Analysis of Core Cooldown Performance According to the High Burnup Fuel Deformation Modeling

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1. Introduction

The discharge burnup of UO_2 fuel assemblies (FAs) from domestic pressurized water reactors (PWRs) has been gradually extended to 60 GWD/MTU [1]. Therefore, it is necessary to evaluate the core cooling performance in case of the design basis accidents, considering the changes of cladding properties under high burnup conditions [2].

In the previous study, an evaluation was conducted on the fuel rod deformation and cooldown performance of the high burnup fuel for the DBAs in relation to the acceptance criteria for the performance of the emergency core cooling system of the PWR [3]. For the study, APR1400 was selected as the reference plant. APR1400 input model has been developed using one-dimensional thermal-hydraulic system code, MARS-KS 1.5 [4], considering the high burnup fuel distribution and deformation of the actual fuel rods in the range of 0-60 GWD/MTU burnup.

In this study, the developed MARS-KS input model was improved in the aspect of core modeling to evaluate the cooldown performance conservatively for the condition of high burnup fuel, and analysis of large break loss of coolant accident (LBLOCA) was performed for the APR1400 reference plant. In addition, a sensitivity analysis of the core fuel damage was performed considering sensitivity parameters affecting the cladding rupture.

2. Methods and Results

2.1 Analysis of Core Cooldown Performance using Multiple Fuel Rod Modeling

LBLOCA analysis of the APR1400 with the core at the end of cycle (EOC) condition of Shin-Kori-unit 3 was performed using the improved core model. APR1400 LBLOCA nodalization of the MARS-KS code is shown in Fig. 1. The cooldown performance of the core was analyzed assuming the initial and boundary conditions of full-power normal operation, a double-ended break of the cold-leg in LOOP-A (C395, C396), and the ANS 79-1 decay heat curve as presented in the final safety analysis report of Shin-Kori Units 3 and 4 [5].

2.1.1 Fuel Rod Swelling and Rupture Model

Basic core fuel swell and rupture model of the 241 full core FAs was simulated in the previous studies [3] in accordance with the thermal and hydrodynamic multi-channel grouping method based on the 30 GWD/MTU burnup considering the power and burnup distribution. The core is hydraulically composed of two average channels (C220, C221) and two hot channels (C230, C231) as shown in Fig 2. The average channels C220 and C221 components include 142 and 97 FAs respectively, and each hot channel C230 and C231 components include one fuel assembly. To reflect the actual core flow phenomena, the cross flow between the average and hot channels and between the average channels in each group was simulated using multi-junction components [3]. For the conservative analysis, the fuel rod of each channel was simulated as a specific rod by selecting the one with the highest power peaking factor with the same burnup. The numbers of specific rods for C220, C221, C230, and C231 are 7, 8, 9, and 4, respectively, assigning the rods from the highest peaking factors in each average and hot channel. Other fuel rods were simulated as lumped rods in each channel.

The head loss due to core flow area change by swell and rupture of fuels was implemented to hydraulic channels C220, C221, C230, and C231 using the concept of flow blockage model in accordance with the thermal and hydrodynamic multi-channel grouping method based on the 30 GWD/MTU [3]. In order to simulate the flow path deformation of the core due to fuel rod swell and rupture, as shown in Fig. 3, the flow path between nodes 12 to 13 of each core channel is connected with valves. The flow blockage and hydraulic loss of the contraction part are simulated by the change in the valve area according to the change in the outer diameter of the cladding, which is determined by the cladding deformation model of the MARS-KS code. A single junction (sj295, 296, 297, 298) was added between nodes 13 to 14 of each core channel to simulate the change in flow rate through the loss coefficient of the extension part according to the change in valve area between nodes 12 and 13.

