Evaluation of Fuel Burnup Effects on LOCA PCT Using MARS/FRAPTRAN Coupled Code

Hyong Chol Kim *, Young Jin Lee, Sam Hee Han
NSE Technology Inc.
**Corresponding author: hckim@nsetec.com*

1. Introduction

The MARS thermal-hydraulic system code has been coupled with the FRAPTRAN code to enhance the state-of-the-art fuel performance modeling features of FRAPTRAN. As a demonstration study of the MARS/FRAPTRAN coupled code application, a Loss-of-Coolant Accident (LOCA) of OPR-1000 reactor was analyzed using the coupled code [1] and the effects of cladding failure on peak cladding temperature (PCT) was assessed [2].

Recently, safety concern has been raised regarding fuel thermal performance analysis codes that do not account for fuel thermal conductivity degradation [3]. Therefore, fuel performance software needs to be updated to account for the thermal conductivity degradation due to fuel burnup. Also, this should be properly taken into account in such safety analyses as the LOCA analysis.

In this study, the effect of fuel burnup on PCT during LOCA was evaluated using the MARS/FRAPTRAN coupled code.

2. Methods of Analyses

2.1 Methods of Coupled calculation

In the MARS/FRAPTRAN coupling calculations, MARS calls the main routine of FRAPTRAN-DLL, which is FRAPTRAN in Dynamic Link Library (DLL) format, and provides the boundary conditions for FRAPTRAN-DLL calculation. Depending on user option, FRAPTRAN-DLL calculated surface heat flux, cladding surface temperature, and/or cladding outer radius are fed back to MARS. Multiple FRAPTRAN-DLL coupling is possible allowing simultaneous simulation of more than one heat structure. A separate mapping file is used to define the correspondence between the heat structures of MARS and the fuel model of FRAPTRAN-DLLs.

2.2 Input Preparations for Analysis

A large-break LOCA of an OPR-1000 PWR reactor was selected as the reference scenario [4]. MARS core model consists of three heat structures and two flow channels.

The three heat structures represent the hottest rod, the hot assembly, and the remaining average rods. The hottest rod and the hot assembly are separately coupled to two FRAPTRAN fuel models.

Power source data of an OPR-1000 equilibrium cycle are used, but the radial peaking factor and the axial power distribution are modified to consider the adverse conditions allowed for the normal plant operation.

To consider burnup of the fuel rod in the coupled calculation, FRAPCON [5] depletion calculation is performed for the generation of restart file for FRAPTRAN. For analysis purpose, a constant linear power rate of fuel rod is assumed with cycle-average axial power profile.

In order to represent the correct stored energy in the fuel at the designated fuel burnup, the FRAPCON results are used to obtain MARS steady-state restart file. The thermal conductivities of the coupled fuel rods in the MARS steady-state input were adjusted until the resulting average fuel temperatures are close to the FRAPCON results at the given burnups.

2.3 Formulation of Analysis-State Points

As fuel depletes, the linear power rate tends to decrease as shown in fuel rod survey data of Fig.1, indicating BOC(beginning-of-cycle), MOC(middle-of-cycle), and EOC(end-of-cycle) fuel rods. In this figure, an envelope line is drawn to cover all the fuel rods data points at each burnup.

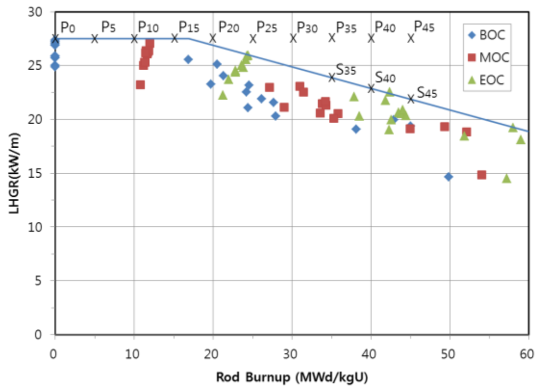

Fig. 1. Fuel rod survey data and analysis-state points.

For a conservative PCT determination, the analysis-state points should be selected on the envelope line as the analyses with the data points inside the envelope would result in lower PCT values.

In order to evaluate the PCT trend as a function of fuel burnup for LOCA analyses, the initial linear power rate of fuel needs to be fixed since both the burnup and the linear power rate of fuel competes to change PCT.

Ten LOCA analyses were carried out for the state points, P_0~P_{45} indicated in Fig. 1, to evaluate the PCT as function of burnup. Then, three more LOCA analyses were carried out for the state points on the slope line, S_{35}~S_{45}, to evaluate the effects of the reduced linear power rate. In these analyses, MARS and FRAPCON inputs were modified to accommodate the reduced linear power rate.

3. Results of Analysis

3.1 Results of FRAPCON Calculation

FRAPCON calculation was carried out with constant linear power rate corresponding to BOC radial peaking. Fig. 2 shows the stored energy as a function of fuel burnup, which is one of the major factors affecting the PCT.

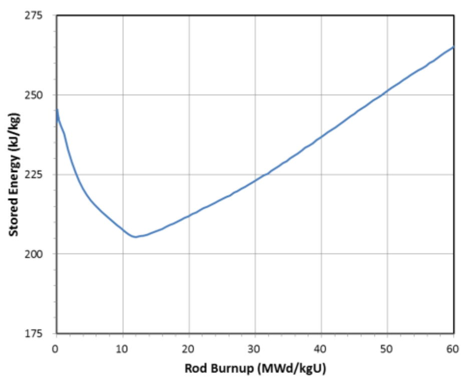

Fig. 2. Stored energy for rod with fixed linear power rate.

