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A Preliminary Assessment of APR1400 LBLOCA for Integral Time at Temperature

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1. Introduction

In order to address the performance of the advanced cladding alloys under LOCA, especially at high burnup operation, the U.S.NRC has established newly revised embrittlement criteria to ensure adequate safety margin. Equivalent cladding reacted (ECR) plays an important role for enacting new criteria. DG-1263 [1] has been released to establish analytical limits for zirconium alloy cladding material. For all those reasons, current 10 CFR 50.46 (b) (2) criteria will be replaced with a revised acceptable analytical limit on the ECR as a function of pre-transient hydrogen content in the cladding metal.

This study is intended to evaluate the compliance with the revised performance-based safety criteria. Through the sensitivity analysis of CAREM-based uncertainty variables, in terms of the integral time at temperature (ITT), the more conservative case between the calculations applying the maximum and the minimum uncertainty value was adopted as the value of limiting case. Three burnup conditions such as about 1.0, 30.0, and 60.0 GWd/MTU were selected and their ECRs were predicted for limiting case under LBLOCA condition for APR1400.

2. Sensitivity Analysis of Uncertainty Variables

2.1 Phenomena Identification

To see the effects of burnup, it is an essential prerequisite to identify phenomena influencing on the ECR. Candidate parameters affecting the ECR significantly were picked out from the uncertainty variables of CAREM [2]. Limiting case was selected from this sensitivity study [3].

2.2 Limiting Case Selection

Table 1 shows the effect on the ECR of each uncertainty variable. Based on the ITT definition, they were categorized into three groups. The first group (G1) is the case that the blowdown or reflood PCTs compared to the base case are increased by more than 10 degrees Celsius. The word “base” means that all of uncertainty variables have the nominal values. Fig. 1 shows the base case and the calculation results applying the maximum and the minimum uncertainty values for variables classified as G1. In Fig. 1 minimum forced-convection heat transfer coefficient (HTC) to vapor leads to the higher cladding temperature on the whole and the PCT differences between maximum HTC and base case are 47.4 K (blowdown) and 97.1 K (reflood), respectively. The second group (G2) is the case that the quenching time has 30 s delayed time more than that of base case. Transition boiling heat transfer can be selected as G2. When the transition boiling HTC has the minimum multiplier, it leads to 110 s delayed quenching time. Finally, the third group (G3) is the others, excluding G1 and G2. They have the higher cladding temperature or the delayed quenching time but their differences are below standards of selecting G1 or G2. The higher cladding temperature and the delayed quenching time contribute to the delayed ITT. Therefore, focused on the ITT, 13 uncertainty variables are adopted as the parameters of limiting case and their uncertainty values are determined from the sensitivity study of G1, G2, and G3. Note that SIT water temperature and downcomer wall-related parameters are excluded from this selection because they have little or adverse influence on PCT or ITT.

3. Preliminary Assessment for Burnup Effect

3.1 Steady State Calculation

A preliminary assessment was conducted for limiting case. FRAPCON-3 code calculated the change with time of burnup-dependent parameters. Variables written by FRAPCON were used by RELAP5/MOD3.3/K and FRAPTRAN for burnup initialization. Initial conditions and assessment results such as burnup conditions, hot spot average temperature, PCT, ITT, and maximum ECR are summarized in Table 2. Steady state calculations show that the axial average pellet temperatures in a hot spot are decreased in order of MOL, EOL, and BOL and their maximum temperatures are predicted as about 1,415 K, 1,310 K, and 1,200 K, respectively. This tendency is occurred owing to the thermal conductivity degradation (TCD) of pellet and radial fall-off. NRC information notice [4] reported the reduction of 5~7 % in TCD per burnup of 10 GWd/MTU.

3.2 Transient Calculation

From the transient calculations in Fig. 2, the maximum ECR is calculated as 4.04 % under MOL. It conflicts the conventional predictions that BOL will have the largest ECR owing to the most delayed ITT among three burnup conditions. Based on the experiments to elucidate the effect on the ECR distribution of the Zircaloy cladding temperature [5], the transient oxide thickness is exponentially increased from the inception temperature and, from the following Eq. (1), ECR is predicted as the largest value under MOL although its PCT is smaller than that of BOL.

$$ECR\ (\%) = \frac{Oxide\ Thickness_{Transient}}{Initial\ Cladding\ Thickness - Oxide\ Thickness_{Pre-transient}} \times 100 \quad (1)$$

3.3 Two-sided Oxidation

Fig. 3 compares the ECR distributions under three burnup conditions with the new embrittlement criteria. In Fig. 3, ECRs are predicted as 1.69 %, 4.04 %, and 1.92 % under BOL, MOL, and EOL, respectively, which meets the revised criteria. Eq. (2) is the newly revised CP-ECR equation in which NRC considers the two-sided oxidation toward the pellet cladding. In Eq. (2), PB-factor is assumed at 1.56 to consider the erosion of inside oxidation layer. Following the guideline of NRC [1] in which the two-sided oxidation effect should be considered beyond 30.0 GWd/MTU, ECRs are recalculated under MOL and EOL. The predicted ECR under MOL meets the newly revised criteria whereas that of EOL does not. The reason is responsible for the limiting case consisting of the conservatively selected uncertainty values.

$$ECR\ (\%) = \frac{Oxide\ Thickness_{Transient}/PBFactor + Oxide\ Thickness_{Pre-transient,Inside}}{Initial\ Cladding\ Thickness - Oxide\ Thickness_{Pre-transient}/PBFactor} \times 100 \quad (2)$$

4. Summary

A preliminary assessment of APR1400 LBLOCA was conducted for three burnups. Focused on the ITT, 13 uncertainty variables were categorized into three groups and selected as the parameters of limiting case.

