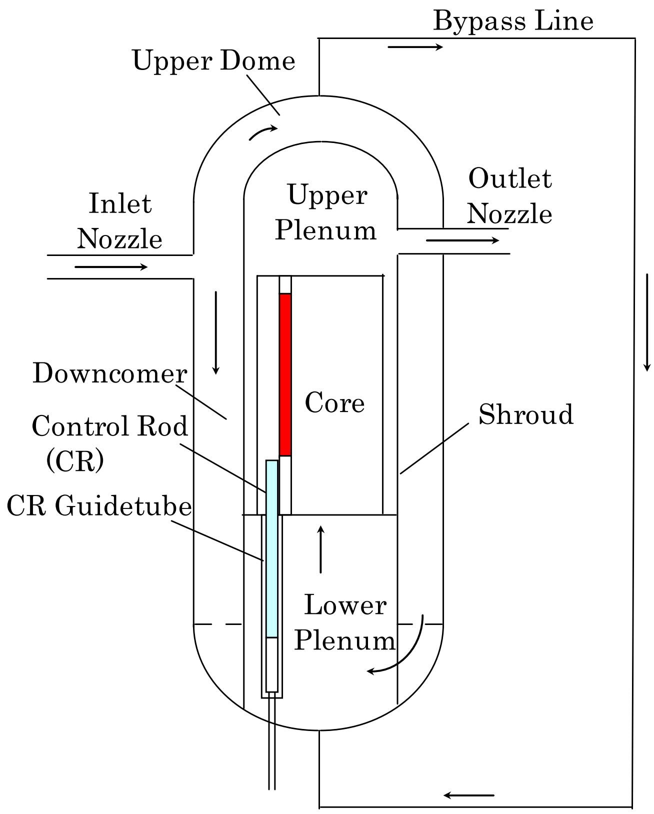


Fig.5 Configuration of Reactor Pressure Vessel and Coolant Flow

2.4 Reactor auxiliary systems

The main auxiliary systems in the nuclear island consists of the auxiliary feedwater system (AFS), the residual heat removal system (RHR), the reactor building closed cooling water system (RCW), the reactor building seawater system (RSW), the fuel pool cooling and cleanup system (FPC), the suppression pool cleanup system (SPC). In addition there are many other auxiliary systems such as instrument and service air system, heating ventilating and air conditioning (HVAC) system. Basically the same technology used in BWR plants can be applicable to the JSCWR except for the auxiliary feedwater system (AFS).

The AFS provides additional feedwater to the core in case the flow rate of main feedwater decreases for some reasons. It consists of piping, valves, a steam-driven turbine, and a pump. The system configuration is similar to that of the reactor core isolation cooling system (RCIC) in BWR except that the AFS works at much higher pressure.

Because the JSCWR consists of a once-through reactor and direct cycle turbine system, all reactor coolant flows in a single circuit. So it does not need a water filtering and purification system in the nuclear island. The JSCWR has a demineralizer/filter system in the turbine island.

2.5 Fuel cycle

The standard fuel cycle for the JSCWR is same as that of LWRs in Japan. The JSCWR has a potential to utilize to fully utilize uranium and plutonium resources as the fuel due to the flexible neutron spectrum. The aqueous-reprocessing technology is applicable to the JSCWR fuel.

3. Safety concept

The JSCWR safety philosophy is based on that of advanced LWRs, which reflects experiences and lessons learned of the past and current LWRs.

The design philosophy for safety and reliability are as follows:

- Maximum utilization of the matured, proven technologies that have been accumulated in the successful commercial operation of LWRs as well as supercritical pressure fossil-fired power plants.
- Safety system development based on inherent feature of water-cooled reactor and well-developed LWR safety technologies. The inherent feature includes negative void (density) and Doppler coefficients. The well-developed LWR safety technologies mainly include reactivity control systems and emergency core cooling systems (ECCS).

Safety systems mainly consist of high-pressure auxiliary feedwater systems (AFS), automatic depressurization systems (ADS), and LPCIs that also work as RHR. Reactor scram, AFS and LPCI are actuated by low core flow rate signals instead of low water level signals, which is commonly used in current BWRs.

4. Turbine –generator systems

One of the most attractive advantages of the JSCWR over conventional LWRs are its high thermal efficiency, which is estimated about 43% without reheating, and no or little need for R&D because supercritical pressure fossil-fired power plant systems can be applicable with minor design changes.

4.1 Turbine system

The turbine system of the JSCWR consists of one dual-exhaust high-pressure (HP) section, one dual-exhaust intermediate-pressure (IP) section and three dual-exhaust low-pressure (LP) sections (that is, a six flow, tandem compound system). The cycle uses a moisture separator to reduce the wetness fraction of steam to prevent damages of the LP turbine blades.

The turbine system could be simplified by adopting a combined high-pressure and intermediate-pressure turbine, which is under development in the fossil-fired power industry, if the steam flow rate is low enough. The adoption of the combined turbine as well as full-speed turbine system might reduce the length of total turbine system and hence reduces the volume of turbine building.

