Sensitivity Analyses of Water Density in the Degraded Reactor Core on the Potential of Recriticality during Early Phase of Severe Accident

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1. Introduction

The temperature difference between eutectic formations of boron carbide (B_4C) and cladding of the control rod material (~1150°C) and melting of the fuel (~2800°C) makes a configuration that shows high potential for recricalty during early phase of the severe accidents.

Numerous studies on such possibility of the recriticality have been performed by U. S. NRC [1], SKI [2], EPRI [3], Darnowski et al., [4] and etc. In the case of EPRI, they performed analyses on the possibility of the recriticality for Fukushima Daiichi unit 1F2 using a surrogate model for 1/4 reactor core of BWR [3]. They concluded that borated water with concentrations higher than 2000 ppm should be injected to prevent the recriticality. The authors of Ref. 4 concluded that there is recriticality during the progression of the accident if there is adequately large part of the reactor core without control materials and with intact fuel materials.

The authors have performed the analyses on the pressurized water reactors (PWRs) using whole-core modeling on the degraded reactor core derived from MELCOR calculations and the configuration high power reactor core [5]. We also have provided boron concentrations to make the degraded reactor core sub-critical.

There are competitive effects between excess reactivity and the aforementioned boron concentrations depending on the water density in the degraded reactor core, i.e., if the water density is reduced, the excess reactivity would be reduced, however, boron worth would also be competitively reduced. Hence such effects would require higher sub-critical boron concentrations.

In this paper, we will perform sensitivity analyses of the water density on the criticality of the degraded reactor core. We will also analyze the sensitivity on the sub-critical boron concentrations for the various water densities.

2. Configuration of the Degraded Reactor Core during Early Phase of the Severe Accidents

2.1 Coupling of MELCOR and Serpent 2 to obtain the configuration

MELCOR and Serpent 2, reactor analysis code via Monte Carlo method are coupled to obtain the configuration of the degraded reactor core. In MELCOR calculation, LBLOCA (Large Break Loss of Coolant Accident) scenario is selected. In this analyses, the reactor core consists of 5 rings in radial direction and 10 cells in axial direction. The main events during LBLOCA are summarized in Table 1.

Table 1. Main events during LBLOCA

Events	Time [sec]
Initiation of LBLOCA (Double-ended pipe break at the cold leg connected to pressurizer)	0.0
Initiation of core uncover (Water level of 99.0% relative to active core height)	60.0
Initiation of control rod material relocation	3169.2
Loss of ~80% of control rods at the center part of the core	4220.0
Core dryout	4240.0
UO_2 relocated to lower head	7330.9

The modeling on the reactor core for Serpent 2 is performed in three dimensional to perform the neutronic analyses based on Ref. 6. In the modeling the reactor core is in equilibrium cycle. The reactor core consists of three types of assemblies with enrichment from 4.08 w/o to 4.78 w/o. In the modeling, the reactor core is divided into five rings and ten axial cells as shown in Figs. 1 and 2. The fuel assemblies in each ring have the same values of the remaining fractions of the nuclides and those of control rods during severe accident.
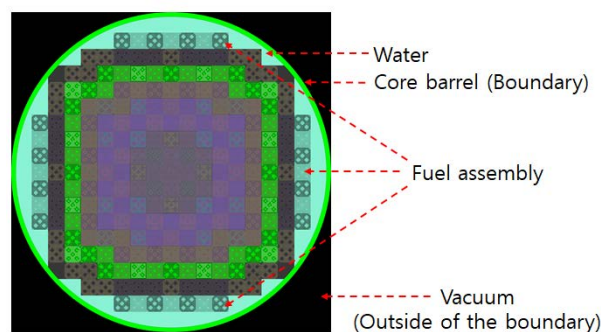

