Preliminary Whole Core Analyses on Sub-Critical Boron Concentrations of High Power Pressurized Water Reactor during the Reflooding Phase of a Severe Accident

Yoonhee Lee*, Yong Jin Cho, and Kukhee Lim
Korea Institute of Nuclear Safety
62 Gwahak-ro, Yuseong-gu, Daejeon, Korea 34142
**Corresponding author: yooney@kins.re.kr*

1. Introduction

Oxidation of fuel cladding and control rod cladding causes eutectic formation of boron carbide (B_4C), which is used as control rod absorber materials and control rod cladding at a temperature (~1150°C) lower than melting temperature of the fuel (~2800°C). By the eutectic formation, relocation of B_4C to lower head of the reactor occurs earlier than that of the fuel. During such relocation, fission products in the reactor core are released. Alternative water injection according to severe accident management guideline then is done in order to prevent from and mitigate such degradation of the reactor core. The aforementioned water injection, however, provides medium to moderate fast neutrons to thermal neutrons, which leads to insertion of positive reactivity. Therefore, recriticality during a severe accident can be one of the important issues if water with insufficient boron concentrations is injected.

Numerous studies have been performed to evaluate the possibility of recriticality in boiling water reactors (BWRs), such as Fred et al. [1], Monsteller and Rahn [2], EPRI report [3], Darnowski et al. [4], and etc. Based on the previous studies, the authors also performed analyses on possibility of the recriticality during reflooding phase in a fuel assembly of pressurized water reactors (PWRs) [5].

In this study, coupling with the severe accident analyses code, MELCOR [6] and reactor analysis code via Monte Carlo method, Serpent 2 [7], we perform preliminary analyses on the whole core of the high power PWR loaded with B_4C control rods during the reflooding phase of a severe accident in order to obtain the 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]. We also compare the sub-CBCs to critical boron concentrations (CBCs) to quantify how much boron concentration is required to prevent the recriticality during a severe accident.

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

2.1 MELCOR calculations on a large break loss of coolant accident scenario of the high power PWR

In order to select a geometry having high possibility of recriticality, a simulation on Large Break Loss of Coolant Accident (LBLOCA) scenario for a high power PWR is performed using MELCOR 1.8.6. In this analysis, the reactor core consists of 5 rings in the radial direction and 10 cells in the axial direction.

In the analysis, the reactor core starts to be uncovered at the time of ~60 sec. Relocation of the control rods starts at the time of ~3100 sec. At the time of ~4200 sec, 80% of control rod materials in the first ring of the reactor core are melted. However, geometries of the fuel rods are maintained, i.e., cladding of the fuel rods are not collapsed as shown in Figs. 1 and 2. In addition, at this time, most noble gases having large neutron absorption cross sections, i.e., xenon, krypton, are released from the degraded core as shown in Fig. 3, which results in increasing reactivity. In this geometric and isotopic configurations, there is high possibility of recriticality depending on the boron concentrations.

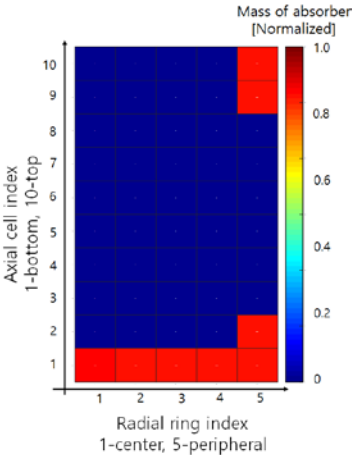

Fig. 1. Distribution of absorber materials (B_4C) in the reactor core at *t*= 4200 sec

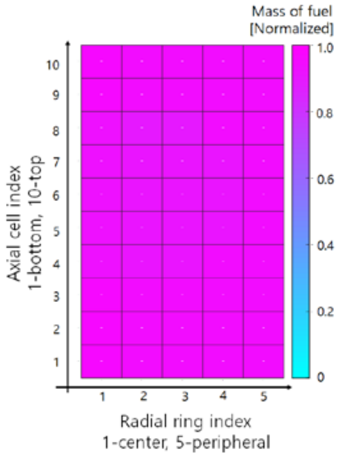

Fig. 2. Distribution of fuel materials (UO_2) in the reactor core at *t*= 4200 sec

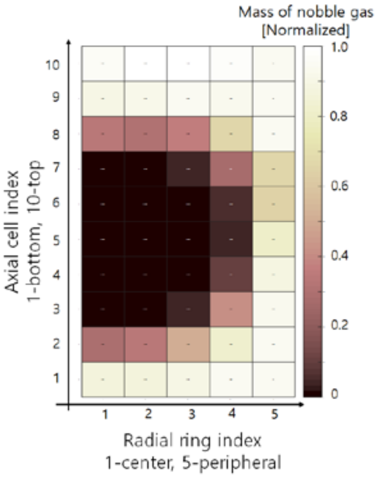

Fig. 3. Distribution of noble gas in the reactor core at *t*= 4200 sec

2.2 Modeling for whole core analyses on sub-CBCs via Serpent 2 Code

For the selected geometric and isotopic configurations, we model the reactor core of the high power PWR in three dimension to perform the neutronic analyses on sub-CBCs via Serpent 2 [7]. In the modeling, the reactor core is divided into five axial cells as shown in Figs. 4 and 5. The reactor core consists of 16 types of fuel assemblies with enrichment from 1.71 w/o to 3.64 w/o. All fuel assemblies loaded in the core consist of fresh fuel. The detailed design parameters for the core are taken from Ref. 9.

