JAPANEASE SCWR FUEL AND CORE DESIGN STUDY

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Abstract

A study on design of fuel and core for a Japanese Supercritical Water-cooled reactor (JSCWR) was carried out The SCWR core and fuel characteristics have been studied with a 3D core simulator which is based on a 3D BWR core simulator, because SCWR core characteristics strongly depend on fuel loading pattern and control rod patterns. Maximum cladding surface temperature (MCST) has been evaluated by a subchannel analysis code, because MCST depends on coolant flow distribution and local power distribution in a fuel assembly. The fuel assembly concept that is suitable for the JSCWR is developed. A radial enrichment distribution, an axial enrichment zoning in the fuel assembly, a fuel loading pattern and an orifice pattern that satisfy the core design criteria and its MCST targets were studied. Other characteristics (maximum linear heat generation rate, shutdown margin, etc.) and MCST were also studied. Engineering uncertainties were considered for the evaluation of MCST . It was shown that the highest MCST satisfied the design target with 99.99% probability and 95% confidence limits.

1. Introduction

Supercritical Water-cooled Reactor (SCWR), it was chosen as one of the next generation nuclear systems by Generation-IV International Forum (GIF) in September 2002. [1] The SCWR operates above the thermodynamic critical point of water (374^{o}C, 22.1MPa). The key advantages over the current light water reactors (LWRs) include high thermal efficiency and system simplicity. In Japan, the SCWR system has targets such that the coolant pressure is 25MPa, and the coolant temperature is 290^{o}C at the core inlet and 510^{o}C at the core outlet in the reactor. Several designs of the Japanese Supercritical Water-cooled Reactor (JSCWR) core and fuel were studied to meet requirement of higher economical advantage and higher reliability [2, 3]. But they assumed the coolant temperature distribution was flat in the fuel assembly, and had not considered any statistically change of MCST with engineering uncertainties. In this study, engineering uncertainties were considered. Statistical variation could MCST by tens of degrees from nominal condition, make the design for fuel and core more difficult. Thus we aim to clarify the relationship between CST (Cladding Surface Temperature) and an axial power distribution. Then we aim to clarify the relationship between CST and radial power distribution in fuel assembly.

First, we mention the fuel and core concept that are suitable for JSCWR. Second, we mention axial enrichment zoning and radial enrichment distribution that satisfies the MCST design criteria, as well

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as other core design conditions. Third, we mention the equilibrium core design and its characteristics. Last, we mention the items of engineering uncertainties and their variation ranges, and the consequent change of MCST which was clarified in this study. The highest MCST value experienced during the fuel lifetime (We call it "Highest MCST") was evaluated based on this result.

2. Axial enrichment zoning and radial enrichment

2.1 Axial enrichment zoning

Because supercritical water is single phase flow, the boiling transition does not occur. However the heat transfer deterioration occurs, which could make cladding surface temperature, high. We must pay attention to the influence of the axial power distribution to cladding surface temperature (CST). CST cannot be estimated correctly without subchannel analysis, because CST depends not only on power distribution but also on coolant flow distribution around fuel rods. Thus, to study the axial power distribution effects on the fuel clad surface temperature, we used the subchannel analysis code for SCWR, named "SILFEED-SC", that is based on subchannel analysis code for BWR "SILFEED" [5].

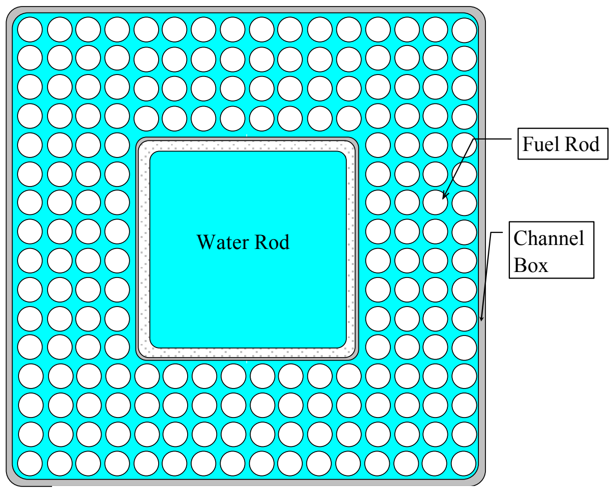

Figure 1 Horizontal cross sectional view of a fuel assembly

The horizontal cross sectional view of the fuel assembly is shown in Figure 1. The vertical cross sectional view of the fuel assembly is shown in Figure 2. The bundle has a channel box that isolates the coolant flow and prevents the cross flow between fuel assemblies. The fuel rods are arranged 16x16 square lattices. There is a large square water rod that has the area equivalent to 8x8 fuel rods in the centre of the fuel assembly. So, there are 192 fuel rods in the fuel assembly. The channel box, water rod and fuel rods are made of stainless steal.