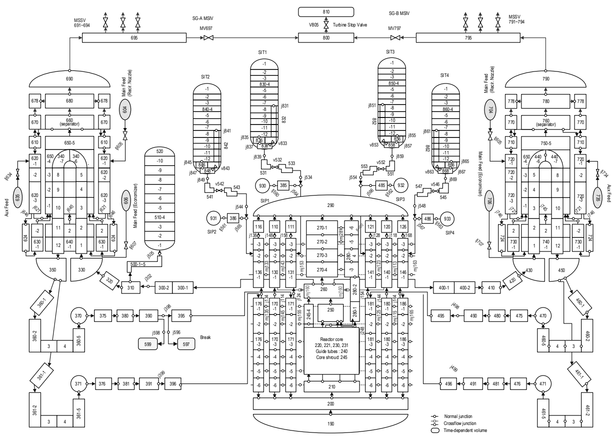


Fig. 1. MARS-KS nodalization for LBLOCA of APR1400

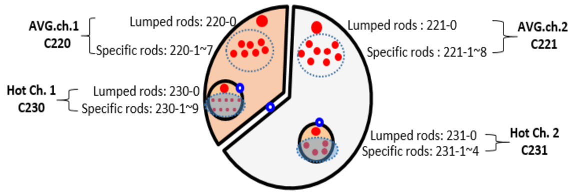


Fig. 2. Grouping of multiple fuel rod

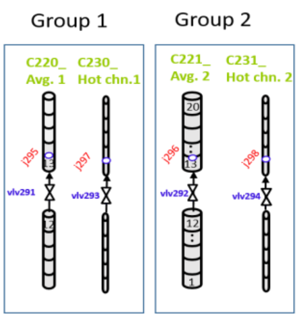


Fig. 3. Core flow path modeling

2.1.2 *Core Cooldown Performance Analysis Result*

Figures 4 and 5 show the flow rate according to core flow area change and cladding temperature due to swell and rupture of the fuel rod during a postulated LBLOCA accident of the APR1400. As the coolant is discharged through the broken part, the RCS flow decreases and the gap pressure increases along with the expansion of the fuel rod until the reflood period when the safe injection water is injected into the core, and the cladding expands accordingly. The core flow path area is reduced due to an increase in the outer diameter of the cladding, which leads to an increase in the cladding temperature due to a decrease in the coolant flow rate.

In the fuel rod of channel 230-9, the flow path area decreases rapidly along with the expansion of the cladding and, as shown in Table 1, the flow path blockage rate is 68.3% in 45.4 seconds, and the fuel rod ruptures first. Afterward, other fuel rods were ruptured in the same channel.

The flow rate of the hot channel 230 with the largest reduction in the flow path area approaches 0 kg/s as the accident progresses. After that, 1131.2 K reflood PCT occurred at 84 seconds after the accident. This is about 240 K higher than the peak cladding temperature shown in the 231-3 specific rod, which is the highest peak cladding temperature among group 2.

Fig. 6 shows the peak local cladding oxidation (PLO) changes of fuel rods for each channel. The local cladding oxidation of the 230-9 specific rod, which is the hot channel 1 of the low burnup group with high power peaking factor, increases the most (Fig. 6-b). The change in cladding oxidation of the high burnup group 2 fuel rods (HS 221, 231) was insignificant compared to that of the group 1 due to the relatively small power peaking factor.