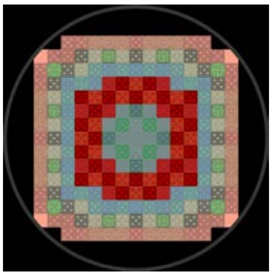

Fig. 4. Geometric configuration of the high power PWR core (Radial view)

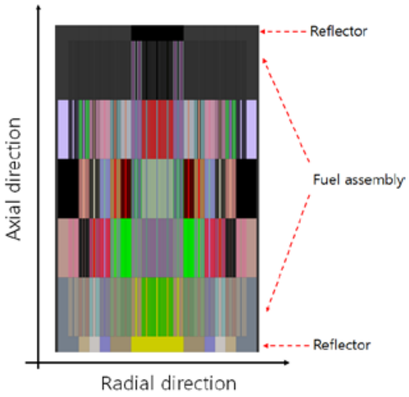

Fig. 5. Geometric configuration of the high power PWR core (Axial view)

With the modeling of the reactor core, we perform the calculation on the criticality of the core with all rod in (ARI) and all rod out (ARO). Computation conditions and results of the calculation are shown in Tables 1 and 2, respectively.

Table 1. Computational conditions for the reactor core with ARO and ARI

Parameter	Data
Cross section libraries	Continuous energy ENDF/B-VII libraries
# of particles	100,000
# of inactive cycles	500
# of active cycles	1000

Table 2. Criticality (k_{eff}) of the high power PWR (Fresh fuel loaded core)

Control rods	k_{eff}	Std [pcm]
ARO	1.15500	6
ARI	0.860375	5

We also perform depletion calculations to obtain isotopic configurations of the intact reactor core since the isotopic configurations are required to perform sensitivity studies on the burnup during the reflooding phase. Computation conditions used in the depletion calculations are the same as listed in Table 1. The results of the depletion calculations are shown in Fig. 6.

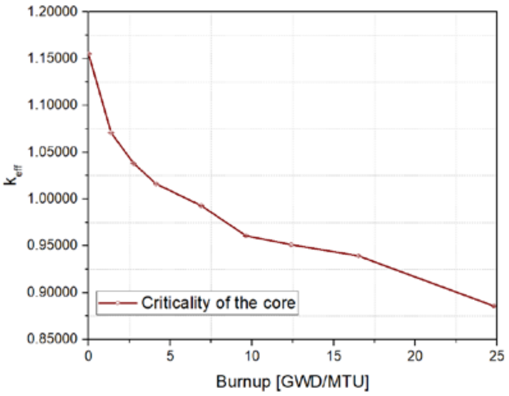

Fig. 6. Criticality of the reactor core in the depletion calculation

2.3 Coupling of MELCOR and Serpent 2 to obtain sub-CBCs

For the coupling of geometric configurations of the MELCOR and Serpent 2 modelings, the reactor core in Serpent 2 is divided into 5 rings in the radial direction so that the radial rings in MELCOR modelling match with those in Serpent 2 modeling. In the axial direction, since the number of axial cells in Serpent 2 is two times smaller than that in MELCOR modelling, two axial cells in MELCOR modelling match with one axial cell in

Serpent 2 modelling, i.e., cells 1 and 2 in MELCOR modelling match with cell 1 in Serpent 2 modelling.

For the isotopic configurations, 278 nuclides considered in Serpent 2 modelling are classified into 12 classes of fission products in MELCOR modelling. The amount of isotopes remaining in the degraded core are calculated with the results of depletion calculation from Serpent 2 for intact core and the remaining fractions of the each class for fission products obtained from MELCOR calculations. This calculations are done by an in-house code named MELSER. The coupling of the two codes are shown in Fig. 7.

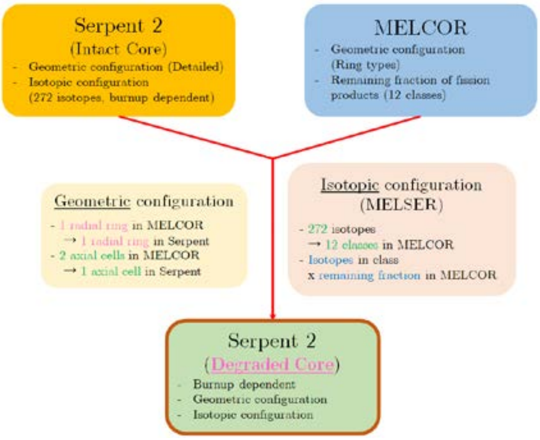

Fig. 7. Coupling procedure of MELCOR and Serpent 2 for sub-CBC calculation

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

Calculations on the sub-CBCs are performed via Serpent 2 with the aforementioned modeling on the degraded core. In this calculation, the degraded core is assumed to be fully submerged by water for conservative evaluation on the boron concentrations. The computation conditions are shown in Table 3. In the calculations, number of the particles, inactive cycles and active cycles are less than those in the depletion calculations since iterative calculations are required at each burnup step. We perform the calculations for two cases: Case 1 considers geometric degradation of the core only, Case 2 considers geometric degradation and release of fission products simultaneously. Sub-CBCs for both cases are shown in Fig. 8. In this figure, they are compared to CBCs of the intact core for various burnup