The coolant flow in the fuel assembly is shown in Figure 2. A part of coolant flows through the "out-channel" that is the area outside of channel box, and through the water rod subsequently. Then it is mixed with another part of flow that comes from core bottom directly. Finally they flow through the channel between fuel rods and cool fuel rods.

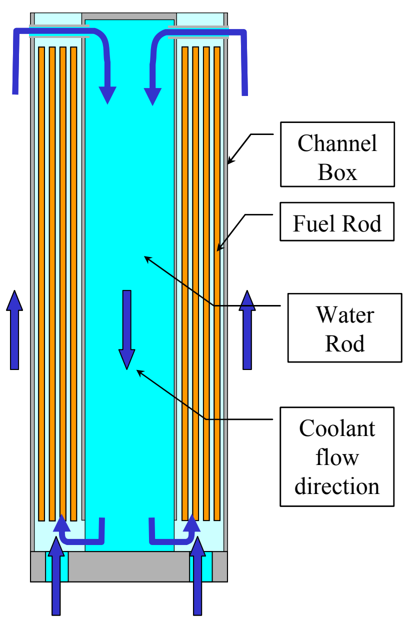

Figure 2 Vertical cross sectional view of a fuel assembly

To decide the axial enrichment zoning, we have clarified the relationship between CST and axial power distribution as summarized below [6].

1) It is necessary to avoid the peak position between 50cm and 100cm from the core bottom so as not to cause the heat transfer deterioration.

2) It is desirable to control the axial power peak position below 3m from the core bottom.

3) Bottom peak axial power distributions are better than top peak axial power distributions in the viewpoint of the CST decrease.

4) It is necessary to match power and coolant flow of a fuel assembly

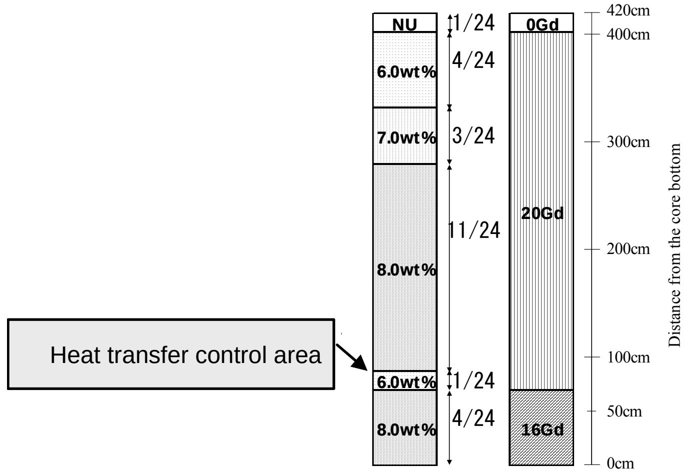

Figure 3 Axial enrichment zoning

To achieve the bottom peak axially power distribution as well as to avoid the peak position between 50cm and 100cm from the core bottom, we introduced “heat transfer control area” (refer to Figure 3) which has slightly lower enrichment than that in the neighbour zones. Based on BWR fuel design technology, we determined the axial enrichment zoning and Gd rods distribution. To avoid the top peak power distribution, we use the higher enrichment in bottom zone than top zone. We use a natural uranium top blanket. We introduce “Heat transfer control area”. The heat transfer control area is a low enrichment zone between 70cm height through 90cm height. It can reduce the axial power peak and cladding surface temperature. We reduce 20 Gd rods to 16 Gd rods in a zone under the heat transfer control area. Gd concentration in these rods is 12 wt%

3. Radial enrichment distribution

Next, we study the relationship between CST and the radial power distribution in fuel assembly (we call it “local power distribution”). In this study, we know that the flat local power distribution does not make the flat CST distribution. The flat CST distribution makes MCST lowest. Therefore, we search local power distribution that makes the flat CST distribution [4,6].