Figure 6 shows the BOP system of the JSCWR and its heat balance.

4.2 Condensate and feedwater system

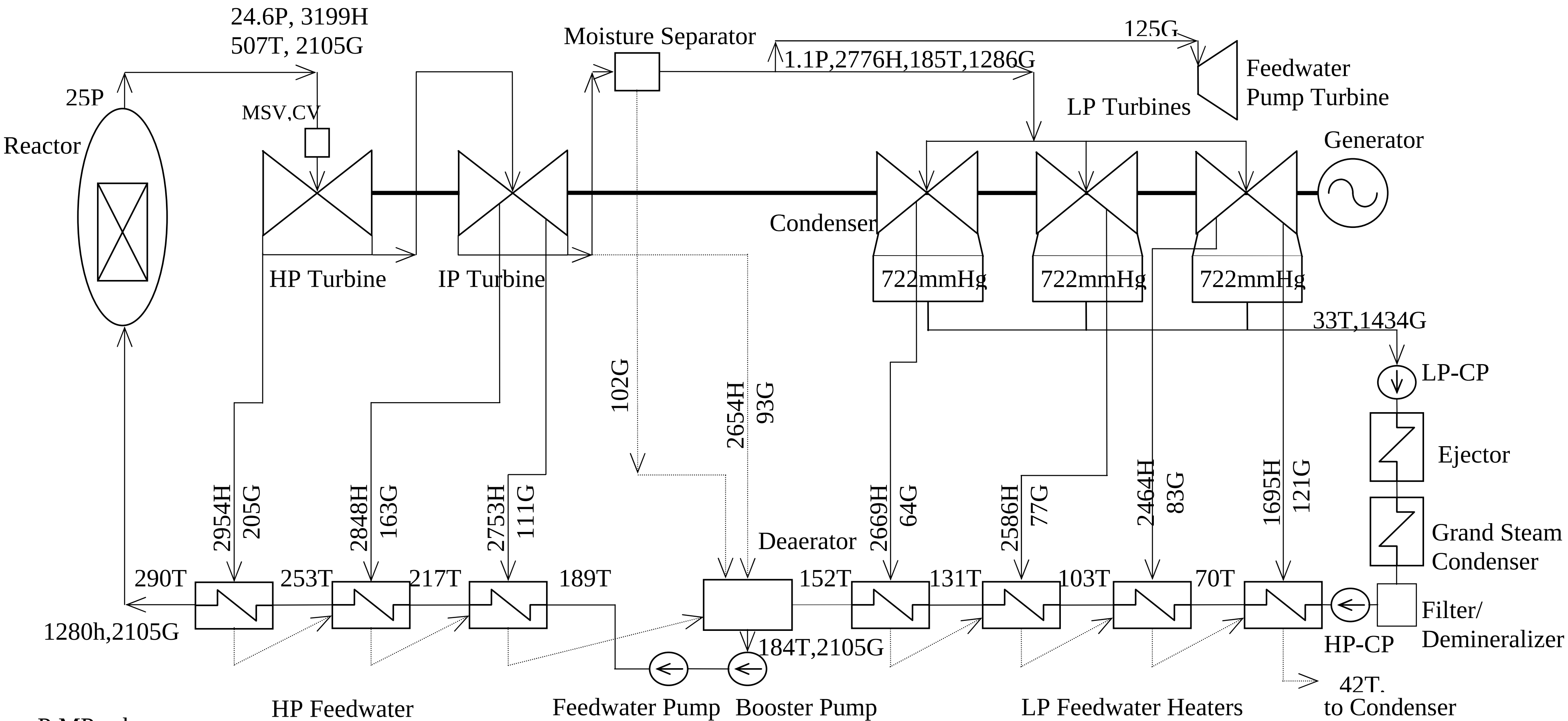
The steam cycle of the JSCWR employs eight-stage re-generative system consisting of four-stage low-pressure feedwater heaters, one-stage deaerator, and three-stage high-pressure feedwater heaters as shown in Fig. 6, whose thermal efficiency is estimated 43%. Steam bled from the HP, IP and LP turbine is conveyed to high-pressure and low-pressure feedwater heaters (HP/LP-FWHs).

The condensate collected in the condensers is pumped by low-pressure condensate pumps (LP-CPs) to an air ejector, a grand steam condenser and a set of demineralizer and filters. Being pumped up further by high-pressure condensate pumps (HP-CPs), the condensate passes through the low-pressure feedwater heaters including a deaerator. The feedwater from the deaerator is pumped up to supercritical pressure by booster and reactor feedwater pumps (RFPs) and passes through the high-pressure feedwater heaters. The feedwater heaters heat feedwater to the temperature of 290ºC at the rated condition.

The volumetric capacity of the turbines as well as the feedwater heaters used in the JSCWR is much smaller than those used in current LWR plants because of the small volumetric flow rate per electricity production resulted from high enthalpy/pressure of supercritical coolant.

