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Sub-Critical Boron Concentrations of Pressurized Water Reactor during the Late Phase of a Severe Accident via Monte Carlo Whole-Core Analyses

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1. Introduction

The temperature differences for the relocation of the materials (e.g., melting, eutectic formation and etc.) in the reactor core have led to perform numerous researches on the potential for recriticality during severe accidents [1-4]. The researches have been focused on the boiling water reactors (BWRs), since there is high possibility on the earlier relocation of control rod absorber materials (B_4C) in BWRs due to the temperature difference between eutectic formation of B_4C and cladding in the control rods in the control rods at ~1150ºC and fuel melting at ~2800ºC. In addition, due to the design of the reactor core, the control rods are inserted from bottom of the core to the active core via active safety system, which also cause earlier relocation of the control rods via gravity if the active safety system fails.

Among the aforementioned possibilities on the earlier relocation of control rod materials, the temperature difference between the eutectic formation and the fuel melting can also be applied to pressurized water reactors (PWRs), if the control material in the reactor core made by B_4C. Therefore, it is essential to perform the research on the potential for recriticality in PWRs with B_4C.

Coupling with the severe accident analyses code, MELCOR [5] and reactor analysis code via Monte Carlo method, Serpent 2 [6], the authors performed preliminary analyses on the whole-core of the PWR loaded with B_4C control rods during early phase of a severe accident especially when the most of control rods materials are relocated to the lower head but the fuel rods remain intact [7]. The authors also provided sub-critical boron concentrations (Sub-CBCs) which make criticality of the reactor 0.95, which is the regulatory criterion on the criticality safety in U.S. NRC [8].

In this paper, based on the previous study [7], we perform the analysis focusing on when the relocation of the fuel rods is in progress to provide sub-CBCs during the late phase of the severe accident.

2. MELCOR and Serpent Calculations for Geometric and Isotopic Configurations of the Degraded Core

2.1 MELCOR calculations to obtain the geometric and isotopic configurations of the degraded PWR

A simulation on Large Break Loss of Coolant Accident (LBLOCA) scenario for PWR is performed using MELCOR 1.8.6 in order to obtain geometric and isotopic configuration of PWR during relocation of the fuel rods. For the modification of the source code to make input files for reactor analysis via Serpent 2, MELCOR 1.8.6 is used, instead of state-of-the-art version of MELCOR, MELCOR 2.2, In this analysis, the reactor core consists of 5 rings in the radial direction and 10 cells in the axial direction.

In the analysis, at the time of ~4200 sec, 80 % of the control rod materials in the first ring of the reactor core are relocated to the lower head as discussed in the previous work [7]. Then, at the time of ~4400 sec, the fuel rods in the first ring are started to be relocated. In this work, we focus on the configurations shown after ~4400 sec in order to obtain sub-CBCs during the late phase of the severe accident, i.e., when the fuel rods are being relocated.

2.2 Modeling for whole-core analyses during relocation of the fuel rods via Serpent 2 Code

As the fuel rods are being relocated, UO_2 in the fuel pellets and zircaloy in the cladding are mixed so that the characteristics of the U-Zr-O debris are different from simple arithmetic average of characteristics on the two constituents. In addition, the debris is not directly relocated to the lower head of the reactor, instead, it goes to the other assemblies located below the degraded assemblies. Then, the assemblies consist of intact fuel rods and U-Zr-O debris. It is essential to perform sensitivity analyses on the characteristics of U-Zr-O debris and geometric configuration of the debris in the assemblies in order to specify the configurations for conservative estimation of the sub-CBCs of the degraded core.

First, composition of U, Zr, O in the debris for this study are shown in Table 1 [9]. In Ref. 9, the compositions were derived based on the thermochemical equilibrium calculations under severe accident conditions.

Table 1. Composition of U-Zr-O debris under severe accident conditions

	Fraction		Density
	U	Zr	[g/cm^3]
U-Zr-O-1	0.82	0.18	10.20
U-Zr-O-2	0.59	0.41	9.16
U-Zr-O-3	0.52	0.48	8.83
U-Zr-O-4	0.48	0.52	8.63
U-Zr-O-5	0.26	0.74	7.51

The results on sensitivity analyses of the characteristics of U-Zr-O debris are shown in Fig. 1. Note that as the fraction of Zr increases, infinite multiplication factor also increases as shown in Fig. 1. The causes of the results are that the among the debris materials, Zr plays a role of moderator well.

