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Evaluation on Effect of Heat Transfer Change by Cr-coated Cladding for Large Break-Loss of Coolant Accident

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1. Introduction

After Fukushima accident in 2011, issues on hydrogen generated by oxidation reaction of cladding based Zr have been brought out. Therefore, concepts of Accident Tolerant Fuel (ATF) were suggested to enhance integrity of fuel and reduce hydrogen generation on BDBA (Beyond Design Basis Accident) and severe accident. The researches for various ATF have been widely conducted worldwide. The Cr-coated cladding, Cr-doped UO2 pellets, FeCrAl cladding, SiC cladding, etc. are mainly taken into account as ideas of ATF [1]. Among them, Korea will adopt Cr-coated cladding, so this present study focused on it.

Many studies about Cr coating have been conducted until now. Mostly, differences on oxidation of Cr and Zr are compared, and their major conclusions are oxidation resistance of Cr is significantly lower than that of Zr. It means that hydrogen generation would be reduced on BDBA or severe accident. However, effect on heat transfer change by Cr coating does not have actively evaluated so far. The heat transfer of cladding surface is changed depending on the surface character of Cr and Zr. It could affect on PCT (Peak Cladding Temperature) in terms of DBA (Design Basis Accident). The experiments on partial heat transfer change exist such as critical heat flux (CHF) and Leidenfrost temperature respectively, but those are not to conduct research considered for overall heat transfer change together. So, in this study, LB-LOCA (Large Break-Loss of Coolant Accident) of Zion plant was analyzed to identify and evaluate the effect on entire heat transfer change by Cr coating using MARS-KS 1.6 code.

2. Effect of heat transfer change by Cr coating

2.1 Review on Cr Coating Effect

Many studies suggested that Cr coating on the surface of cladding affects the heat transfer such as CHF and rewet temperature following dryout. For CHF related study, the CHF variation compared to the bare Zr cladding was suggested [2, 3, 4, and 5]. These studies dealt with various conditions; pool and forced boiling, surface polishing method, etc. Following the research results, the CHF at Cr coated surface is 67~180% of bare Zr cladding. In case of quenching related study, studies have been rarely conducted. Seshadri et al. reported that Cr coating affects Leidenfrost temperature and quenching speed, which depends on gamma-ray irradiation [6]. However, this result is hard to apply in post dryout heat transfer model of MARS-KS. By the way, INL found out that the experimental results for film boiling heat transfer (FBHT) is about 30~100% of the prediction of RELAP5-3D [7]. The film boiling heat transfer model in RELAP5-3D are very similar with that in MARS-KS code. Furthermore, nucleate boiling heat transfer (NBHT) and transition boiling heat transfer (TBHT) would be also affected by Cr coating, but we could not find related study.

According to survey on the effect of heat transfer by Cr coating as shown in Table I, the Cr coating effect could be directly applied to MARS-KS calculation using multiplier.

Table I: Summary of literature review on Cr coating heat transfer effect

Parameter	**Ranges compared to bare cladding**	**Remarks**
CHF	67~180%	-
FBHT	30~100%	RELAP5-3D assessment

2.2 Review of BE LOCA Analysis

The effect on heat transfer change by Cr coating can be analyzed through value of Table I using MARS-KS code. But, since the heat transfer model of MARS-KS code contains uncertainty itself, it is necessary to additionally consider the uncertainty range of heat transfer model with heat transfer change due to Cr coating.

The best estimate approach uses BEPU (Best EstimatePlus Uncertainty) which is uncertainty quantification procedure for KINS-REM (KINS Realistic Evaluation Method). KINS-REM presents 22 uncertainty parameters. Among them, 11 parameters are related with the heat transfer models in MARS-KS code as follows:

Blowdown Models
(1) Groeneveld CHF lookup table (AECL)
(2) Dittus-Boelter liquid convection
(3) Dittus-Boelter vapor convection
(4) Chen nucleate boiling

Reflood Models
(5) Zuber CHF correlation
(6) Chen transition boiling
(7) Weismann TB (Transition Boiling) correlation
(8) Bromley FB (Film Boiling)

(9) QF (Quenching Front) Bromley correlation
(10) Forslund-Rohsenow FB correlation (reflood)
(11) Vapor correlation (reflood).