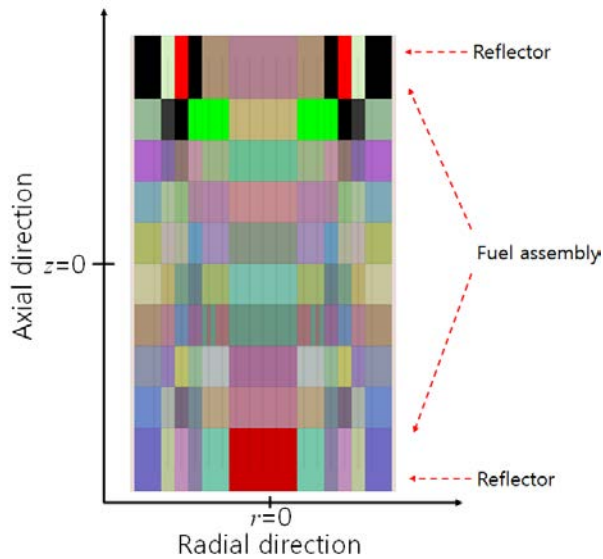Fig. 1. Geometric configuration of the high power PWR core (Radial view)

Fig. 2. Geometric configuration of the high power PWR core (Axial view)

MELSER, an in-house code is used for coupling of the results for MELCOR calculations and input for Serpent 2 for analyses on the criticality of the degraded reactor core. The coupling via MELSER is performed in terms of geometrical degradation of the reactor core and remaining fraction of the isotopes as shown in Fig. 3.
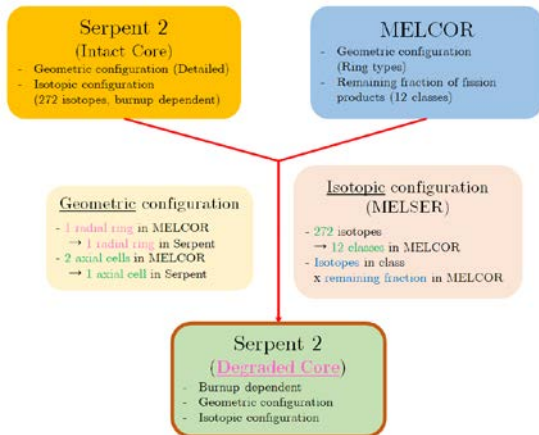

Fig. 3. Coupling procedure of MELCOR and Serpent 2 for the neutronic analyses of degraded reactor core

2.2 Selection of Configuration of the Degraded Reactor Core

With the modeling on the degraded reactor core, we perform the analyses on the criticality of the core for various configurations obtained from MELCOR calculations. The computation conditions used in this calculations are shown in Table 2. Changes of criticality for various water levels are shown in Fig. 4. From the results, we select the configuration at the time of 4200 sec to perform the sensitivity analyses on the water density in the core since criticality at this time is the largest among the various configurations during the scenario.

Table 2. Computational conditions used in the Serpent 2

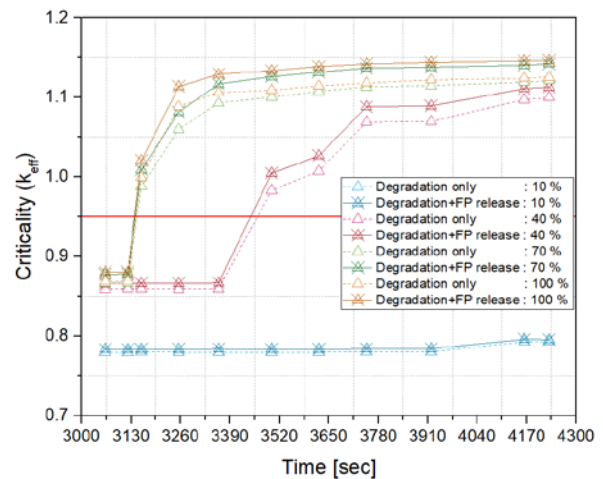| Parameter	Data
Cross section libraries	Continuous energy ENDF/B-VII libraries
# of particles	50,000
# of inactive cycles	300
# of active cycles	300

Fig. 4. Comparison of criticality for the degraded reactor core with the burnup of 0 GWD/MTU in the equilibrium cycle