Using subchannel analysis code, we evaluated the relations between local powers and CST. Those relations have local position dependency. Using

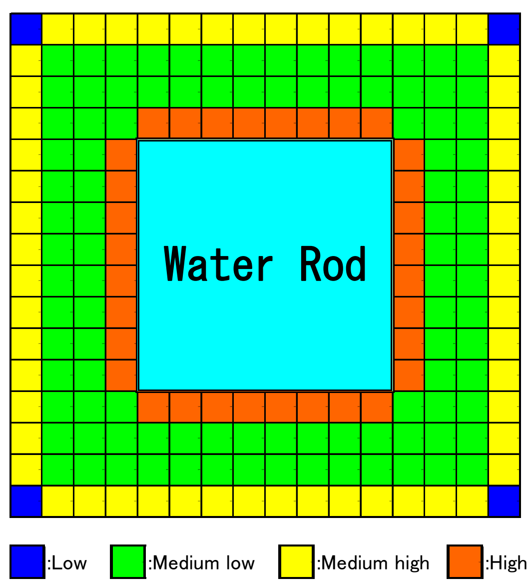

Figure 4 Target local power distribution

those relations, we search the local power distribution that makes the flat CST distribution. Figure 4 shows the local power distribution that makes the flat CST distribution. We call it the target power distribution. In this figure, each square means fuel rod. Corner rod has low power and the rods that faced the water rod have high power. Using the lattice analysis code which is based on BWR lattice analysis code, we calculated the radial enrichment distribution that makes the target power distribution.

Figure 5 shows the radial enrichment distribution that makes the target power distribution. It is easy to obtain the target local power distribution at one burn-up point. But it is required to obtain the target local power distribution while bundle exposure is 0GWd/t through 35GWd/t. So we have studied Gd rod position and enrichment distribution at same time. Figure 6 shows the Gd rod position and an enrichment distribution.

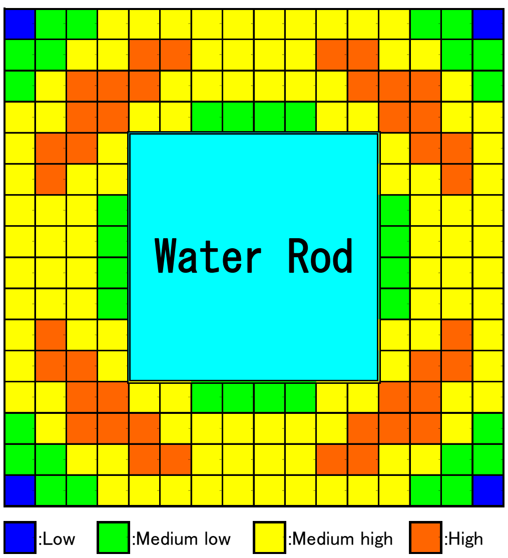

Figure 5 A radial enrichment distribution (no Gd)

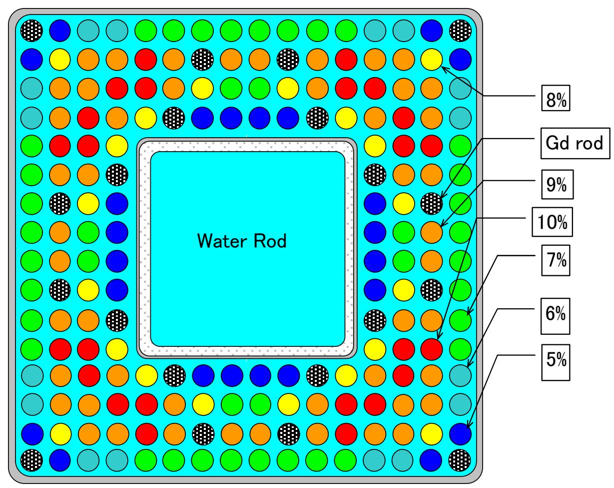

Figure 6 A radial enrichment distribution (with Gd)