4.3 Turbine auxiliary systems

The main auxiliary systems in the turbine island consists of the turbine building closed cooling water system (TCW), and the turbine building seawater system (TSW). In addition there are many other auxiliary systems. Basically the same technology used in BWR plants can be applicable to the JSCWR.



P:MPa abs
G:kg/s
T:℃
H:kJ/kg (steam)
h:kJ/kg (drain, water)

Fig.6 Balance of Plant system of JSCWR

5. Plant layout

Layout of the reactor building is designed based on the technologies used in the current advanced boiling water reactor (ABWR) plant. The primary containment of the JSCWR is a pressure suppression containment with a suppression pool, and the main components in the reactor building are almost the same as those of the ABWR plant.

Layout of the turbine building is designed based on the technologies used in current BWR and supercritical pressure fossil-fired power plants.

An interim bird's eye view of the JSCWR power plant is shown in Fig. 7.

The volume of reactor building could be much smaller per electricity generation than that of current LWR plants because the main components are significantly smaller and fewer.

Other buildings such as service building, control building and radioactive waste building are almost the same as those of current LWRs.

Fig. 7 Interim Bird's Eye View of JSCWR Power Plant

6. Development status of technologies

The R&D of the JSCWR is planned to progress in three phases defined in GIF [1].

In the first phase, viability phase, preconceptual design of the system is established and the feasibility of key technologies is examined. In the second phase, performance phase, performance data such as material capabilities and thermal-hydraulic characteristics are verified and the conceptual design of the system is optimized. In the last phase, demonstration phase, the detailed design of the system is performed and a prototype or demonstration plant is licensed, constructed, and operated.

The development of the JSCWR is at the last stage of the first phase now.

Assuming the successful completion of the viability phase, a performance phase will start in 2011. Major R&D activities for the performance phase will be conducted through the GIF collaboration and are expected to complete by 2020.

7. Summary

This paper summarizes the JSCWR concept, which has been developed by a Japanese consortium consisting of the Institute of Applied Energy, the University of Tokyo, Kyushu University, Kyoto University, Japan Atomic Energy Agency, Hitachi-GE Nuclear Energy, Ltd., Hitachi, Ltd., and Toshiba Corporation under the financial support of the Ministry of Economy, Trade and Industry (METI).

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8. References

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Table 1 Summarized Technical Data of the JSCWR Concept

General plant data		
Reactor thermal output	4039	MWth
Power output	1725	MWe
Plant efficiency	42.7	%
Plant design life	60	Years
Reactor Coolant	H_2O	
Moderator	H_2O	
Thermodynamic Cycle	Rankine cycle	
Type of Cycle	Direct cycle	
Nuclear steam supply system		
Steam flow rate at nominal condition	2105	kg/s
Steam pressure/temperature	25.0/510	MPa(a)/℃
Feedwater flow rate at nominal condition	2105	kg/s
Feedwater temperature	290	℃
Reactor coolant system		
Primary coolant flow rate	2105	kg/s
Reactor operating pressure	25.0	MPa(a)
Core coolant inlet temperature	290	℃
Core coolant outlet temperature	510	℃
Mean temperature rise across core	220	℃
Reactor core		
Active core height	4.2	m
Equivalent core diameter	3.34	m
Average linear heat rate	13.5	kW/m
Average fuel power density	48.1	kW/kgU
Average core power density	110	MW/m^3
Fuel material	Sintered UO_2	
Cladding tube material	Modified SS	
Outer diameter of fuel rods	7.0	mm
Rod array of a fuel assembly	16x16 square lattice	
Number of fuel assemblies	372	
Number of fuel rods in an assembly	192	
Enrichment of reload fuel at equilibrium core	7.2	Wt%
Fuel cycle length	10.2	months
Average discharge burnup of fuel	45000	MWd/t
Burnable absorber (strategy/material)	Gd	
Control rod absorber material	B_4C	
Number of control rods	89	

Reactor pressure vessel		
Inner diameter of cylindrical shell	4800	mm
Wall thickness of cylindrical shell	470	mm
Total height, inside	16500	mm
Base material	Low Alloy Steel	
Design pressure	27.5	MPa
Primary containment		
Type	Pressure suppression containment	
Overall form (spherical/cylindrical)	Cylindrical	
Dimensions (diameter/height)	+	m
Design pressure/temperature	+	MPa(a)/℃
Design leakage rate	+	Vol%/day
Is secondary containment provided?	+	
Residual heat removal systems		
Active/passive systems	Active system	
Safety injection systems		
Active/passive systems	Active system	
Turbine		
Type of turbines	Six flow, tandem compound	
Number of turbine sections per unit (e.g. HP/IP/LP)	1 HP/ 1 IP/ 3 LP	
Turbine speed	3000	rpm
HP turbine inlet pressure/temperature	24.6/507	MPa(a)/℃
Condenser		
Type	Shell type	
Condenser pressure	5	kPa(a)

Symbols in the data column:
+: under evaluation or to be evaluated in future
-: not in use in the JSCWR