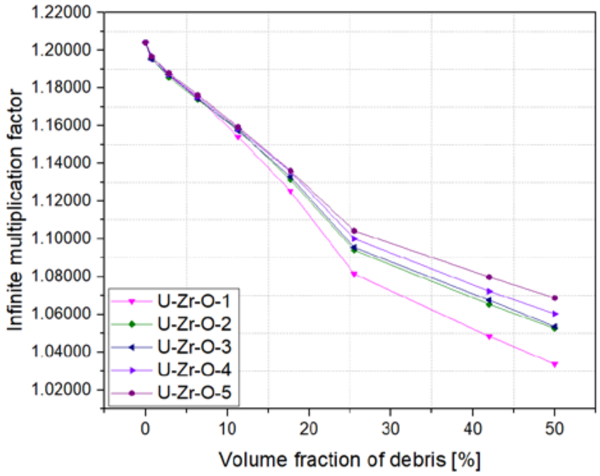


Fig. 1. Infinite multiplication factors for the fuel assembly with U-Zr-O debris

Meanwhile, in order to find the geometric configuration of the relocated debris for the conservative evaluation, we also perform sensitivity studies on the configuration shown in Fig. 2. In the analyses, as shown in Fig. 3, corner centered scheme, shows the largest infinite multiplication factors for the various volume fraction of debris in the assembly.

(a) Periphery (b) Corner Centered (c) Line Centered

Fig. 2. Geometric configurations of the debris relocated in the fuel assembly

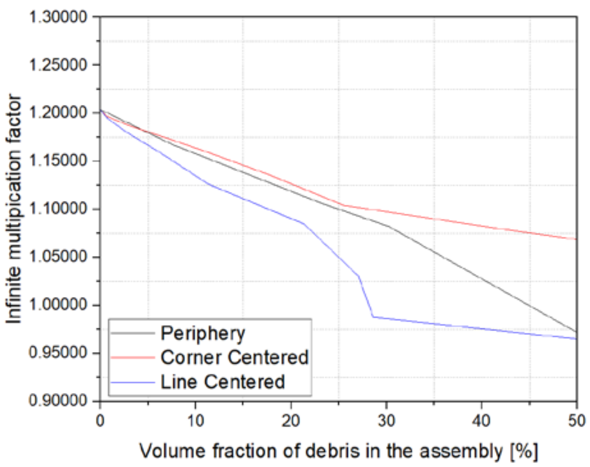


Fig. 3. Infinite multiplication factor for the various configuration of the debris in the fuel assembly

From the above sensitivity analyses, U-Zr-O-5 debris with corner centered configuration in the fuel assembly is used for the conservative estimation of the sub-CBCs during the late phase.

The coupling of MELCOR and Serpent 2 is done in terms of geometric and isotopic configurations as in the previous work [7].

3. Sub-CBCs to Prevent Recriticality during the Late Phase of the Severe Accident

Sub-CBCs are calculated via Serpent 2 with the aforementioned modeling on the degraded reactor core. Similarly with the previous work [7], the degraded reactor core is assumed to be fully submerged by the water for the conservative estimation on the boron concentrations. Th computation conditions are shown in Table 2. Sub-CBCs for the late phase of the severe accident are shown in Fig. 3.

Table 2. Computational conditions

Parameter	Data
Cross section libraries	Continuous energy ENDF/B-VII libraries
# of particles	500,000
# of inactive cycles	500
# of active cycles	1000

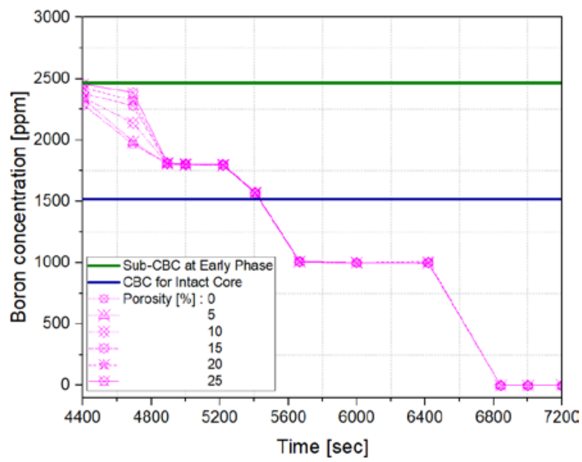
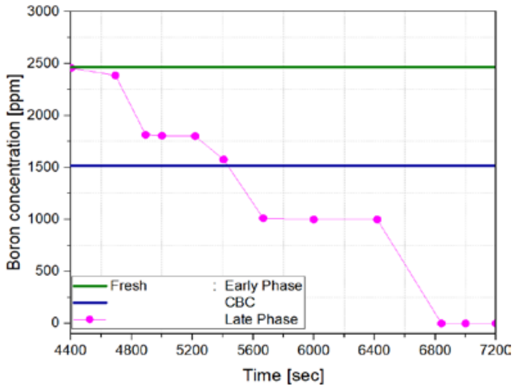


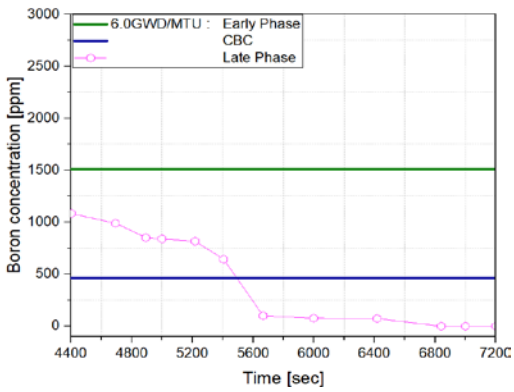
Fig. 3. Sub-CBCs during the late phase of the severe accident.