4. Equilibrium core design

4.1 Method

The 3D simulator for BWR in Toshiba Corporation 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. On the viewpoint of nuclear module, the neutron spectrum of the supercritical water-cooled power reactor is similar to that for BWRs. There is no concern about applying Toshiba BWR core simulator to SCWR neutronics, though the supercritical water-cooled reactor of U enrichment is higher. On the viewpoint of thermal hydraulic module, there are many differences between BWR and SCWR. 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 modelled with the latent heat. So, A 3D core simulator for SCWR has been newly built by incorporating thermal hydraulic module for SCWR into a BWR core design code in Toshiba Corporation.[4,6] Based on BWR core design technology, we designed the equilibrium core of SCWR. The CST strongly depends on a bundle power and coolant flow rate. Therefore we have to make a fine channel flow division group. Then we have controlled the bundle power changes within 7% using the fuel loading pattern and the control rod patterns through the operation cycle.

4.2 Design

The design conditions are summarized in Table 1. Thermal power is designed for 1700MWe electric output. (Thermal efficiency: 42.7%) Power density is almost same as PWR's one and twice of BWR's one. It is designed for economy improvement of SCWR. Average discharge exposure is as same as BWR's one in JAPAN. Moderator temperature is 290°C (core inlet) and 510°C (core outlet). Moderator enters from the bottom side of core, flows out from the top of the core. There is also no recirculation system in the reactor. So the flow in the core is very simple. The channel box and cladding are made of improved stainless steal. MCST target is decided from material study. MLHGR and SDM are designed from BWR's design targets.

Figure 7 shows the cross sectional view of loading pattern of an equilibrium core. In Figure 7, each cell shows one fuel assembly and the numbers in the cells stand for the fuel's cycle, namely 1 is for the first cycle fuel, 2 for the second and so on. For the radial power distribution flattening, the first cycle fuels, which have the highest reactivity, are loaded in the most outer region of the core. The second cycle fuel and the third cycle fuel are loaded like a checkerboard.

Figure 8 shows the cross sectional view of flow distribution pattern of an equilibrium core. In figure 8, each cell shows one fuel assembly and the numbers in the cells stand for the flow group, from No.1 with lowest ratio to No. 10 with the highest. For the MCST decreasing, 10 flow groups are used. The flow distribution is very complex.

Table 1 Core design condition

Parameter	Value
Thermal power	4049MWt
Power density	110MW/m^3
Reactor core flow	2106kg/s
Average discharge exposure	45GWd/t
Cycle exposure	15GWd/t
Channel flow division group	10
Channel flow distribution	Constant in cycle
Assemblies	372
Control rods	87
Average linear heat generation rate	13.5kW/m
Moderator Temperature	290°C
Core inlet	510°C
Core outlet	25MPa
System pressure	316SS
Channel box and cladding	
material	700°C or
Design targets	less
MCST*	40kW/m or
MLHGR**	less
	1%δk or
SDM***	more

* MCST: Maximum Cladding Surface Temperature
** MLHGR: Maximum Linear Heat Generation Ratio
*** SDM: Shutdown Margine

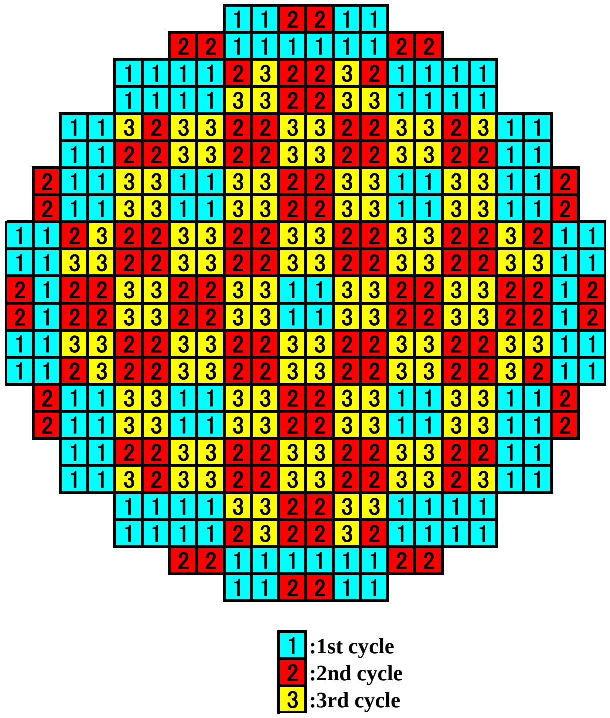

Figure 7 Equilibrium core loading pattern
(Full core)