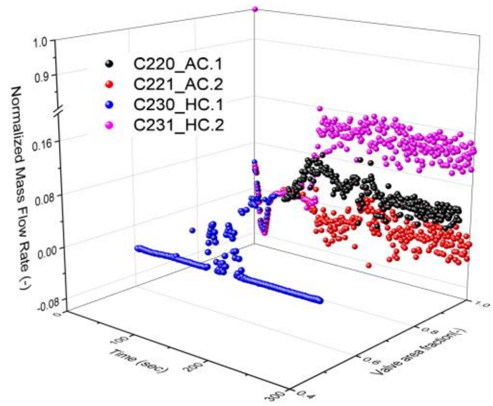


Fig. 4. Flow rate according to core flow area change

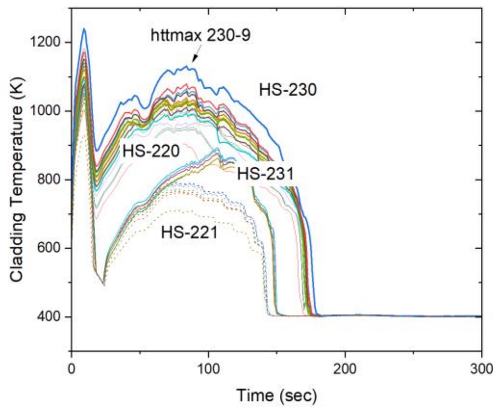
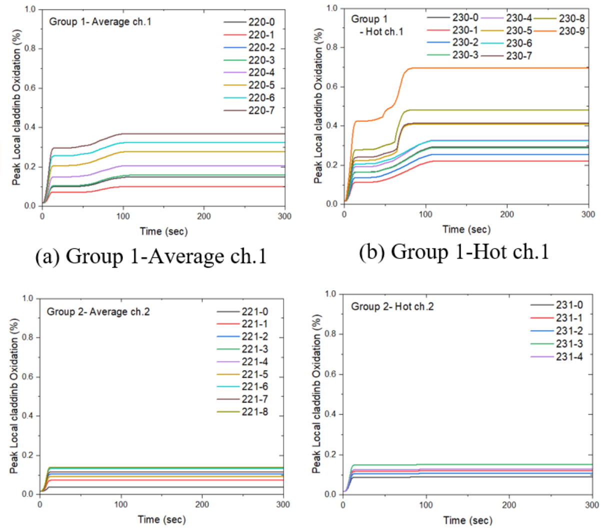


Fig. 5. Cladding temperature

Table 1. Rupture of fuel rod and channel blockage

Burnup, GWD/MTU	Heat structure ID	Ruptured time, sec	Channel Blockage, %
30	230-9	45.4	68.3
30	230-8	61.5	67.6
25	230-5	64.6	68.6
20	230-7	64.6	66.9



(a) Group 1-Average ch.1 (b) Group 1-Hot ch.1

(c) Group 2-Average ch.1 (d) Group 2-Hot ch.2

Fig. 6. Peak local cladding oxidation

2.2 Sensitivity Analysis

Sensitivity analysis with respect to the fuel rod damage was performed for the core modeling method considering the effect of fuel rod burnup. For sensitivity analysis, as shown in Table 2, multiple fuel rod inputs were generated first according to the thermodynamic modeling of the core and the grouping method based on the power and burnup conditions [6], and then the sensitivity analysis was performed.

2.2.1 Selection of Sensitivity Parameters

For the sensitivity analysis of the fuel rod rupture fraction according to the core modeling method, three kinds of sensitivity parameters were selected as shown in Table 2.

To assess the effect of the thermodynamic modeling by the heat structures connected to each flow channel, the number of specific rods of the average and the hot channel in group 1 were chosen as parameter 1. The number of specific rods of each channel of group 1 was changed to 5, 7, and 9 (HS-A/H1-#).

Parameter 2 is the case of changing the core power between groups according to the number of fuel rods by changing the reference burnup within the range of 25 ~ 45 GWD/MTU during grouping (G-#BU).

Parameter 3 relates to the uncertainty of the core flow blockage model. The flow blockage multiplier ζ used in the model is changed in the range of 0.0 to 1.5 (ζ- #) for the G-45BU case[3].

For each case, the cooldown performance was evaluated by analyzing the peak cladding temperature, the number of ruptured fuel rod, and the peak local cladding oxidation.

Table 2. Sensitivity parameters for the fuel rod rupture fraction

	Sensitivity parameter (Case)	Range
Parameter 1	No. of spcific rod (HS - A/H1 - #)	Average channel 1 : 5, 7, 9
		Hot channel 1 : 5, 7, 9
Parameter 2	Reference burnup (G - # BU)	25 ~ 45 (GWD/MTU)
Parameter 3	Flow blockage multiplier (ζ - #)	0.0 ~ 1.5

2.2.1 Sensitivity Analysis Result

Sensitivity analysis results are shown in Figures 7-9.

When analyzing the core thermal modeling sensitivity with the change in the number of specific rods, the peak cladding temperatures of 1152.8 K and 1152.7 K were calculated, respectively, in the case of selecting a large number of specific rods in the average channel (HS–A1–9) and selecting a small number of specific rods in the hot channel (HS-H1–5). The result showed 154 and 155 fuel rods were ruptured, respectively.

In the sensitivity analysis using parameter 2, the highest peak cladding temperature of 1209.9 K and rupture of 243 fuel rods were calculated when grouping up to 45 GWD/MTU, which is the largest reference burnup (G – 45BU). It is evaluated that high peak cladding temperature is determined because of the increase of cross-flow due to high power within the same group for the case of grouping by the high burnup.