As shown in Fig. 3, the sub-CBC is the highest (~2,450 ppm) when the fuel rods are started to be relocated, i.e., at 4400 sec. The sub-CBCs during the late phase are higher than critical boron concentrations for normal operations until 80 % of the fuel rods are being relocated, i.e., at 5500 sec. From when 80 % of the fuel rods are being relocated to when all fuel rods are relocated (~6800 sec), sub-CBC is ~ 1000 ppm. When the fuel rods are fully relocated (after ~6800 sec), the degraded reactor becomes sub-critical.

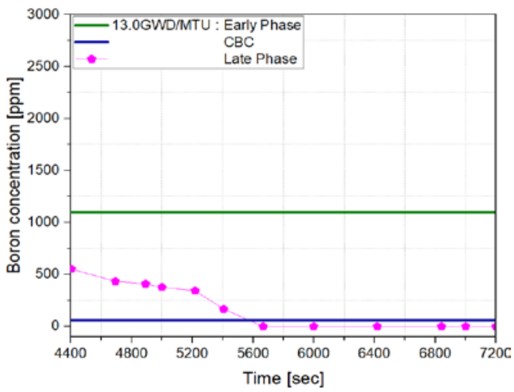
We also performed sensitivity analyses on the burnup. The results are shown in Figs. 4~6. Similarly with the results of the previous work [7], the sub-CBC decreases as the burnup of the reactor increases. In addition, the degraded reactor becomes sub-critical 800 sec faster at EOC than BOC of the reactor since the fission products in the degraded reactor core shows effects of negative reactivity insertion as the burnup increases.



(a) Beginning of cycle (BOC)



(b) Middle of cycle (MOC)



(c) End of cycle (EOC)

Fig. 4. Comparison of sub-CBC during early and late phase with critical boron concentration

With the comparison of the sub-CBCs during early phase (Green lines) and those during late phase (Magenta lines), recriticality can be prevented during the severe accident if the boron concentration in the degraded reactor core maintains sub-CBCs at the early phase (Green lines).

4. Conclusions

In this paper, coupling with MELCOR and Serpent 2 codes, we performed the analyses to obtain sub-critical boron concentrations during the late phase of a severe accident when the fuel rods are being relocated.

From the sensitivity analyses on the configurations of the debris relocated in the fuel assemblies, we obtained the configurations of the fuel assemblies with debris for the conservative estimation of the boron concentrations.

During the late phase, regardless of the porosity in the debris, sub-CBCs are higher than the critical boron concentrations for normal operations until 80% of the fuel rods are being relocated. In addition, when more than 80% of the fuel rods are being relocated, ~ 1000 ppm of boron is required to maintain the degraded reactor sub-critical.

Similarly with the results of the previous work, sub-CBCs decrease as burnup increases. In addition to that, the degraded reactor becomes sub-critical faster at EOC than BOC of the reactor since the fission products in the degraded reactor core shows effects of negative reactivity insertion as the burnup increases.

With the comparison of the sub-CBCs during early phase and those during late phase, we can conclude that recriticality can be prevented during the severe accident if the boron concentration in the degraded reactor core maintains sub-CBCs at the early phase.

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REFERENCES

[1] W. Frid et al., Severe Accident, Recriticality Analyses (SARA), Swedish Nuclear Power Inspectorate, Stockholm, Sweden, 1999.

[2] R. D. Monsteller and F. J. Rhan, “Monte Carlo calculations for recriticality during the reflood phase of a severe accident in a boiling water reactor,” *Nucl. Technol.*, **110**, pp. 168-180, 1995.

[3] F. J. Rhan et al., Technical Evaluation of Fukushima Accidents Phase 2 – Potential for Recriticality During Degraded Core Reflood, EPRI, Palo Alto, CA, 2012.

[4] P. Darnowski, et al., “Investigation of the recriticality potential during reflooding phase of Fukushima Daiichi Unit-3 accident,” *Ann. Nucl. Energy*, **99**, pp. 495-509, 2017.

[5] R, O. Gaunnt et al., MELCOR Computer Code Manuals Vol. 1 : Primer and Users’ Guide, Version 1.8.6

Sandia National Laboratories, Albuquerque, NM, pp. RN-UG-11 - RN-UG-12, 2005.

[6] J. Leppänen, "The Serpent Monte Carlo code : Status, development and application in 2013," *Ann. Nucl. Energy*, **82**, pp. 142-150, 2015.

[7] Y. Lee et al., "Whole-core analyses on recriticality of conventional high power pressurized water reactor in Korea during early phase of severe accident," *Ann. Nucl. Energy*, **143**, 107461, 2020.

[8] U. S. NRC, 10CFR 72.124 – Criteria for nuclear criticality safety, Washington, DC, 1988.

[9] A. Seibirt et al., "Thermophysical properties of U, Zr-oxides as prototypic corium materials," *J. Nucl. Mat.*, **520**, pp. 165-177, 2019.