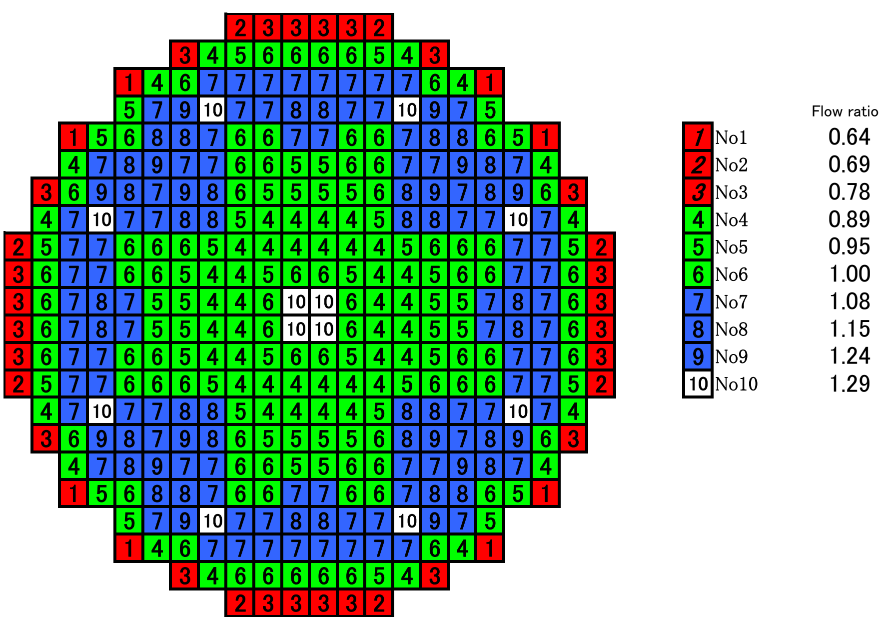

Figure 8 Equilibrium core flow distribution pattern (Full core)

4.3 Characteristics (Nominal Value)

Figure 9 shows the dependencies of the equilibrium core's k-infinity to the water density at the beginning of operating cycle (BOC) and the end of operating cycle (EOC). It is understood that k-infinities increase as the water density increasing. This means that the moderator density coefficient is positive and the power coefficient is negative.

Figure 10 shows excess reactivity change. Excess reactivity at the beginning of cycle is about 4.2%δk. Although it is larger than that in the conventional BWR design, it can be controlled by using control rods.

Figure 11 shows the shutdown margin (SDM) change. SDM meets the design criteria (1%δk or more).

Figure 12 shows the burn-up change of MLHGR. The MLHGR changes mainly due to control rod operation, and is less than 38.5kW/m through the cycle.

Figure 13 shows the burn-up change of MCST. The MCST does not change due to control rod operation, and is less than 610 °C through the cycle. (MCST is calculated by subchannel analysis code[6]).

Figure 14 shows the burn-up change of an axial power distribution. In this figure, BOC means the beginning of operation cycle, MOC means the middle of operation cycle, EOC means the end of operation cycle. The axial power distribution changes due to control rod operation, and has almost bottom peak shapes through the cycle. And the heat transfer control area works well through the cycle.

