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Re-criticality Assessment Following Reactor Core Damage in Fukushima Unit 2

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1. Introduction

Following the severe core damage accident at the Fukushima nuclear power plants (NPPs) [1], many researchers have studied a possible re-criticality caused by core melting or corium. However, no one can accurately examine the internal conditions of the reactor vessel, and thus there have been different opinions from some organizations depending on their assumption and analysis methods. If there is a potential re-criticality in the reactor vessel, some counter-plans for the accident management should be established to prevent and mitigate re-criticality, and to return the plant to a safe and stable state.

In this study, the criticality level following a severe core damage accident was first analyzed using the MCNPX 2.6.0 code. Based on this result, practical strategies in terms of accident management were obtained by charging soluble boron (H_3BO_3) into re-flooded water.

2. Materials and Methods

Under a severe core accident condition, it is easy to melt the neutron absorbing rods and control blades faster than nuclear fuel rods. This occurs because the control materials are contained in metallic structures which have lower melting points than the oxide fuel (UO_2) rod material. Thus, the control rods and fuel rods will become separated during the core melt, and re-flooding of the core then has the potential to result in a re-criticality.

To specifically investigate the severe core damage accident in the Fukushima NPP [2], a series of criticality calculations, considering the above-mentioned phenomenon, were conducted using the MCNPX 2.6.0 code. **Figure 1** shows a conceptual geometric model of corium arranged at the bottom of the reactor pressure vessel a after significant core melting. The reference design for the reactor vessel was derived from data based on the Peach Bottom-2 NPP, which has an identical containment model as Fukushima Units 2, 3, and 4 [3-5]. The density and material compositions of corium were reflected by means of the GE 7×7 fuel specifications provided from the SCALE6.1 code [6].

To conservatively model the unknown/ill-defined accident conditions, several assumptions were made. First, the shape of the corium was spherically arranged to achieve the least leakage of neutrons and critical mass. The holes within corium were assumed to be completely filled with pure water (density = 1.0 g/cm^3) which encourages the critical condition as a good moderator. In addition, the existence of gadolinium oxide (Gd_2O_3) in the fuel was neglected in this study. The geometrical model of the poles was set to have a body-centered cubic (BCC) structure to reproduce the irregular placement of the original accident conditions.

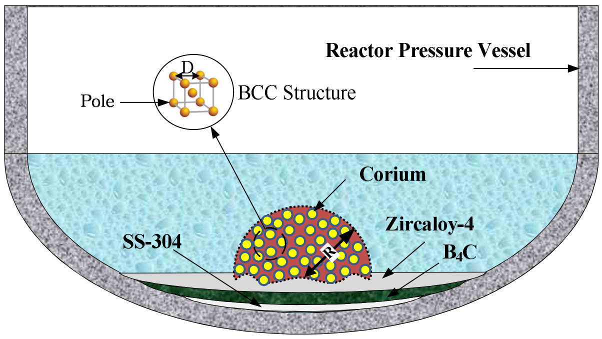

Fig. 1 Conceptual Model of Corium Arrangement in the Reactor Pressure Vessel

A series of criticality calculations were performed by changing the core melting fraction and soluble boron (H_3BO_3) concentration in re-flooded water. The total amount of corium was decided upon by changing the interval (D) between poles, *i.e.* related with the packing ratio and radius (R) of the whole corium shape. As shown in Table 1, the melting fraction of 548 fuel assemblies was selected with a range of approximately 0% to 77%. The soluble boron (H_3BO_3) concentration in re-flooded water was also changed from 0 ppm to 5,000 ppm ($\simeq$ 1,000 ppm ^{10}B).

Table 1 Melting Fraction of Fuel Assembly upon Changing the Packing Ratio and Radius of the Whole Corium Shape

Packing Ratio of Corium [%]	Radius of Whole Corium Shape (R)			
	50 *cm*	100 *cm*	150 *cm*	200 cm
10	0.20%	1.60%	5.39%	12.77%
30	0.60%	4.79%	16.16%	38.30%
50	1.00%	7.98%	26.93%	63.83%
60	1.20%	9.57%	32.31%	76.59%

**The radius of the poles within BCC structure was fixed to 0.075 cm*

3. Results and Discussions

To evaluate a possible re-criticality following a severe core damage accident, the criticality was analyzed by varying the total amount of corium. As shown in **Table 2** and **Figure 2**, the effective multiplication factor (k_{eff}) of corium under the Fukushima NPP accident represented a range of 1.03241±0.00194 to 1.40801±0.00157. Also, when radius (R) of the whole corium shape is fixed, the highest criticality was indicated at a corium packing faction of 30%, regardless of increasing the total amount of corium. From these results, it was recognized that the reactor core damaged by a severe accident has a potential to reach re-criticality condition, and hence it should be taken with a measure suitable for the occasion.

