Evaluation of Recriticality in a Debris Bed on the Reactor Cavity during a Severe Accident

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1. Introduction

Various structure, systems and components are designed and installed for the safety of a nuclear power plant. In spite of their presence for the safety functions, the sequence of a severe accident under the assumption of the safety systems failure has to be predicted and estimated for proving the mitigation capability on a severe accident.

In most of the severe accident scenarios, the core melt is cooled inside a reactor vessel and the structural integrity of a reactor vessel is preserved. In spite of that, as the failure of a reactor vessel is considered for further safety, the ex-vessel phenomena during a severe accident are analyzed to prove that the integrity of containment is preserved.

When a reactor vessel is failed, a core melt is discharged to the reactor cavity and exists in debris and melt form. In that state, reaching the recriticality causes the generation of large thermal energy from the core melt. Therefore, a recriticality estimation of the core melt in the reactor cavity has to be performed for proving the coolability of the core melt in the reactor cavity.

Criticality properties and control strategies after reflooding of a damaged reactor core were analyzed using the MCNPX-2.5 code in the previous study [1]. In addition, the recriticality potential during reflooding phase of Fukushima Daiichi Unit-3 accident was investigated using the MELCOR-2.1 and SERPENT-1.1.19 code [2].

The criticality analysis for the ex-vessel core melt also has been performed. The modeling of the porous internal structure of the debris on the fuel particles characterized by their shape, size and spatial distribution was focused in the previous study [3]. In that paper, MCNP-6.1 and SERPENT-2.1 code were used to construct the debris bed models and compute the infinite multiplication factor.

In another study on the ex-vessel core melt, the criticality of corium arranged in a core catcher for a 1400 MWe nuclear power plant developed in Korea was analyzed with MCNP-5 code [4]. In the research paper, all the evaluation results for the assumed scenarios showed the core catcher satisfies the regulatory guidelines for criticality safety.

The purpose of this paper is to estimate the possibility of recriticality of a debris bed in the reactor cavity during a severe accident. For the analysis, a small pressurized water-cooled reactor was selected as a reference nuclear power plant.

MCNP version-6.2 computer code utilizing the Monte Carlo method was used in the analysis of this paper. For the sensitivity analysis, two following uncertain variables were selected and varied in the analysis:
1) Melting fraction of control rod materials (Ag-In-Cd)
2) Boron concentration in water

2. Analysis Method

2.1 Composition of Debris Bed

The composition and mass of each element in a debris bed were calculated by the MELCOR-2.2 code [5]. The representative severe accident scenario in the reference nuclear power plant was selected by the engineering judgement from the standpoint of the conservative assessment of the coolability in the reactor cavity. Table I shows the composition and cumulative mass in the debris bed discharged from the reactor vessel. The enrichment of uranium was assumed to be a rather high 5 %.

Ag-In-Cd was adopted as a control rod absorber material in the reference reactor. For the first uncertain variable, the melting fraction of Ag-In-Cd was selected. This value varied from 0 to 100 % in the analysis.

Table I: Composition and Mass of the Debris Bed

Composition	Approximate Mass (ton)
UO_2	16
Zr	3
ZrO_2	2
Stainless Steel	7
Stainless Steel Oxide	0.1
Control Rod (Ag-In-Cd)	0 to 7

2.2 Formation of Debris Bed

In the sequence analysis using the MELCOR-2.2 code, the temperature, velocity, diameter and composition of the core melt discharged from the reactor vessel were calculated. Those were used for the input values in the melt spreading analysis using the MELTSPREAD-3.0 code [6]. The analysis result showed the core melt was spread over the area of a circle with a diameter of 3.5 m. Accordingly, in the recriticality evaluation calculation, the debris bed was assumed to exist in the form of a cylinder having a diameter of 3.5 m. The height of the cylinder was calculated by the total mass and porosity of the debris bed in each analysis case.