The uncertainty range of each heat transfer model in KINS-REM is presented in Table II.

2.3 Method to Estimate Cr Coating Effect on LOCA

To evaluate the effect of heat transfer change by Cr coating, the best way would be to replace the existing heat transfer models to specific model of Cr coating, and then to determine the uncertainty of specific Cr coating model by assessing the experiment the Cr coated cladding is used. However, there is no Cr-coated cladding experiment for the parameter range determination, so it is impossible in current status. Therefore, in this study, the range of heat transfer change due to Cr coating was estimated as shown in Table II. To determine the uncertainty range, the coating effect on heat transfer and KINS-REM uncertainty range are combined in the method that multiplies two ranges. The variation in NBHT and TBHT is estimated from change of CHF and FBHT because it is reasonable to believe that the pre-stage and post-stage of CHF and Leidenfrost temperature are also affect following the boiling curve.

Table II: Uncertainty parameter and range for MARS-KS analysis

Models or Uncertainty Parameters	**Cr coating effect**	**Uncertainty Range in KINS-REM**	**Combined Uncertainty Range**
Groeneveld CHF	0.67~1.8	0.17~1.8	0.114~3.24
Dittus-Boelter liquid	1	0.606~1.39	0.606~1.39
Dittus-Boelter vapor	1	0.606~1.39	0.606~1.39
Chen nucleate	0.67~1.8	0.53~1.46	0.355~2.628
Zuber CHF	0.67~1.8	0.38~1.62	0.255~2.916
Chen transition	0.3~1.0	0.54~1.46	0.162~1.46
Weismann TB	0.3~1.0	0.5~2.0	0.15~2.0
Bromley film boiling	0.3~1.0	0.428~1.58	0.128~1.58
QF Bromley	0.3~1.0	0.75~1.25	0.225~1.25
Forslund-Rohsenow	0.3~1.0	0.5~1.5	0.15~1.5
Vapor	0.3~1.0	0.5~1.5	0.15~1.5

3. Analysis on Effect of Heat Transfer Change for LB-LOCA

The heat transfer change by Cr coating was confirmed through literature review in Table I. In addition, the combined uncertainty range for Cr coating was derived as shown in Table II. Based on these variations, the effect of heat transfer change on PCT and quenching was analyzed through LB-LOCA analysis of Zion plant. The MARS-KS nodalization of the Zion plant is shown in Fig. 1. MARS-KS 1.6 code was used for the calculation.

The analysis was performed in two cases as follows: (1) considering only Cr coating effect and (2) considering the Cr coating effect and uncertainty range of heat transfer model together (combined uncertainty range).

Additionally, this study did not consider the effect of heat addition by oxidation reaction. This is because the Cr coating has the effect of remarkably reducing the amount of hydrogen generated under DBA, and the objective of this analysis is to evaluate the effect of heat transfer change on PCT.

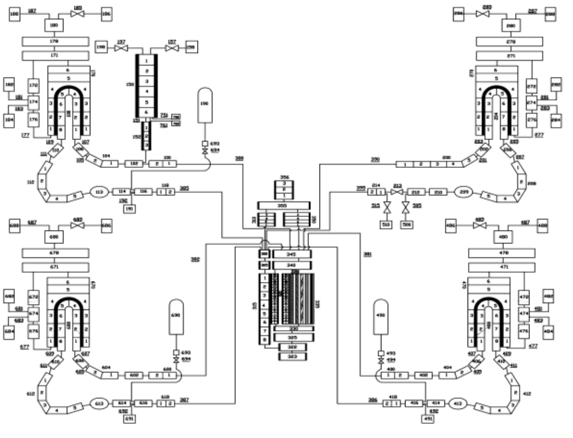

Fig. 1. MARS-KS nodalization for Zion plant [8]

3.1 Effect of Pre-CHF and CHF Heat Transfer Change

From literature review, it was identified that the CHF due to Cr coating would be different at about 67~180% compared to Zr cladding. However, it is reasonable to assume that the change in CHF is affected to that in NBHT as we mentioned in section 2.3. Therefore, under the assumption that change in NBHT is the same as the amount of that in CHF, the effect of estimated NBHT and CHF change was analyzed.

