Design study on a reference SCPR core is done with a 3-D core simulator that was newly built by incorporating thermal hydraulic module for SCPR into a BWR core design code in Toshiba Corporation. The reference core, which was originally proposed by the University of Tokyo, consists of square fuel assemblies with the same number of cluster type control rod units. The fuel assembly is composed of about 300 fuel rods and 36 rectangular water rods in a 30 cm square channel box. The number of control rods per unit was 16 evaluated from a Monte Carlo calculation (MCNP) to achieve relevant worth.

The objective of this study is to propose a feasible core design that can bring high outlet temperature over 500°C. The key to achieve such temperature is power flattening in radial direction throughout the fuel operating cycle. The number of fuel rods containing burnable poison (\(\text{Gd}_2\text{O}_3\)) and the \(\text{Gd}_2\text{O}_3\) concentration were evaluated with the 3-D simulator so that the reactivity differences among fuels through cycle should not change. We optimize the fuel loading pattern and control rods pattern to flatten the radial peaking. With those measures, the radial peaking factor is kept below 1.3 throughout the fuel operating cycle assuming that the individual channel flow is constant.

**KEYWORDS:** SCPR, Supercritical-pressure water, innovative reactor

I. Introduction

Supercritical Water Cooled Reactors, which was chosen as one of the next generation nuclear systems by Generation-IV International Forum (GIF) in September 2002, operate above the thermodynamic critical point of water (374°C, 22.1 MPa). The key advantages over the current generation light water reactors (LWRs) include:

- The estimated thermal efficiency is exceeding 40% due to high-pressure, high-temperature steam at the turbine inlet.
- Thermal components such as heat exchangers and turbines are compact and the need for steam separation systems, re-circulation systems as well as steam generators, is eliminated because of the higher enthalpy content of the supercritical-pressure (SCP) water and because of no phase change in supercritical regime.
- The R&D cost and duration is minimized because this technology is based on matured LWR technologies as well as matured SCP fossil power technologies.
- High coolability of the SCP water facilitates designing the moderator volume to achieve either thermal or fast neutron spectrum.

Today, we develop the 3-D core simulator for SCPR. And we designed the equilibrium core, which has thermal neutron spectrum.

In this paper, we describe the 3D simulator for SCPR and the equilibrium core design of SCPR.

II. Development of 3D simulator for SCPR

3D simulator for BWR has two modules, one is nuclear module that evaluates 3D power distribution, and another is Thermal hydraulic module that evaluates flow distribution in a core and 3D water density distribution. (Fig.1)
On the viewpoint of nuclear module,

- The neutron spectrum of the supercritical water-cooled power reactor looks like BWR’s one.
- There is especially no problem though the supercritical water-cooled reactor of U enrichment is higher.

Otherwise, on the viewpoint of thermal hydraulic module, there are many differences between BWR and SCPR. We show main differences in the following.

- The boiling phenomenon is lost when pressurizing to 22.1MPa or more of the critical point, and a clear phase change does not show up.
- Specific heat changes greatly near the critical point, and the temperature dependent of specific heat is large. So the change in specific heat cannot be modeled with the latent heat. (See Fig.2)

The relation between enthalpy and the specific volume change monotonously. (See fig.3) However, the relation between enthalpy and the temperature, the temperature and the density changes rapidly near the critical point. (See fig.4 and 5)

From these common features and differences between BWR and SCPR, we decided to make the new thermal hydraulic modules for SCPR. And we reuse the nuclear module for BWR.

The new thermal hydraulic modules for SCPR have the following features.

- The supercritical water is assumed to be a single phase
- The latent heat model is not adopted.
- All the specific volumes and the temperatures, etc. which the reactor core simulator needs are calculated from enthalpy.
- The calculation routines of the specific volume and the temperature, etc. were made based on the steam table of Institution of Mechanical Engineers.
III. Equilibrium Core Design

1. Control rod design

The reactor core consists of relatively large square fuel assemblies (about 300x300mm) proposed by Univ. of Tokyo (Fig. 6). The fuel assembly consists of 300 fuel rods and 36 water rods. The fuel rod mainly contains UO₂ like LWRs in SUS (Stainless Steel). Since coolant flow distribution in the fuel assembly is mainly influenced by the gap between the fuel rod and the water rod, the gap width is optimized through sub-channel analysis to achieve flat coolant flow distribution.

The water rods in the fuel assembly compensate small moderation resulted from the large change in coolant (water) density along the core as well as to guide the control rod insertion into the core. In the water rods, cold coolant descends from the RPV top head through the control rod guide tubes located in the hot plenum. Along the coolant channels between the fuel rods or between the fuel rod and the water rod in the channel box, coolant ascends from the core bottom to the hot plenum. This arrangement facilitates neutron moderation by cold water in the water rods and core cooling by water along the coolant channels.

According to our evaluation, U₂³⁵ enrichment for the equilibrium core is 6.2% to achieve similar discharge burn-up of current LWR fuels (45GWD/t, 3 Batches). This enrichment is mainly resulted by the relatively high neutron capture of the structure materials (non Zircaloy) including the fuel cladding and the channel boxes. To ensure adequate shut down margin during the entire operation cycle, gadolinia (burnable poison) is incorporated in the fuel.

The reactor is shut down by inserting cluster type control rods into all fuel assemblies from the top of core. We investigated the requisites for the control rods to achieve cold shutdown for SCPR.

