Preliminary Multi-dimensional Analysis of Long Term Cooling Process following LBLOCA under Deformed Core Condition

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1. Introduction

Long term cooling (LTC), as one of the acceptance criteria of Emergency Core Cooling System (ECCS), is defined as follows [1]:

"*After any calculated successful initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.*".

To this end, restricting boric acid precipitation (BAP), which may interfere with cooling of the core after quenching by ECCS following a loss of coolant accident (LOCA), has been applied as a specific acceptance criterion [2]. The limit of boron precipitation is defined as the saturated boron concentration at that temperature.

Changes in thermal and mechanical properties of cladding and pellet and in geometric shapes due to cladding swell and rupture under high burnup condition may affect long-term cooling performance as well as LOCA itself [3]. Research on the effects of fuel burnup has so far focused on short-term LOCA phenomena, however, it is necessary to evaluate the effect of burnup on long-term cooling behavior leading to boron precipitation. In particular, since changes in the shape of the fuel rods by cladding swell and rupture can cause local deformation of the core, analysis of this effect may require calculation of multi-dimensional core flow.

In order to reasonably predict the distribution of boron concentration in the core, we analyzed LTC process following a large break LOCA using the multid component model [4] of the MARS-KS code which calculates three-dimensional hydrodynamics, in this paper. In this preliminary analysis, the deformation of the core was a hypothetical case in which 70% of the flow area was blocked in the hot channel of the core.

2. Code and Modeling

All calculations in this study used the MARS-KS code version 1.5 [4].

Fig. 1 shows a nodalization of the reactor vessel (RV) used in the present analysis. The analysis was done for the APR1400 design in which PLUS7 fuel was loaded. RV was simulated by 6 azimuthal sectors, 4 radial rings and 29 axial cells. Specifically, downcomer, lower plenum, upper head, and the rest of the reactor vessel are simulated as four separated multid components, respectively. The hot channel of highest peaking factor was located at the first ring, and the second azimuthal sector, ($r=1$, $\theta=2$).

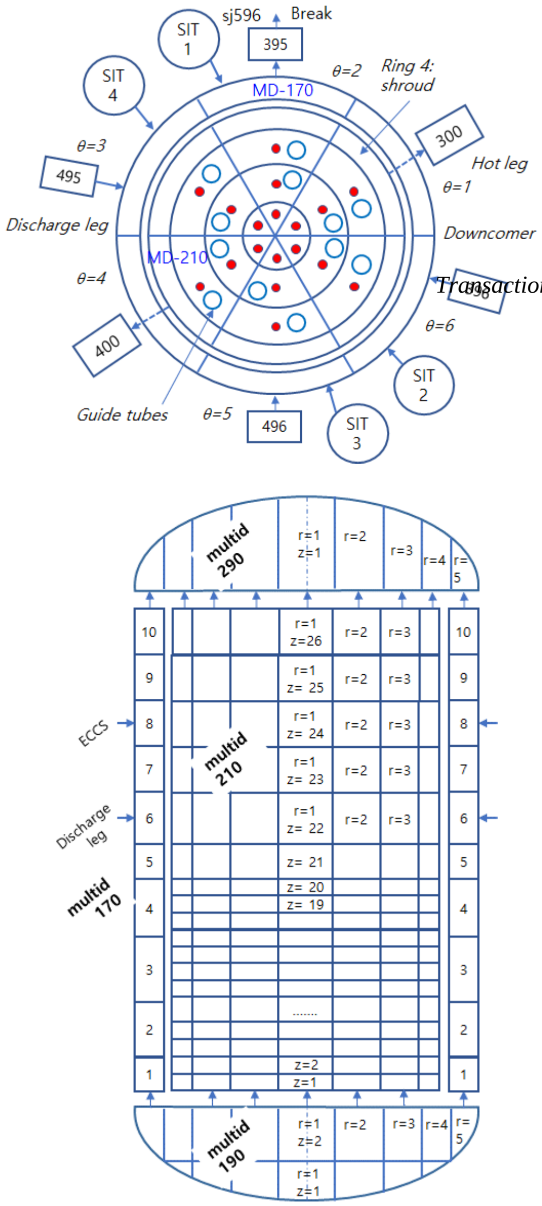

Fig. 1. Nodalization of RV by multid components

The reactor power was assumed 100% nominal one and the ANS73 core decay heat model was applied to the calculation.

ECCS water is supplied from In-containment Refueling Water Storage Tank (IRWST). The temperature and pressure of water in the IRWST were determined using the data provided in the containment minimum pressure for ECCS performance analysis described in the Final Safety Analysis Report (FSAR) [5]. The peak value of the temperature was up to 90°C at about 30,000sec.

The concentration of boric acid in IRWST begins at an initial concentration of 4,400 ppm (2.52 weight %) and continues to increase as it mixes with the water released from the reactor coolant system. Therefore, the boric acid concentration of ECCS water should be determined by the ECCS flow, boil-off rate in the core, the break flow, the inventory of IRWST, and their boric acid concentrations, but the present paper assumes it reaches 3 wt% at 3,000 seconds based on the assumption of FSAR.