Figure 2 compares the PCT results in LOCA of Zion plant. In terms of minimum value in combined uncertainty range, the PCT is the highest at about 1202.5 K. On the other hand, in case of heat transfer enhanced by Cr coating, PCT is predicted lower than the base cases. Table III summarizes the results of calculating the effect of PCT on changes in CHF and NBHT. It is confirmed that the heat transfer change has a significant effect on PCT.

3.2 Effect of Post Dryout Heat Transfer Change

The FBHT affects the quenching time in the reflood phase. Zion plant analysis was performed to assess the effect on PCT as well as quenching time. We assumed that the all post dryout heat transfer (PDOHT) that consists of FBHT, TBHT, and vapor heat transfer is changed with same ratio, because only the effect of FBHT could be identified from previous studies.

Figure 3 shows the PCT according to the change of all PDOHT in Zion plant analysis. It is shown that the cooling of fuel rods in reflood phase is significantly affect following the PDOHT is reduced. In terms of the most conservative multiplier, the PCT reaches to 1368.8 K, and the quenching is delayed compared to the result of base case. Table IV presents the comparison of quenching time in all calculation results. It is difficult to obviously analyze the PDOHT changes by complicated phenomena in reflood phase, but it is clear that the change of PDOHT affects the PCT and quenching time.

3.3 Effect of overall heat transfer change

The analysis was conducted to evaluate the effect of estimated overall heat transfer change including pre-CHF, CHF and PDOHT at the same time. The multipliers for each heat transfer model were used in minimum values of variation by Cr coating effect and combined uncertainty range.

Figure 4 and Table V are LBLOCA analysis results of Zion plant considering the overall heat transfer change from NBHT to FBHT and gas heat transfer as well. The PCT is remarkably higher than the base case. And the maximum PCT in combined uncertainty case is reached at about 1385 K. The quenching time also is considerably delayed, and combined uncertainty case which is most conservative seems not to be quenched within the calculation time.

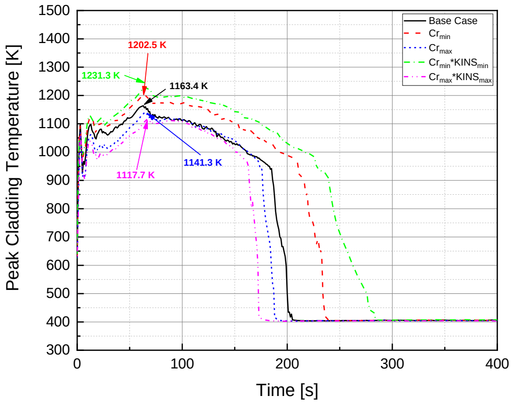

Fig. 2. PCT results according to estimated pre-CHF and CHF change

Table III: Summary on effect of estimated pre-CHF and CHF change

No.	Multiplier	Blowdown PCT [K]	Reflood PCT [K]
BC	-	1096.5	1163.4
Pre-CHF(NBHT)/CHF			
1	AECL:0.67, Zuber:0.67, Chen NB:0.67	1095.9	1202.5
2	AECL:1.8, Zuber:1.8, Chen NB:1.8	1070.6	1141.3
3	AECL:0.1139 , Zuber:0.2546, Chen NB:0.3551	1046.8	1231.3
4	AECL:3.24, Zuber:2.916, Chen NB:2.628	1062.0	1117.7