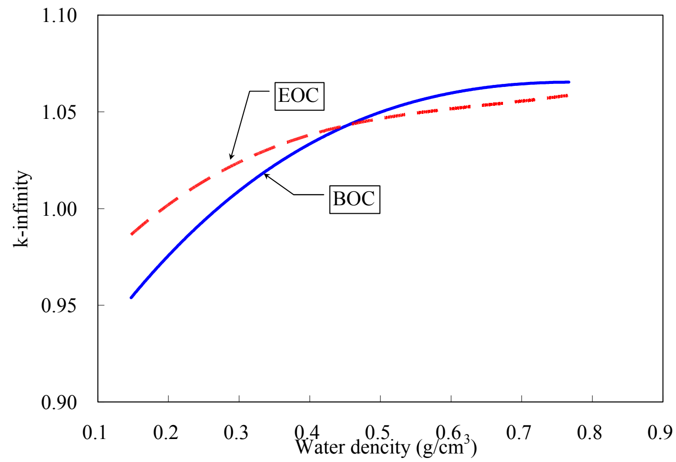

Figure 9 Dependencies of k-infinity to water density at BOC &EOC

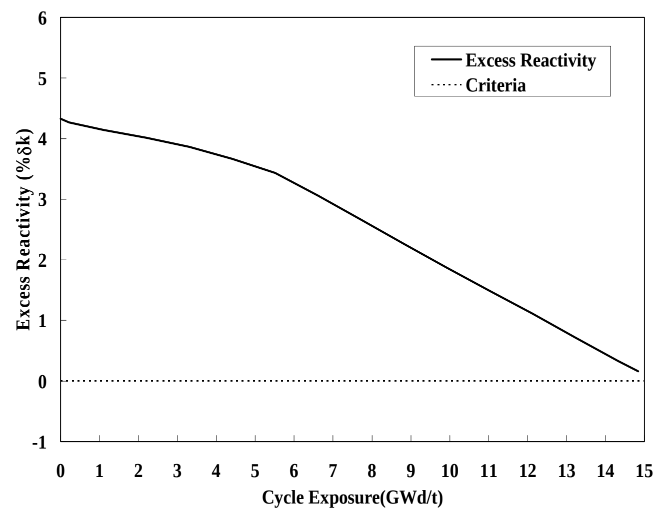

Figure 10 Excess reactivity

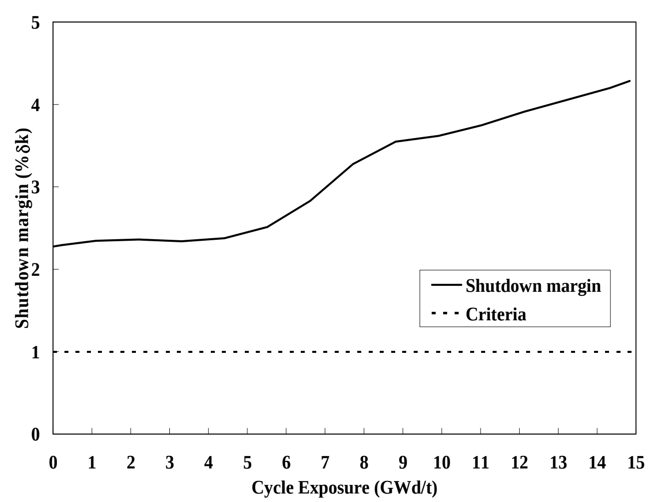

Figure 11 Shutdown margin (SDM)

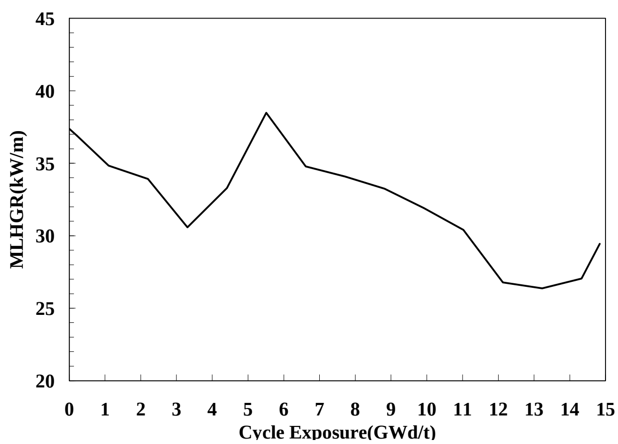

Figure 12 Maximum linear heat generation rate (MLHGR) change

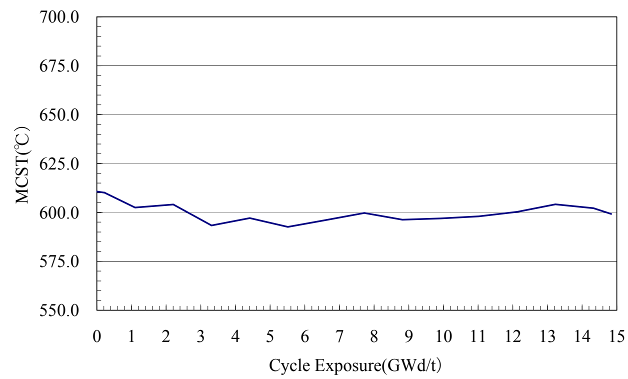

Figure 13 Burn-up change of Maximum cladding surface temperature (MCST) calculated by subchannel analysis

5. Subchannel analysis and statistical thermal design

In order to evaluate the MCST under normal operating condition with engineering uncertainties, the statistical thermal design procedure is incorporated into the Univ. Tokyo's subchannel analysis code and applied to the JSCWR introduced in the previous section.