In the case of sensitivity analysis of the flow blockage multiplier ζ, the highest peak cladding temperature and the largest number of ruptured fuel rods were calculated for the case when ζ was 1.0.

Through the sensitivity analysis for the core cooldown performance by the thermal and hydrodynamic core modeling method, the most conservative result was obtained when grouped with a high burnup of 45 GWD/MTU (G-45BU). This result shows a difference in peak cladding temperature of about 143 K and rupture of up to 242 fuel rods compared to the most non-conservative sensitivity case. Fig. 9 shows the peak local cladding oxidation change corresponding to each sensitivity analysis. The peak local cladding oxidation showed the highest oxidation degree in the case G-45BU with the same trend as peak cladding temperature and fuel rod rupture rate.

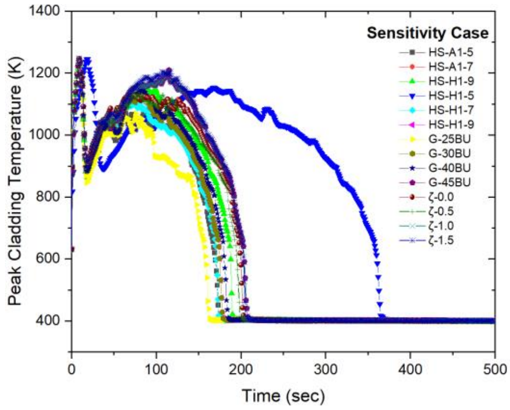


Fig. 7. Peak cladding temperature

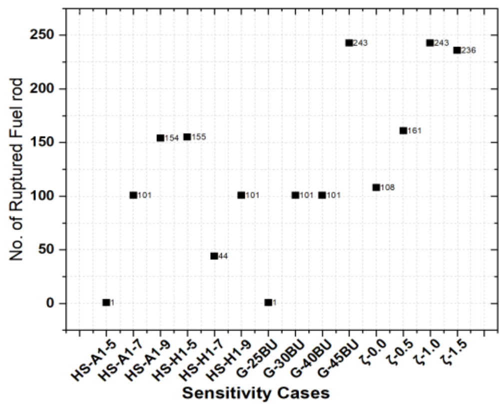


Fig. 8. Number of ruptured Fuel rod

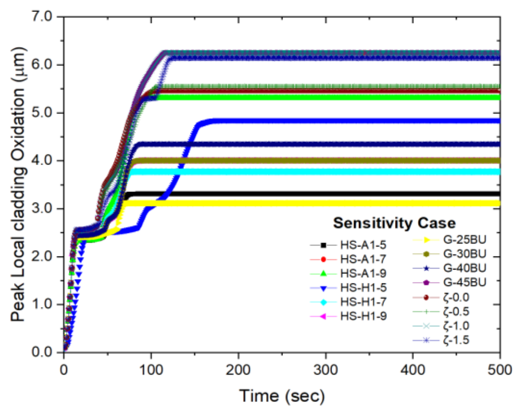


Fig. 9. Peak local cladding oxidation

3. Conclusions

The MARS-KS-based 1D hydrodynamic core model was improved by using the core design data under the EOC condition of Shin-Kori Unit 3 in the range of 0 to 60 GWD/MTU burnup as well as considering the burnup distribution and deformation of fuel rods. The core cooldown performance was evaluated through the APR1400 LBLOCA analysis, and a PCT of 1131.2 K was determined for the fuel rod with the highest power peaking factor of the low burnup group with high power. And the sensitivity analysis was performed according to the core modeling method considering the burnup effect during the LBLOCA analysis. Three kinds of sensitivity parameters were selected to find more conservative modeling scheme. The number of specific rods in the channel, the reference burnup for grouping, and the channel blockage multiplier considering the uncertainty of the model were selected as the sensitivity parameters and evaluated the core cooldown performance for each case. As a result, in the case of grouping based on 45 GWD/MTU, the largest cladding expansion, flow path contraction, and many fuel rod ruptures were calculated, which determined the highest peak cladding temperature and peak local cladding oxidation.

In the next step, the core cooldown performance evaluation will be performed using multi-dimensional core modeling through the application of the MARS-KS multi-dimensional core thermodynamic model that applies the multi-dimensional phenomena due to the deformation and flow of fuel rods under high burnup conditions.

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