Transactions of the Korean Nuclear Society Spring Meeting
Gwangju,Korea,May 30-31, 2013

Analysis on the Multiplication Factor with the Change of Corium Mass and Void Fraction

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1. Introduction

When a severe accident including core melt-down occurs, the neutron absorbing rods fall the bottom of the reactor pressure vessel down faster than nuclear fuel rods. Thus, the neutron absorbing materials and fuel rods would be separately arranged and relocated, since the control materials in metallic structures have lower melting points than that of the oxide fuel (UO_2) rod materials. In addition, core reflood for a BWR is normally accomplished by supplying unborated water unlikely for a PWR [1]. Therefore, a potential for a re-criticality event to occur may exist, if unborated coolant injection is initiated with this configuration in the reactor core.

The re-criticality in this system, however, brings into question what the uranium mass is required to achieve a critical level. Furthermore, the additional decay heat from molten fuel (corium) will produce an increase of void and eventually results in under-moderation of neutrons. The prior verification of these consequential physical variations in criticality eigenvalue (effective multiplication factor, k_{eff}) should be greatly contributed to control and termination of re-criticality.

Therefore, this study addresses what uranium mass of corium could achieve re-criticality of an accident core, and how effect the coolant void fraction has on eigenvalue (k_{eff}) and its reactivity.

2. Materials and Methods

The design data (*e.g.*, material composition, density, geometric dimension) for the reactor vessel were based upon the Peach Bottom-2 reactor. The density and material compositions of the corium were reflected according to the detailed specifications of General Electric (GE) 7×7 fuel assembly provided from SCALE6 code [2]. **Figure 1** illustrates the conceptual geometric model of corium arranged at the bottom of the reactor pressure vessel.

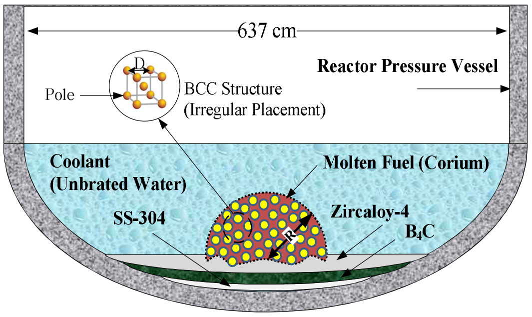

Fig. 1 Conceptual Model of Molten Fuel (Corium) Arrangement within the Reactor Core

With several assumptions in this study, the molten fuel was piled up in a hemispherical shape to achieve least leakage of neutrons, and the holes within corium were completely filled with pure water which encourages the critical condition as a good moderator. The existence of gadolinium oxide (Gd_2O_3) in corium was neglected. The calculation model of poles was set to have a body-centered cubic (BCC) structure to reflect the irregular placement of the original accident conditions.

A series of calculation for effective multiplication factor (k_{eff}) were performed using the MCNPX 2.5.0 code [3] to verify the critical mass of corium and the effect by coolant void occurred. The criticality source (KCODE) mode of MCNP was applied to all calculation using 1000 particles per a cycle with 50 inactive cycles and 150 active cycles. In this simulation, the ENDF/B-VI.5 cross section library was used. The critical configuration was set depending on the core melting fraction as a function of the radius (R) of the whole corium shape. The critical level was conservatively set to $k_{eff} = 0.95$. Based on the condition with k_{eff} greater than unity, the void fraction of the supplied water was gradually adjusted from 0% to 95% (coolant density: 1 g/cm^3 to 0.05 g/cm^3).

3. Results and Discussions

The critical mass for corium and the k_{eff} values by the variance of coolant density were calculated, and the reactivity change was also analyzed. As shown in **Figure 2**, a large change in corium mass led to a little change in k_{eff} value. However, this result indicates that only quantities slightly more than 60 kg of uranium are necessary to achieve a critical level. Considering the quantities of uranium per a GE 7×7 fuel assembly is over about 200 kg and hundreds of assemblies are loaded in the reactor core, therefore, it is found that a few amounts of total corium can result in re-criticality.

