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SBLOCA Analysis Using Modified MAAP4 Code through Semi-empirical CHF Correlation Application

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1. Introduction

A lower part of the reactor pressure vessel was overheated and then rather rapidly cooled down [1,2] during the Three-Mile Island Unit 2 (TMI-2) accident. This accounted for the possibility of cooling in the narrow gap on the order of millimeters and centimeters, which may have been formed between the solidified core debris and the reactor vessel lower head. Post-test analyses, completed as part of the TMI-2 Vessel Investigation Project [3], suggested the presence of core material-to-vessel gaps. For this reason, additional data were obtained to quantify the critical heat flux (CHF) in narrow gaps, and an engineering correlation was developed through the CHF data for the gap cooling between the molten core and the inner surface of reactor vessel during natural convective boiling with the one-dimensional inclined and confined rectangular channels [4]. The developed CHF correlation was applied to the MAAP4 code in lieu of Monde et al.'s correlation [5].

2. Analytical Work

The molten core configuration and thermal load analyses were performed for typical accident sequences of cold leg break areas in APR1400 probabilistic safety assessment (PSA) [6] using the Modular Accident Analysis Program 4 (MAAP4) code [7,8]. According to the higher core damage frequency (CDF) [events/year] contributions and the greater conservative core damage sequences, accident sequences 17, 22, and 23 in the small break loss of coolant accident (SBLOCA) were chosen for the analysis.

Sequences 17, 22, and 23 in the SBLOCA event tree have higher CDF values than those of the others, in other words, they have 7.24e-9, 1.45e-7, and 2.16e-7, respectively. Sequence 23 has the highest valve and the most conservative accident sequence in the SBLOCA event tree, and no action is taken after a reactor trip. Furthermore, as a part of a sensitivity analysis, the thermal loads were evaluated in each of three break areas (i.e., 0.01, 0.015 and 0.02 ft^2) for the SBLOCA.

The MAAP4 source code used in this SBLOCA analysis was modified using a newly developed CHF correlation and an angular heat flux in the lower head concept, as shown in Fig. 1. Excluding a fully downward facing position (180^o), the semi-empirical CHF correlation was obtained as follows.

$$\frac{q_{CHF}/\rho_g h_{fg}}{\sqrt[4]{\frac{\sigma g \sin(\theta)\left(\rho_f-\rho_g\right)}{\rho_g^2}}} = \frac{0.163}{1+6.431\times10^{-4}\left(\frac{\rho_f}{\rho_g}\right)^{0.564}\left(\frac{g\sin(\theta)(\rho_f-\rho_g)s^2}{\sigma}\right)^{0.011}\left(\frac{l}{s}\right)}$$

The developed correlation agrees with the experimental CHF data within about ±12%.

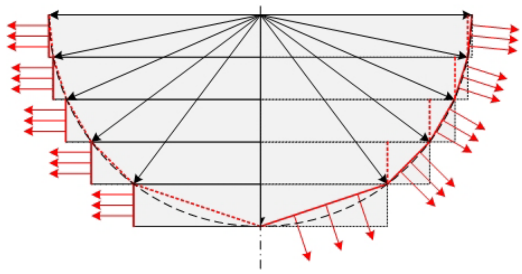

Fig. 1. Angular heat flux in the lower head of the MAAP4 code (existing model on the left-hand side and modified concept on the right-hand side).

3. Results

Figure 2 shows that the molten core relocation time and reactor vessel failure time were decreased while the debris crust thickness was increased for the SBLOCA as the break size increased. In particular, the debris crust thicknesses for three break areas (0.01, 0.15 and 0.02 ft^2) were 25, 75 and 91 cm, respectively, in sequence 22. In addition, the starting time at which the molten core relocated to the lower head, and the reactor vessel failure time were lengthy, but the masses were smaller than those of other sequences.

The amount of total upward-facing heat transfer (i.e., the heat transfer from oxide pool to metal layer) plays an important role in calculating the maximum sideward-facing heat flux from the metal layer. The thermal load from the molten core configuration is presented for accident sequences 17 and 23 in the SBLOCA event tree, as plotted in Figs. 4 and 5.