Table 3. Computational conditions for sub-CBC calculations

Parameter	Data
Cross section libraries	Continuous energy ENDF/B-VII libraries
# of particles	50,000
# of inactive cycles	300
# of active cycles	600

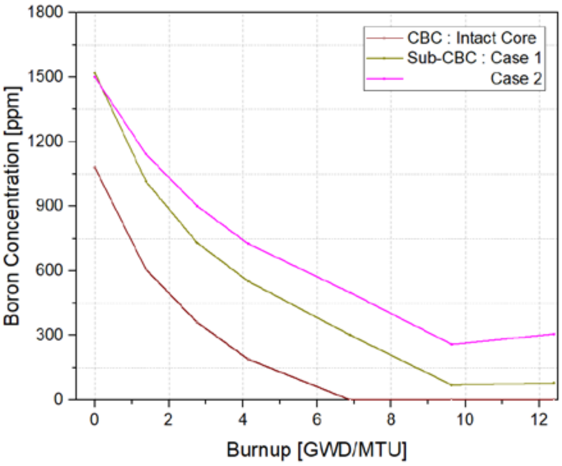

Fig. 8. Comparison of sub-CBCs and CBCs for various burnup

As shown in Fig. 8, when the fuel loaded in the core is fresh, i.e., burnup is 0, ~1500 ppm is required to make the reactor sub-critical and the Sub-CBCs for the various burnup are 400~600 ppm higher than CBCs. The cause of the difference is that degradation of the control rods are started at the center part of the core at which control rod worth is the highest among the all parts of the core and large amount of fission products is released at this part as well. In addition, sub-CBCs are the concentrations that make the criticality of the reactor 0.95, meanwhile CBCs are the concentration that make the reactor critical, i.e., k_{eff}=1.0.

Sub-CBCs decreases as burnup increases, i.e., ~1500 ppm is required at the burnup of 0 GWD/MTU, ~500 ppm is required at the burnup of 7 GWD/MTU, and ~300 ppm is required at the burnup of 12 GWD/MTU for case 2. The results are due to that the remaining minor actinides and fission products in the core provide negative reactivity during the reflooding phase.

By comparing cases 1 and 2, we can find that 200~300 ppm boron are required as additional. The results are attributed to the release of fission products having large neutron absorption cross sections, such as xenon-135, cesium-133 and 134, etc.

From the comparison between CBCs and sub-CBCs of both cases, additional 300~400 ppm of boron is required due to degradation of control rods. Additional 200~300 ppm boron is also required due to release of fission products. The additional concentrations, however, can be different if the reactor core is in the equilibrium cycle since the enrichment of the fuel in the equilibrium is much higher than that in the first cycle considered in this study.

4. Conclusions

In this paper, coupling with MELCOR and Serpent 2 codes, we performed the preliminary analyses on the whole core to obtain sub-critical boron concentrations during the reflooding phase of a severe accident.

The coupling of MELCOR and Serpent 2 is done in terms of geometric and isotopic configurations. In the case of geometric configuration, the reactor core in Serpent 2 is divided into the five radial rings so that the radial rings in MELCOR modelling match with those in Serpent 2 modelling. In axial direction, two cells in MELCOR modelling match with one cell in Serpent 2 modelling. For the isotopic configuration, 278 nuclides in Serpent are classified into 12 classes of fission products in MELCOR. The remaining amounts of fission products in the reactor core are calculated by the in-house code MELSER using the results of depletion calculations via Serpent 2 and MELCOR calculations.

In this study, we found that ~1500 ppm is required to make the reactor sub-critical and the sub-CBCs for various burnup are 400~600 ppm higher than CBCs. The results are attributed to that the degradation of the control rods was started at the center of the core at which control rod worth is the highest and large amount of fission products are released at this part as well.

From the comparison between CBCs and sub-CBCs considering geometric degradation and release of fission products, additional 300~400 ppm of boron is required due to degradation of control rods. Additional 200~300 ppm boron also is required due to release of fission products. The additional concentration, however, can be different if the reactor core is in the equilibrium cycle since the enrichment of the fuel in the equilibrium is much higher than that in the first cycle considered in this study.

As future work, we will perform analyses on sub-CBCs for the reactor core in the equilibrium cycle to obtain how much more boron concentrations are required to make the reactor sub-critical, compared to CBCs in the equilibrium cycle. We will also perform analyses on sub-CBCs for the various geometric and isotopic configurations during severe accidents. Such analyses will help providing insights on the boron concentrations for a management of severe accidents.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using financial resources granted by Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1805001).

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