Evaluation of Possibility for Reactor Corium Re-criticality in Fukushima NPP Accident

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1. Introduction

With a growing concern of Fukushima nuclear power plant (NPP) accident, there has been a widespread effort to prevent further damage throughout the world. At the end of 2011, however, a possibility for the reactor corium re-criticality was issued, as a slightest amount of xenon (Xe^{133} and Xe^{135}) was detected in gas samples taken from the filter of the gas-control system at the Unit 2 containment vessel [1, 2]. Xe^{133} and Xe^{135} are isotopes created during the nuclear fission of U^{235}, and are not usually detected even when the reactor is in operation due to the fuel rods covered with the zirconium metal. Hence, the presence of these materials could only mean that nuclear fissions may have occurred in the molten fuels. In addition, the xenon was proven to be probably created recently, since they have short half-lives of 5 days and 9 hours, respectively.

As a result, some organizations have announced the significantly different accident scale of Unit 2, depending on used computer codes and their assumptions, and especially molten degree of the fuel assembly. In this study, therefore, a criticality evaluation for the unit 2 reactor corium of the ravaged Fukushima daiichi NPP was performed by changing the total amount of the reactor corium.

2. Methods and Materials

2.1 Characteristic of Unit 2 Reactor

Unit 2 was built with a Mark I type containment system of BWR-4 and loaded with 548 General Electric (GE) fuel assemblies with a 7×7 array [3]. As shown in Figure 1, the assembly features an asymmetric structure consisting of three types of fuels with the different enrichment degree (none, 3 *wt%*, and 4 *wt%*) of Gadolinium Oxide (Gd_2O_3). The density and the material compositions of the corium were reflected according to the detailed GE 7×7 fuel specifications provided from SCALE6 code [4].

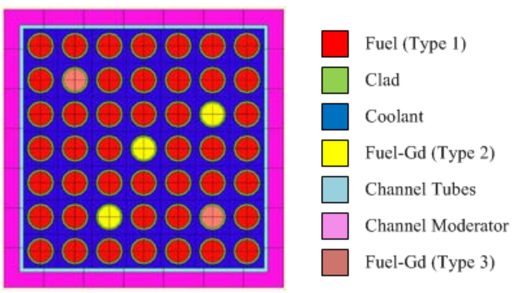

FIG. 1 Configuration of GE 7×7 Fuel Assembly

2.2 Criticality Calculation

Figure 2 shows a conceptual geometric model for MCNP criticality calculation. For conservative results, the shape of the corium was spherically arranged to achieve the least leakage of neutrons and critical mass. The holes within the corium were assumed to be completely filled with pure water (density = 1.0 g/cm^3) which encourages the critical condition as a role of a moderator. The geometrical model of the holes was set to have the body centered cubic (BCC) structure to reproduce the irregular placement of the original accident condition.

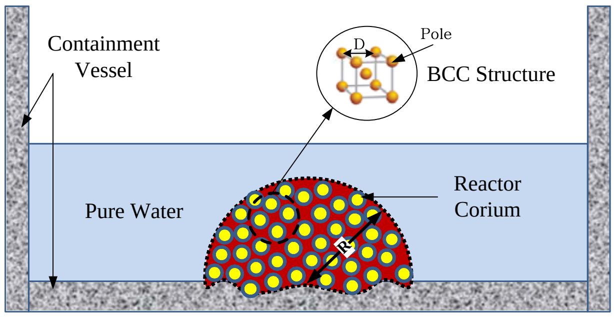

FIG. 2 Conceptual Model of Reactor Corium Arrangement

Total amount of the corium was decided upon changing the interval (D) between the poles, *i.e.* related with packing ratio, and the radius (R) of whole corium shape. The criticality for the molten level (approximately 0% ~ 50%) of the 548 fuel assemblies was calculated (see Table 1). In addition, two kinds of the corium materials were also considered to additionally analyze the effects on the criticality when including or not including Gd_2O_3 in the fuel. In the case of the fuel assembly without Gd_2O_3, the ratio of material compositions was proportionally scaled up based on those of reference assembly.