2.3 Boron Concentration in Water

To cool the core melt in the reactor cavity, the water in the IRWST (In-containment Refueling Water Storage Tank) is discharged to the reactor cavity. The boron concentration in water is normally 4,000 ppm. For the second uncertain variable, the boron concentration was selected considering the conservative condition in which raw water was injected from the outside. The value varied from 0 to 4,000 ppm.

2.4 Acceptance Criterion for Recriticality

The regulatory guide (KINS/RG-N10.01) for the criticality safety in the nuclear fuel storage and handling facilities was applied to the acceptance criterion for this ex-vessel corium criticality analysis [7]. Accordingly, the effective multiplication factor (k_{eff}) derived from the calculated multiplication factor, bias and uncertainty in the calculation method has to be less than 0.95.

3. Preliminary Analysis for Formation of Debris Bed

The porosity of debris bed is the key variable for the recriticality calculation because the empty space in the debris bed is assumed to be filled with the light water as a neutron moderator. In order to find the most conservative condition including the porosity, a stacked structure of particles and particle size, six stacked structures were set and the size of the particles were varied in each structure. The three stacked structures were SC (Simple Cubic), BCC (Body Centered Cubic) and FCC (Face-Centered Cubic). In the other three structures, the particles and moderators were set to be structurally opposite. In each stacked structure, the sizes of mesh and particle radius were varied each.

Finally, the maximum k_{eff} was calculated in the condition that the diameter of the particle was 2.26 cm and the porosity was 0.62 in the FCC particle structure filled with the light water. The FCC particle structure is shown in Fig. 1. This condition selected through the preliminary analysis was used for the sensitivity analysis described in the Chapter 4.

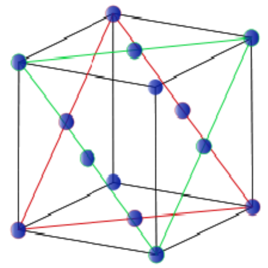

Fig. 1. FCC structure

4. Analysis Results

The effective multiplication factors calculated in each condition of boron concentration in water and control rod melting fraction were shown in Fig. 2. In the conditions that half of the control rods were molten, the k_{eff} was lower than 0.9. The k_{eff} with the boron centration of 4,000 ppm was lower than 0.81 even though no control rod material was included in the debris bed.

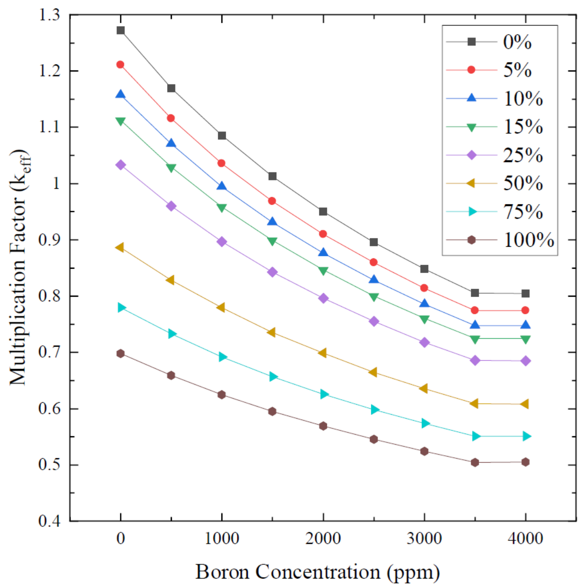

Fig. 2. Effective multiplication factor calculated for each condition of boron concentration in water and control rod melting fraction (percent in legend).

5. Conclusions

The recriticality possibility in a debris bed on the reactor cavity during a severe accident was evaluated in this paper. Consequently, the safety against the recriticality in an ex-vessel debris bed was sufficiently secured except for rare conditions where the control rod materials were hardly melted and the boron concentration in the water was low below 2,000 ppm. Since this analysis was performed for debris bed conditions of small pressurized water reactors, additional considerations and evaluations are needed for nuclear power plants of different types and powers.

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