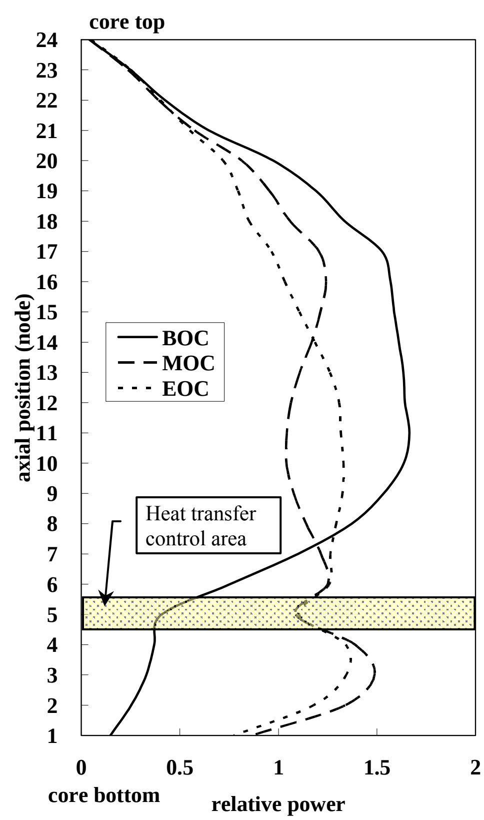

Figure 14 Axial power distribution change

5.1 Statistical thermal design procedure

The statistical changes in the parameters (see Table2) are randomly sampled and used as the input data set of the subchannel analysis. Next, the MCST is calculated in each case. The average value (T_{ave}) and the standard deviation (σ_s) of the calculated MCSTs are obtained by the results. The parameters and their uncertainty values are mostly taken from those of current light water reactors.

Upper limit of 95% confidence interval of T_{ave} and σ_s are calculated.

$$T_{ave95} = T_{ave} + t_{5\%} \frac{\sigma_s}{\sqrt{n}}$$

$$\sigma_{s95} = \sqrt{\frac{n-1}{\chi^2_{95\%}}} \sigma_s$$

Where: n :Sample number
$t_{5\%}$: 5% point of t distribution
$\chi^2_{95\%}$: 95% point of χ^2 distribution

Based on the recommendation from the thermal-hydraulics and safety group, Dittus-Boelter's correlation is applied to predict heat transfer coefficient. Its standard deviation against the existing experimental data is 11.3%. The Ishigai's correlation is applied to predict the friction coefficient Its standard deviation against the existing experimental data is 17.5%[11]. The standard deviations of the MCST caused by those correlation uncertainties are calculated as σ_h and σ_f , respectively.

Finally, the MCSTs with 99.99% probability (from the normal distribution table, Reverse-cumulative probability value is 3.719) and 95% confidence level ($T_{95/99.99}$) are evaluated as follows.

$$T_{95/99.99} = T_{ave95} + 3.719\sqrt{\sigma_{s95}^2 + \sigma_h^2 + \sigma_f^2}$$

5.2 Statistical thermal design results

The nominal MCSTs are calculated first for all the fuel bundles at all the burn-up steps. Among approximately 1500 cases, the "top 6" cases of the MCST are identified. The statistical thermal design procedure is applied to the "top 6" cases. The results are shown in Table 3 and Figure.15 The highest value of $T_{95/99.99}$ is 696.5^{o}C and it is higher than the highest nominal MCST by about 85^{o}C. We call the highest $T_{95/99.99}$ the "highest MCST"

There are 72000 fuel rods in the JSCWR. The probability of the MCST exceeding the predicted the "highest MCST" is 2.9x10^{-7}/cycle. In case of 60 year plant lifetime, only one fuel rod is expected to have "beyond the highest MCST" in the plant lifetime.