From the steady state and the transient calculations, results for three burnup conditions meet the revised embrittlement criteria and the maximum ECR is predicted as 4.04 % under MOL. Considering the two-sided oxidation, the predicted ECR under MOL meets the newly revised criteria whereas that of EOL does not.

REFERENCES

[1] "Establishing Analytical Limits for Zirconium Based Alloy Cladding," Draft Regulatory Guide DG-1263, U.S. Nuclear Regulatory Commission, Washington, DC, 2012.
[2] "CAREM-Realistic Evaluation Methodology for Large-Break LOCA of the APR1400," APR1400-F-A-TR-12004-P Rev. 0, KEPCO Nuclear Fuel Co., Dec. 2012.
[3] "Margin Assessment for Revised LOCA Acceptance Criteria," APR1400-F-A-TM-13001-P Rev. 0, KEPCO Nuclear Fuel Co., June. 2013.
[4] "Nuclear Fuel Thermal Conductivity Degradation," NRC Information Notice 2009-23, Oct. 2009.
[5] D.F. Ross, "Compendium of ECCS Research for Realistic LOCA Analysis," NUREG-1230, NRC, 1988.

Table 1 Sensitivity Analysis Results for Uncertainty Variables

No	Variables		Max / Min	ECR (%)	Group No. (1, 2, 3)
1	Base Case		-	1.220	-
2	Limiting Case			3.039	
3	Single-Phase Forced Convection Heat Transfer to Vapor		Min	1.447	1
4	Low-Pressure & Low-Flow CHF		Max	1.219	3
5	Film Boiling Heat Transfer	Bromley	Min	1.245	2
		F.R	Min		
6	Transition Boiling Heat Transfer		Min	1.217	2
7	Burst Strain		Max	1.235	2
8	Fuel Conductivity		Min	1.292	1
9	Decay Heat		Max	1.261	1
10	Pump K Factor		Max	1.224	3
11	SIT Pressure		Max	1.231	3
12	SIP Flow Multiplier		Min	1.221	3
13	SIT Water Temperature		Max	1.230	-
14	IRWST Temperature		Max	1.224	3
15	Downcomer Wall-Related Parameters	K	Max	1.217	-
		rho * C_p	Max		
16	Discharge Coefficients	1Φ Cd	Max	1.187	2
		2Φ Cd	Max		
17	Containment Back Pressure		Min	1.267	3

Table 2 Initial Conditions and Assessment Results for Limiting Case

Burnup Conditions	BOL	MOL	EOL
Power [%]	100	100	100
Burnup [GWd/MTU]	0.5	34.1	60.1
$F_{\Delta H}$ Fall-off [%]	0	0	25
Hot Spot Avg. Temp. [K]	1200.0	1415.0	1310.0
Blowdown PCT [K]	1111.0	1207.0	1092.0
Reflood PCT [K]	1168.0	1276.0	1154.0
ITT [s]	667	532	525
Max. ECR [%]	1.69	4.04	1.92

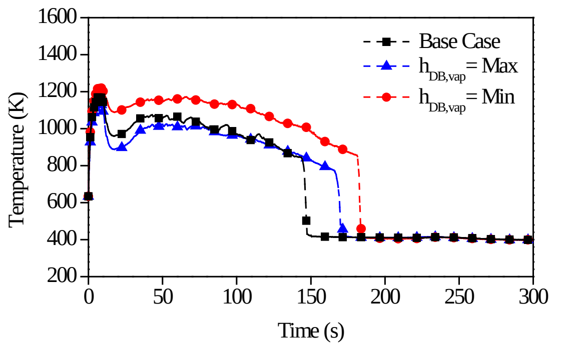

Fig. 1 Sensitivity Analysis Results for G1 (Forced Convection to Vapor)

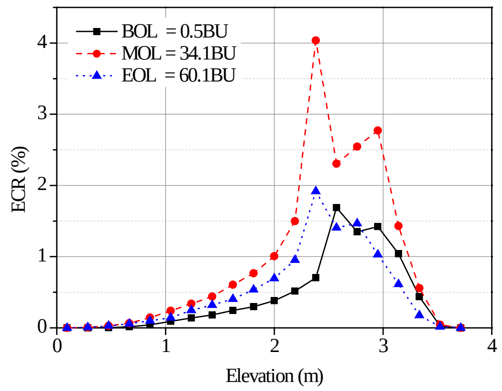

Fig. 2 Axial Distributions of ECRs with Burnup Conditions

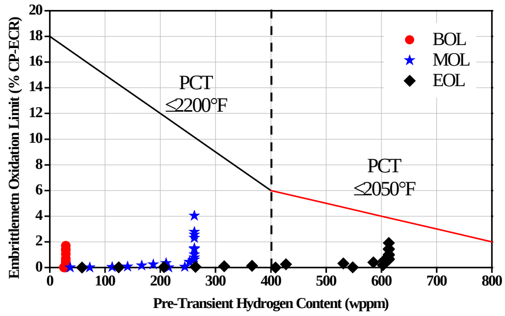

Fig. 3 Comparison between Burnup-based ECRs and Analytical Limit