Table 1 Molten Level of Fuel Assembly upon Changing the Packing Ratio and the Radius of Whole Corium Shape

Packing Ratio of Corium [%]	Radius of Whole Corium Shape (R)		
	50 *cm*	**100 *cm***	**150 *cm***
10	0.30%	2.39%	8.07%
30	0.90%	7.18%	24.22%
50	1.50%	11.96%	40.37%
60	10.79%	14.35%	48.44%

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

Finally, a series of criticality calculations were conducted using MCNPX 2.5.0 code.

3. Results and Discussions

In order to verify the corium re-critical possibility, the criticality for the Unit 2 reactor corium was analyzed from varying total amount of the corium which includes Gd_2O_3 or not. Table 2 shows the expected results for the reactor corium with Gd_2O_3. The reactor corium including Gd_2O_3 was verified to have the sufficient criticality safety as the maximum value of the criticality was calculated as 0.59486±0.00089. In addition, the criticality up to the maximum value was gradually increased along with the growth in the total amount of the reactor corium depending on the packing ratio and the radius 'R'. Thus, it was confirmed that the Unit 2 reactor corium hardly has the possibility of the re-criticality. This is because that Gd_2O_3 functioned effectively as a very strong neutron absorber in the fuel, although pure water was filled in the containment vessel as a neutron moderator.

Table 2 Criticality (k_{eff}) for Reactor Corium including Gd_2O_3

Packing Ratio of Corium [%]	Radius of Whole Corium Shape (R)		
	50 *cm*	**100 *cm***	**150 *cm***
10	0.23462 (0.00039)	0.25749 (0.00033)	0.26275 (0.00035)
30	0.34651 (0.00056)	0.38308 (0.00058)	0.39488 (0.00054)
50	0.45089 (0.00090)	0.51087 (0.00077)	0.52625 (0.00086)
60	0.49758 (0.00099)	0.57373 (0.00088)	0.59486 (0.00089)

In case of not including Gd_2O_3 in the corium, however, the calculated results showed the super critical condition of the range from 1.04671±0.00195 up as high as 1.37803±0.00147 despite a little amount of the corium. It was also founded that the criticality varied regardless of increasing the total amount of the corium changing from the packing ratio while the radius 'R' is fixed. Therefore, the corium without Gd_2O_3 is recognized to have the optimized packing ratio which has the minimum and maximum criticality.

Table 3 Criticality (k_{eff}) for Reactor Corium not including Gd_2O_3

Packing Ratio of Corium [%]	Radius of Whole Corium Shape (R)		
	50 *cm*	**100 *cm***	**150 *cm***
10	1.05990 (0.00132)	1.17743 (0.00115)	1.20648 (0.00102)
30	1.20503 (0.00183)	1.34165 (0.00160)	1.37803 (0.00147)
50	1.11952 (0.00195)	1.25780 (0.00180)	1.29668 (0.00160)
60	1.04671 (0.00195)	1.18205 (0.00178)	1.22068 (0.00172)

4. Conclusions

The criticality for the reactor corium of the Fukushima Daiich Unit 2 was analyzed using MCNPX code in order to verify the re-critical possibility. The criticality was calculated for the molten level up to ~ 50% of the fuel assemblies, and two kinds of the corium materials were considered by including Gd_2O_3 in the fuel assembly or not. As a result, the reactor corium with and without Gd_2O_3 was verified to maintain the sub-critical and super critical conditions over all their tested areas, respectively. Also, the criticality of the corium without Gd_2O_3 was changed regardless of increasing the total amount of the corium. Therefore, further study for the optimized packing ratio, according to the specific accident scenarios, would be needed in the future. With the conservative assumption, consequently, it is recognized that the re-criticality of the reactor corium would be possible if there is no neutron absorber.

REFERENCES

[1] NHK-world (November 2nd 2011) TEPCO: Reactor may have gone critical

[2] ENENEWS (Novenber 2nd 2011) Kyoto Nuke Expert: This amount of xenon would not be detected unless melted fuel had "fission chain reaction"

[3] "Fukushima Daiich Nuclear Power Plant", Wikipedia, *http://en.wikipedia.org/wiki/Fukushima_Daiich_Nuclear_Power_Plant*

[4] ORIGEN Code under SCALE6 System, Oak Ridge National Laboratory