Table 2 Change of each parameter considered by statistical heat design

Parameter	Standard deviation	One-side width
Thermal power	1%	2σ

Feed water temperature	0.6°C	2σ
Feed water flow rate	0.5%	2σ
Radial peaking factor	1%	2σ
Axial peaking factor	1%	2σ
Local power distribution	A set of local power distribution is selected at random from 72 candidates	
Flow distribution among fuel bundles	0.9%	2σ
Flow rate ratio to water rods over total flow rate	3%	2σ
Sub channel area Fuel rod diameter Fuel rod displacement Direction of fuel rod displacement	 333μm 333μm Random in 0-2π	 3σ 3σ -
Other enthalpy rise hot spot factor	0.048	3σ
Other film temperature rise hot spot factor	0.048	3σ

Table 3 Statistical thermal design results for JSCWR

Case No.	1	2	3	4	5	6
Rank of nominal MCST	Highest	2nd	3rd	4th	5th	6th
Nominal MCST (°C)	610.7	610.1	608.8	608.5	608.1	608.0
Sample size	2500	2500	2500	2500	1599	1672
Average MCST (°C)	**618.1**	**617.4**	**613.7**	**616.1**	**615.7**	**615.6**
95% upper confidence limit of average MCST (°C)	**618.6**	**617.9**	**614.2**	**616.6**	**616.4**	**616.2**
Standard deviation σ_s (°C)	16.1	16.1	16.1	16.0	16.4	16.1
95% upper confidence limit of standard deviation σ_{s95} (°C)	16.5	16.5	16.5	16.4	16.9	16.6
Maximum MCST (°C) for sampled cases	682.6	682.0	670.3	680.5	681.8	679.7
σ_h(°C)	12.8	12.6	12.1	13.0	11.3	12.8
σ_f (°C)	1.7	1.7	1.4	1.7	1.8	1.7

$3.719\sqrt{\sigma_{s95}^2+\sigma_h^2+\sigma_f^2}$	77.9	77.5	76.3	78.1	75.9	78.2
95%/99.99% limit (^{o}C)	696.5	695.4	690.5	694.7	692.3	694.4

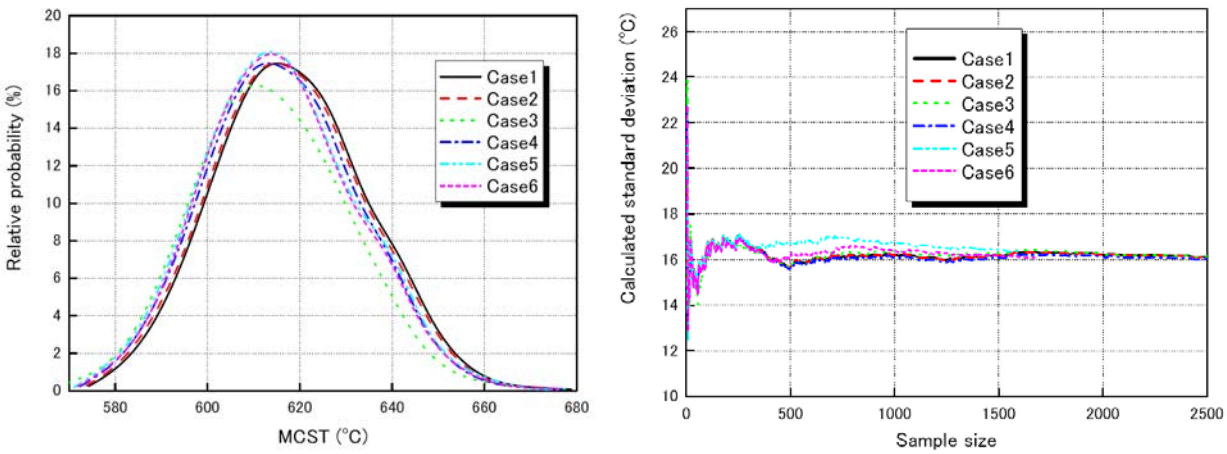

Figure 15 Distributions of MCSTs and convergences of standard deviations for JSCWR

6. Conclusion

We obtained the JSCWR fuel and core design that satisfy the design criteria in nominal condition. The MCST with 99.99% probability and 95% confidence level was calculated by the subchannel analysis and statistical thermal design procedure. As the "highest MCST" was below 700^{o}C, it supports the viability of the fuel and core design of the JSCWR.

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