The worth of the control rods for cold shutdown were calculated by a Monte-Carlo code (MCNP) for different rod radii as well as for different rod numbers per fuel assembly assuming use of natural B₁₅C as neutron absorber. The minimum target of the control rod worth was chosen comparing with that for ABWR. The number of control rods should be kept fewer or equal to the number of water rods that serve as control rod guide in the fuel assembly. Because the inner width of the water rod is about 3 cm, the diameter of the control rods cannot exceed 3 cm. To achieve the target worth under the conditions, number of control rods per fuel assembly and the radius were chosen.

The result shows that the radius of the control rods should be greater than 0.6 cm and that 16 or more control rods are necessary per fuel assembly. (Fig. 7) We selected that the radius of control rods is 0.6cm and the number of control rods is 16, according to the results of the equilibrium core design.

2. Fuel design

In order to make it that the position of the radial peaking does not change through the cycle, we designed the k-infinity of fuel to carry out monotonous reduction.

To reduce the axial power peaking, we made two designs. One is based on the technique “Axial Gd₂O₃ concentration distribution zoning”, another is based on the technique...
“Axial U-235 enrichment zoning”. These two techniques are popular in BWR fuel design.

Figure 8 shows the 1/4 sectional cross section view of the fuel A and enrichment axially distribution. This design is based on “Axial Gd$_2$O$_3$ concentration distribution zoning”.

In fig.8 circled number 1 is UO$_2$ rod, hatched circled number G1 is Gd rod which contains 10wt% Gd$_2$O$_3$ over the total length, and hatched circled number G2 is Gd rod which contains 10wt% Gd$_2$O$_3$ in the lower half and 1wt% Gd$_2$O$_3$ in the upper half. Number difference of 10wt% Gd$_2$O$_3$ rods in upper and lower zone is selected for the flattening of the axial power distribution. The 1wt% Gd$_2$O$_3$ rods in upper zone are used for the improvement of the shutdown margin at the beginning of the cycle.

Figure 9 shows the combustion change in the infinite multiplication factor. In fig.6 the solid line is the combustion change of the infinite multiplication factor in the upper part of the fuel, the dashed line is the combustion change of the infinite multiplication factor in the lower part of the fuel. Also the combustion change in a typical infinite multiplication factor of the BWR fuel is shown in a dot line for the comparison in fig. 9.

Higher one than that of a BWR fuel typical the infinite multiplication factor in BOL is a feature of the SCPR fuel.

The device of this feature and the loading pattern, which is mentioned in section 3, reduces the radial direction power peaking factor. The combustion change in a monotonous infinite multiplication factor suppresses the change of the power peaking factor generation position.

Figure 10 shows the 1/4 sectional cross section view of the fuel B and enrichment axially distribution. This design is based on “Axial U-235 enrichment distribution zoning”.

In fig.11 circled number 1 is UO$_2$ rod, hatched circled number G1 is Gd rod, which contains 10wt% Gd$_2$O$_3$ over the total length. UO$_2$ rod is divided three zones (top, middle and bottom).

Top zone has 1/6 length of active fuel length. U-235 enrichment of the top zone is lower than the middle zone and same as the bottom zone. We have set the length and the enrichment of top zone for the shutdown margin improvement.

Middle zone has 5/12 length of active fuel length. U-235 enrichment of the middle zone is 0.5wt% higher than
another zone. We have set the length and the enrichment of middle zone for the axial power shape improvement.

Fuel A and B have almost same nuclear property. So we will show core performance in next paragraph, which was composed of fuel A.

3. Core design
We set the core design condition as follows:
- Thermal power: 2273MWt
- Electric generating power: 1000MWe
- Reactor core flow: 1157kg/s
- Average discharge burn-up: 45GWD/t
- About three batches
- The channel flow division group is three and the flow distribution is constant during the cycle.

Figure 11 shows the 1/4 cross-section view of loading pattern of equilibrium core. In fig. 11 each mass shows one fuel assembly and 1 is the first cycle fuel, 2 is the second cycle fuel, 3 is the third cycle fuel, 4 is the fourth cycle fuel. For the radial power distribution flattening, we charged the first cycle fuels, which have highest reactivity, in the most outer core, like PWR’s zone loading.

And we charged the second cycle fuel & the third cycle fuel like the corridor.

We show the combustion change of maximum linear heat generation rate (MLHGR) and Peaking axially in fig. 12. In fig. 12, we can see the MLHGR is less than 45kW/m through the cycle.

We show the combustion change of outlet temperature of moderator (highest, centimeter degree) and Radial Peaking in fig. 13. We can see the highest outlet temperature of moderator is less than 580°C and Radial Peaking is less than 1.27. Variation of the highest outlet temperature of moderator during cycle is less than 30 degrees C. Variation of the Radial Peaking during cycle is less than 0.1.

We show the axial power distribution (core average) in fig. 14. In fig. 14, solid line is axial power distribution at
beginning of cycle (BOC), dotted line is one at middle of cycle, and dashed line is one at end of cycle (EOC). Axial power distribution at beginning of cycle (BOC) has a large bottom peak because of part insertion control rod and water density distribution. Axial power distribution at middle of cycle (MOC) has two peaks and is relatively flat. Axial power distribution at end of cycle (EOC) has a large top peak because of reaction of axial power distribution and control rod fully withdrawn.

**Fig. 12** Combustion change of Maximum linear heat generation rate and Axial peaking

**Fig. 13** Combustion change of Outlet temperature of moderator (highest) and Radial peaking

**Fig. 14** Combustion change of Axial power distribution

IV. Conclusion

The equilibrium core of SCPR could be designed, which satisfies the design criteria of BWR. The prospect that the radial power peaking could be reduced was acquired.

Building the new thermal hydraulic module into the 3D core simulator for BWR could make the reactor core simulator for supercritical water-cooled reactor.

**Nomenclature**

Nothing

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