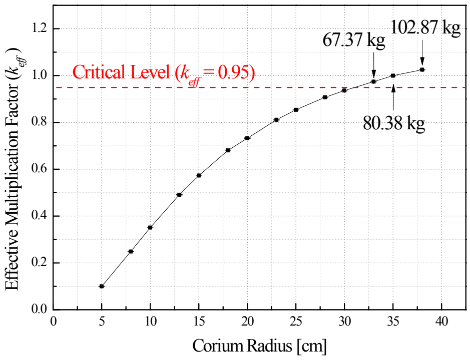

Fig. 2 The Effective Multiplication Factor (k_{eff}) as a Function of Corium Fuel Mass

Under the condition with k_{eff} greater than unity (i.e., 102.87 kg), the criticality change by the void fraction of coolant (initial density: 1.0 $\mathrm{g/cm^3}$) was calculated as represented in **Figure 3**. As the coolant void is more produced from 0% to 95%, the absolute value of decrease rate for k_{eff} was gradually increased. Also, the k_{eff} value approaches the sub-critical state when the void fraction is above 30%. **Table 1** shows reactivity and its coolant density coefficient (CDC) analyzed upon changing the injected coolant density.

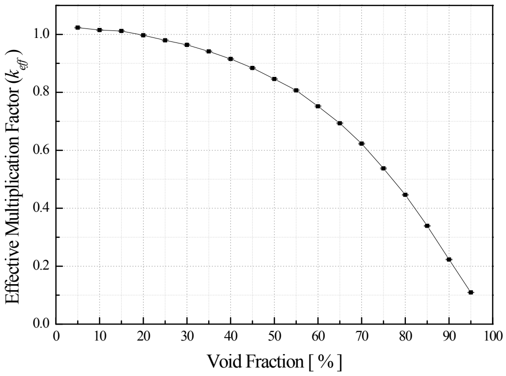

Fig. 3 The Effective Multiplication Factor (k_{eff}) as a Function of Void Fraction of Coolant

Table 1 Reactivity and Coolant Density Coefficient (CDC) under the variation of Coolant Density

Coolant Density $[\mathrm{g/cm^3}]$	Reactivity	CDC $[\mathrm{pcm/(g/cm^3)}]$	Standard Deviation
1.00	0.02434	-	-
0.95	0.02288	-0.02917	0.002263
0.90	0.01492	-0.15920	0.002391
0.85	0.01161	-0.06621	0.002461
0.80	-0.00296	-0.29145	0.002447
0.75	-0.02089	-0.35857	0.002475
0.70	-0.03758	-0.33388	0.002611
0.65	-0.06237	-0.49581	0.002557
0.60	-0.09250	-0.60261	0.002440
0.55	-0.13131	-0.77618	0.002583
0.50	-0.18189	-1.01164	0.002802
0.45	-0.23945	-1.15112	0.002775
0.40	-0.33007	-1.81242	0.002652
0.35	-0.44227	-2.24406	0.002576
0.30	-0.60506	-3.25572	0.002496
0.25	-0.86053	-5.10950	0.002560
0.20	-1.23964	-7.58215	0.002425
0.15	-1.94916	-14.19030	0.002072
0.10	-3.48370	-30.69090	0.001826
0.05	-8.14160	-93.15803	0.001429

3. Conclusions

To analyze the critical mass and the effect on criticality upon changing coolant density, k_{eff} values were calculated using the MCNPX 2.5.0 code, and the reactivity change was also investigated. As a result, a large change in corium mass leads to a little change in k_{eff} value, nevertheless, only about 60 kg of uranium is necessary to achieve a critical level. Thus, the amounts to reach a re-criticality are not fairly large, considering the actual uranium quantities loaded in the reactor core. Based on the condition with k_{eff} greater than unity, the absolute values of k_{eff} decrease rate and the coolant density coefficient were gradually increased due to the steady increments of coolant void (i.e., decrease in coolant density). In addition, the k_{eff} value approaches the sub-critical state when the void fraction is above 30%. With the prior study regarding re-criticality control using ^{10}B [4], therefore, these verifications on the consequential physical behavior could be also contributed to the establishment of practical strategies for accident management as a reference.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT, and Future Planning) (No. NRF-2012M2A8A4025893).

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