The amount of decay heat from the core melt generally increased as the break size was increased. The maximum sideward heat fluxes from metal layer were less than 1 MW/m^2 for sequences 22 and 23, whereas those ranges for sequence 17 were high and wide (i.e., 0.964 to 1.683 MW/m^2). In addition, three ratios of the total upward-facing heat transfer to the decay heat (for break sizes of 0.5, 1.0 and 9.8 ft^2) for sequence 17 were larger than those for the other sequences. In other words, the ratios for sequence 17 were higher than 42%, whereas those for sequences 22 and 23 were lower than 6%.

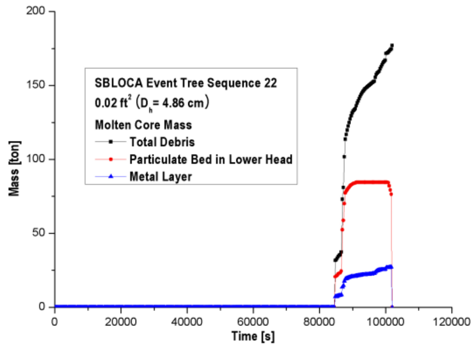

Fig. 2. Molten core mass in lower head with sequence No. 22 for 0.02 ft^2.

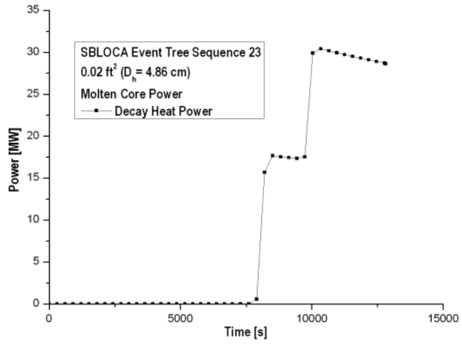

Fig. 3. Molten core power in lower head with sequence No. 23 for 0.02 ft^2.

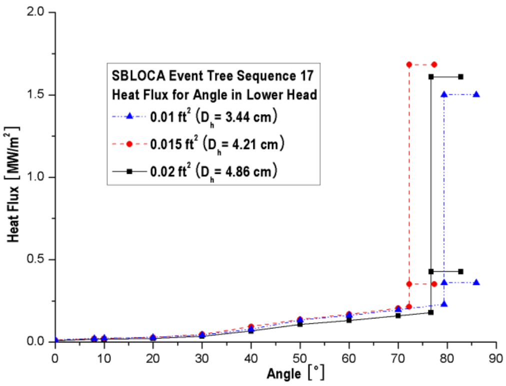

Fig. 4. Angular heat flux (at maximum decay heat) for break sizes with sequence No. 17.

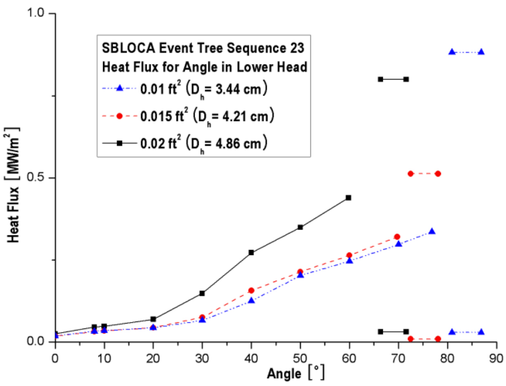

Fig. 5. Angular heat flux (at maximum decay heat) for break sizes with sequence No. 23.

4. Conclusion

The molten core configuration and thermal load analyses for the determined accident sequences and break areas of a cold leg in APR1400 PSA were performed using the MAAP4 code. As the break size increased, the starting time at which the molten core was relocated to the lower head and the reactor vessel failure time decreased while the debris crust thickness increased for the accident sequences 17, 22, and 23 in the SBLOCA event tree.

The angular heat flux generally increased as the break size was increased. However, if the decay heat and ratio of total upward-facing heat transfer to decay heat from the debris are simultaneously greater than those for the other cases, the thermal load of the metal layer could be greater regardless of the break sizes. Furthermore, the difference between the average temperature of the metal layer and the temperature of the internal reactor vessel is also one of the uncertainties for a sideward heat flux from metal layer.

Therefore, the sideward-facing heat flux from the metal layer could depend on the ratio of total upward-facing heat transfer to the decay heat, as well as the temperature difference between the average temperatures of the metal layer and inner vessel wall temperature.

Acknowledgments

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