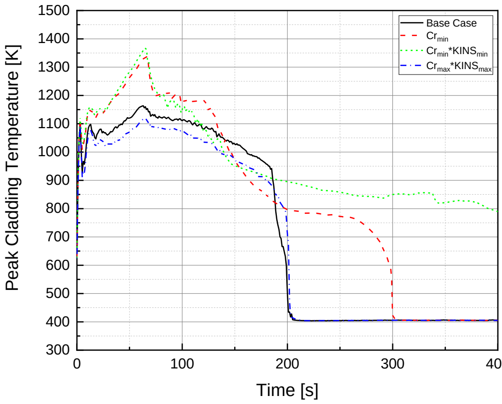

Fig. 3. PCT results according to estimated PODHT change

Table IV: Summary on effect of estimated PODHT change

No.	Multiplier	Quenching Time [s]
BC	-	205
Post-Dryout (FBHT/TBHT/Vapor correlation)		
1	Bromley:0.3, QF:0.3, FR:0.3, Chen:0.3, Weismann:0.3, Vapor:0.3	300
2	Bromley:0.1284, QF:0.225, FR:0.15, Chen:0.162, Weismann:0.15, Vapor:0.15	214
3	Bromley:1.58, QF:1.25, FR:1.5, Chen:1.46, Weismann:2.0, Vapor:1.5	*

* : Quenching does not occur in problem time

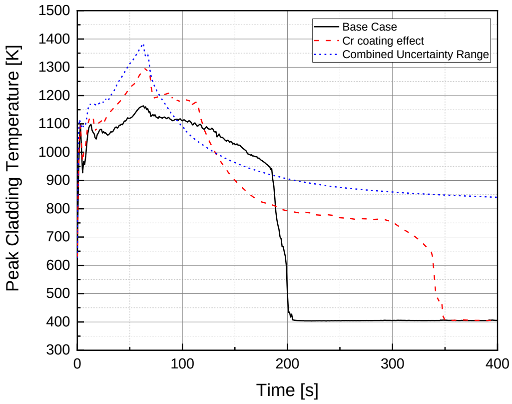

Fig. 4. PCT results according to estimated overall heat transfer change

Table V: Summary on effect of estimated overall heat transfer change

No.	**Multiplier**	**Quenching Time [s]**
BC	-	205
Pre-CHF/CHF/Post-Dryout heat transfer		
1	AECL:0.67, Zuber:0.67, Chen NB:0.67, Bromley:0.3, QF:0.3, FR:0.3, Chen:0.3, Weismann TB:0.3, Vapor:0.3	350
2	AECL:0.1139 , Zuber:0.2546, Chen NB:0.3551, Bromley FB:0.1284, QF:0.225, FR:0.15, Chen:0.162, Weismann:0.15, Vapor:0.15	*

* : Quenching does not occur in problem time

3. Conclusions

ATF has been actively developed, but most researches are focused on hydrogen generation and coping time analysis on BDBA and severe accident. The effect of heat transfer change on DBAs seems not to be studied widely. Therefore, the objective of this study is to identify the effect of heat transfer change by Cr coating on DBA. Several studies on the differences in CHF and FBHT between Zr and Cr have been conducted as shown in Table I. Also, this study estimated the combined uncertainty range to evaluate effect by Cr coating using current MARS-KS code in Table II.

The effect of estimated heat transfer change by applying Cr coating was analyzed for LB-LOCA analysis of Zion plant. This present study did not consider the heat by oxidation reaction. We thought that effect of oxidation by applying Cr coating cladding is remarkably lower on DBA. The changes in the heat transfer model multiplier considerably affected the PCT and quenching time. Considering the conservative cases on the effect of overall heat transfer change, it is confirmed that the PCT and the quenching phenomena change most severe.

In future work, we will consider and apply the oxidation model of Cr coating in MARS-KS code and deduce the more reasonable uncertainty range. So the effect on PCT and hydrogen generation will be evaluated.

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