The deformed fuel condition was defined as blockage of flow area in 70 % which was obtained by the previous study [6]. It was modeled by the reduction of the fluid volume and junction area and by imposing the K-factor induced by the blockage at the cell ($r=1$, $\theta=2$, $z=13$).

Transient calculation should be performed for up to few hours, but this preliminary study, transient up to 3,000 seconds was calculated for. As a result, the temperature behavior of the ECCS water and the pressure behavior of the containment were simulated to occur within 3,000 seconds. Although this is not the real, it can be said conservative in terms of the fact that hotter water enters the core when the core decay heat is greater than the actual case, resulting in more boil-off.

3. Results and Discussions

Fig.2 shows a comparison of the calculated cladding temperature responses for the case of un-deformed case and the deformed case. As shown in the figure, the behavior of cladding temperature begins to differ as it enters the reflood phase, and the quenching is delayed in the deformed case. Thereafter, the temperature remains stable, with no difference between the two cases.

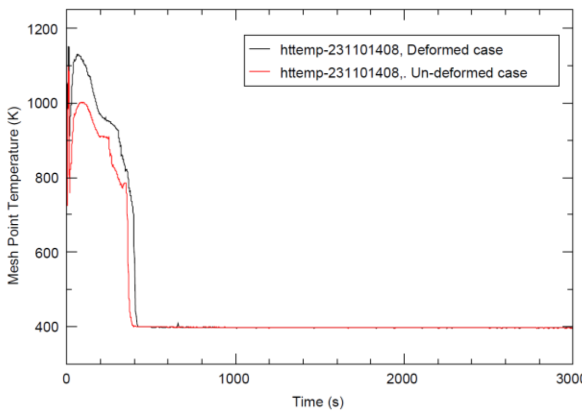

Fig. 2. Comparison of cladding temperature between deformed case and un-deformed case

Fig. 3 shows boric acid concentrations at the upper half of the core for the deformed case. The maximum value was less than 8wt % at 3,000 second. Based on this result, we can estimate the maximum boron concentration at the starting time of the simultaneous injection (i.e., 2.5 hours after LOCA [5]) is less than 12 wt% by simple extrapolation. Specific calculation is under way.

Also, it can be found that the variation in boric acid concentration over the upper half of the core was about 2 wt%, which means a certain amount of mixing of the borated water was achieved during 3,000 second. However, one can see that the range of this variation is getting bigger over time, which means that mixing may not work as well. No significant increase in boron concentration due to rapid boil-off which occurred in the early stage of LOCA is predicted after quenching.

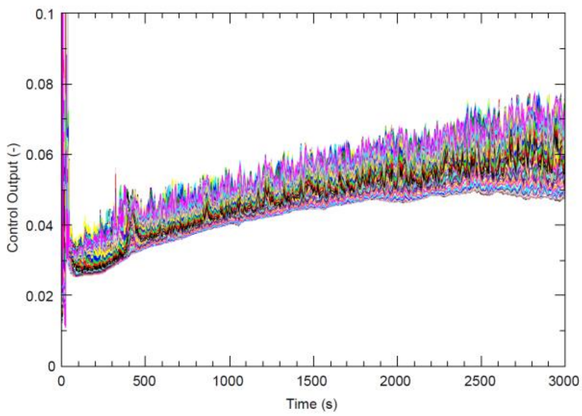

Fig. 3. Boron concentrations at the upper half of the core for the deformed case

Fig. 4 shows comparison of the boric acid concentrations at the cell ($r=1$, $\theta=2$, $z=13$) between the deformed case and the un-deformed case. No significant difference was found between two cases. It indicated that the effect of flow blockage by fuel deformation on the boric acid concentration is not significant up to 70% blockage.

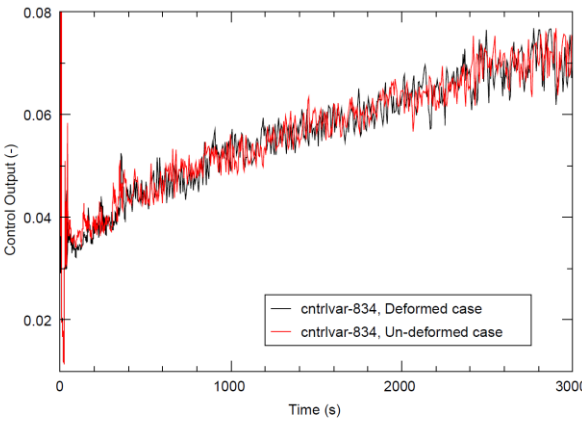

Fig. 4. Comparison of boron concentration between deformed case and un-deformed case

4. Conclusions

Long term cooling process following a LBLOCA under the deformed core condition corresponding to 70% blockage of flow area was calculated. The multid component model of MARS-KS code with the conservative decay heat model were used. The calculated result indicated the maximum boron concentration was at 8 wt% until 3,000 seconds into transient, and the estimated one at 2.5 hours after LOCA is about 12 wt %. The effect of flow blockage up to 70 % due to the core deformation has insignificant effect on the boric acid concentration. However, further study may be required for other burnup-dependent conditions that were not considered in this study.

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