3. Sensitivity Analyses of the Water Density on the Criticality of the Degraded Reactor Core

With the configuration selected in the previous section, first we perform the sensitivity analyses of the water density on the criticality of the degraded reactor core. For the water densities, we consider 0.1~1.0 g/cm^3. The computation conditions are shown in Table 2. The criticality for the water density at various burnup are shown in Fig. 5. Note that the criticality becomes larger as the water densities increase since the water with high density provides more effective medium to sustain the chain reactions.
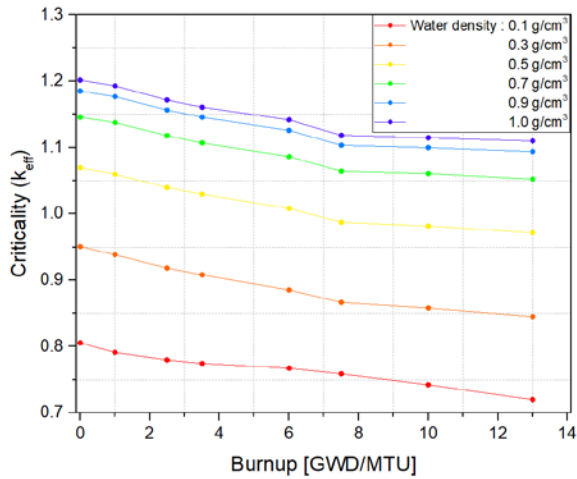
Fig. 5. Comparison of the criticality for the various water density in the degraded reactor core

Boron concentrations that make the criticality of the degraded reactor core less than 0.95, i.e., sub-critical boron concentration are calculated for the water density greater than 0.5 g/cm^3. They are shown in Fig. 6.
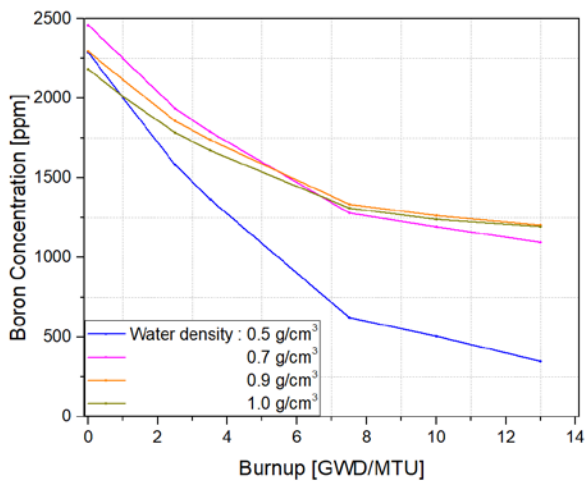

Fig. 6. Comparison of the sub-critical boron concentrations for the various water densities

As shown in Fig. 6, sub-critical boron concentrations with densities of 0.5, 0.7, 0.9, 1.0 g/cm^3 are 2289.1, 2461.0, 2294.0, and 2183.6 ppm, respectively, at beginning of cycle (BOC), which means the effects on the reduction of boron concentrations are more pronounced than those on the excess reactivity at the BOC. However, at the burnup of 13 GWD/MTU, the concentrations are 348.7, 1096.0, 1204.1, and 1194.8 ppm, respectively, which mean the effects on the excess reactivity are more pronounced than those on the reduction of boron concentrations. We can therefore conclude that the sub-critical boron concentration at the BOC with the water density of 0.7 g/cm^3 is a conservative value for the entire fuel cycles of the degraded reactor core.

4. Conclusions

In this paper, we performed sensitivity analyses of the water density on the criticality of the degraded reactor core during early phase of a severe accident. The analyses are performed based on the coupling of MELCOR and Serpent 2. MELCOR code was used to find the configurations on the remaining fractions of the nuclides and those of the control rods in the degraded core. Serpent 2 code was used to analyze the criticality of the degraded reactor core. With the analyses on the various configurations of the degraded core, we selected the configuration when the most of the control rods are relocated but the fuel rods are intact since criticality of the reactor core is the largest among the various configurations.

For the selected geometry, we performed sensitivity analyses of the water density on the criticality of the degraded reactor core. We found that the criticality becomes larger as the water densities increase since the water with high density provides more effective medium to sustain the chain reactions. We also found that the degraded reactor core is sub-critical for various burnup when the water density is lower than 0.5 g/cm^3.

We performed sensitivity analyses on the sub-critical boron concentrations when the water density is higher than 0.5 g/cm^3. We found that at BOC, the effects on the reduction of boron concentrations are more pronounced than those on the excess reactivity. However, the effects on the excess reactivity are more pronounced than those on the reduction of boron concentrations at EOC. Therefore, we concluded that sub-critical boron concentration at the BOC with the water density of 0.7 g/cm^3 is a conservative value for the entire fuel cycles of the degraded reactor core.

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