Table 2 Criticality (k_{eff}) for Reactor Corium Following Severe Core Damage Accident in the Fukushima NPP (with 0 ppm ^{10}B)

Packing Ratio of Corium [%]	Radius of Whole Corium Shape (R)			
	50 *cm*	100 *cm*	150 *cm*	200 cm
10	1.11619 (0.00148)	1.23908 (0.00109)	1.26772 (0.00104)	1.28304 (0.00094)
30	1.21873 (0.00197)	1.3544 (0.00168)	1.3928 (0.00160)	1.40801 (0.00157)
50	1.11008 (0.00170)	1.25127 (0.00211)	1.29148 (0.00178)	1.30467 (0.00169)
60	1.03241 (0.00194)	1.17368 (0.00179)	1.21321 (0.00166)	1.23082 (0.00183)

** ( ) : standard deviation*

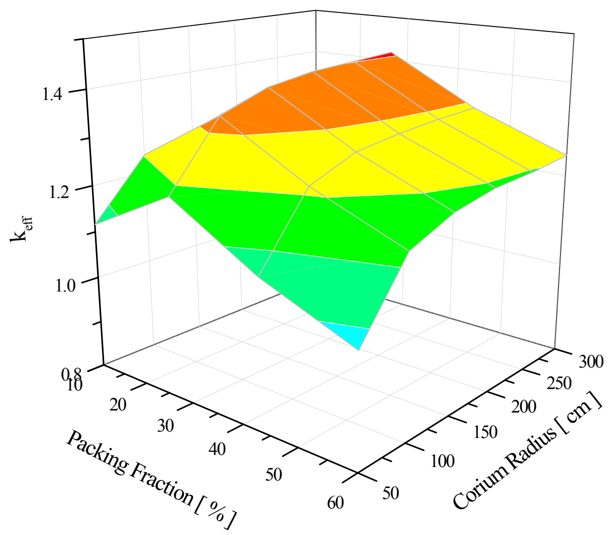

Fig. 2 Calculated k_{eff} for Reactor Corium in Re-flooded Water with 0 ppm ^{10}B

The soluble boron (H_3BO_3) concentration required in re-flooded water was investigated to prevent or mitigate the re-criticality condition of the reactor core damaged by a severe accident. **Figure 3** shows the change in the effective multiplication factor (k_{eff}) according to the boron concentration injected into water. From these results, it was found that at least 600 ppm ^{10}B ($\simeq$ 3,000 ppm H_3BO_3) is required to ensure subcriticality following a severe core damage accident.

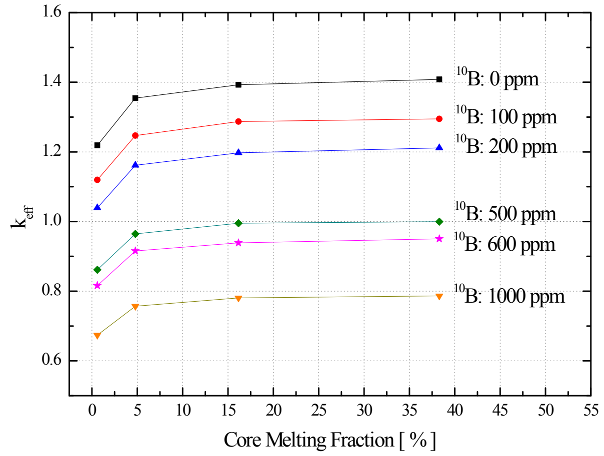

Fig. 3 Calculated k_{eff} for Reactor Corium in Water as a Function of ^{10}B Concentration

3. Conclusions

To specifically investigate the severe core damage accident at the Fukushima NPP, the criticality level for the reactor corium was analyzed using the MCNPX 2.6.0 code. Based on this result, the adequate soluble boron (H_3BO_3) concentration was also evaluated to ensure subcriticality of the reactor core. As a result, the effective multiplication factor (k_{eff}) of corium has a range of 1.03241±0.00194 to 1.40801±0.00157. In addition, when radius (R) of the whole corium shape is fixed, the highest criticality was indicated at a corium packing faction of 30%, regardless of increasing the total amount of corium. According to the boron injection into water, it was found that at least 600 ppm ^{10}B ($\simeq$ 3,000 ppm H_3BO_3) is required to assure the subcriticality condition following a severe core damage accident. Consequently, based on a conservative bounding analysis, this study may be used for practical strategies for accident management to prevent or mitigate re-criticality, and to return the plant to a safe and stable state.

REFERENCES

[1] NHK-world (November 2nd 2011) TEPCO: Reactor may have gone critical
[2] "Fukushima Daiich Nuclear Power Plant", Wikipedia, *http://en.wikipedia.org/wiki/Fukushima_Daiich_Nuclear_Power_Plant*
[3] U.S. NRC: "Expanded NRC Questions and Answers related to the March 11, 2011 Japanese Earthquake and Tsunami", ML120040283, 2012
[4] Maggini. F. 2004. Contributions to study instability in BWR: application to Peach Bottom-2 NPP. Laurea thesis etd-183309, University of Pisa.
[5] Heel, A.M.J.M. Van: "In-vessel core debris retention through external flooding of the reactor pressure vessel: State-of-the-art report", ECN-R-95-022, Patten: ECN, 1995
[6] ORIGEN Code under SCALE6.1 System, Oak Ridge National Laboratory