As shown in Fig. 2, the stored energy decreases in early phase of irradiation and then increases afterwards. It is conjectured that the decrease of stored energy is caused by gap conductance increase due to gap closure in early phase of irradiation, while the decrease afterwards is due to fission gas buildup in the gap and thermal conductivity degradation. Fig. 3 shows the gap conductance of the mid-node.

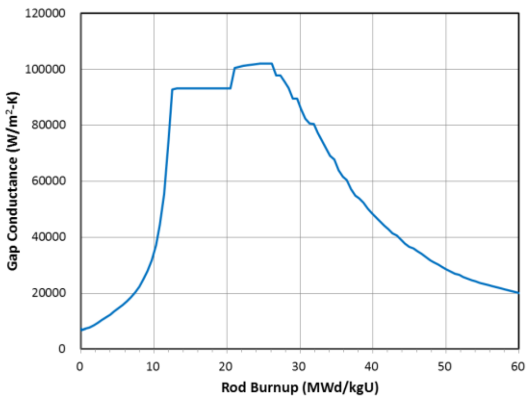

Fig. 3. Fuel rod gap conductance variation.

3.2 Results of Coupled Calculation with Fixed Linear Power Rate

Fig. 4 shows the results of one-way calculation at 0 MWd/KgU and Fig. 5 shows the results of feedback calculation at 35 MWd/KgU.

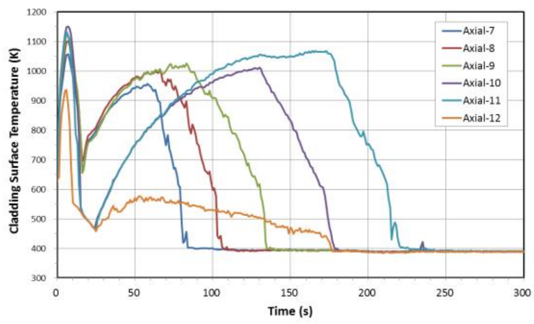

Fig. 4. One-way calculation results at 0 MWd/KgU.

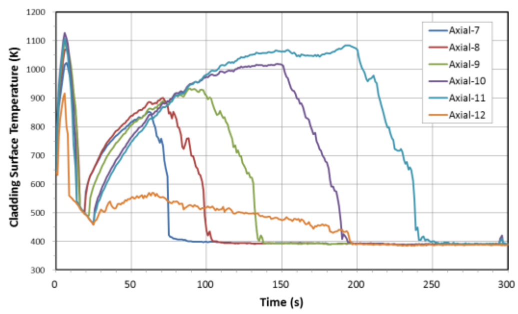

Fig. 5. Feedback calculation results at 35 MWd/KgU.

Figs. 4 and 5 show that as the burnup increases to 35 MWd/KgU, the blowdown PCT decreases while the reflood PCT increases. Cladding rupture occurred around 150 seconds and 180 seconds respectively and the reflood PCT occurred after the rupture. This shows that the rupture model of FRAPTRAN escalates the PCT.

Figure 6 shows the blowdown and reflood PCT results of one-way and feedback calculations with a fixed initial linear power rate.

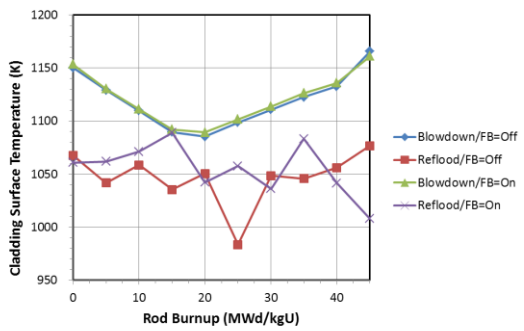

Fig. 6. PCT variation as function of fuel burnup.

As shown in Fig. 6, blowdown PCT has similar trend as the stored energy of Fig. 2. The blowdown PCT reaches a minimum at around 20 MWd/KgU and exceeds that of BOC near 42 MWd/KgU. The reflood PCT has a similar trend with shallower gradient of change and the larger fluctuation. The large fluctuation in reflood PCT is due to the complex thermal-hydraulic phenomena of the reflood phase of LOCA. Feedback calculations show larger fluctuation in the reflood phase than that of one-way calculations.

3.3 Results of Coupled Calculation with Reduced Linear Power Rate

As can be seen in Fig. 6, the PCT of a high burnup fuel rod can exceed the PCT at BOC if the linear power rate of the fuel rod stays the same. However, in actual power reactors, the linear power rates of fuel rods will decrease as burnup increases in the high burnup range. The envelope line in Fig. 1 shows that the reduced linear power rate needs to be taken into account after the fuel burnup of around 20 MWd/KgU.

LOCA analyses with reduced linear power rate were carried out for the three analysis-state points on the slope of envelope line of Fig. 1. Fig. 7 shows the PCT results of these calculations compared to the one-way calculations with fixed initial linear power rate. The results of the reduced linear power rate are indicated as 'LowP' in the figure.

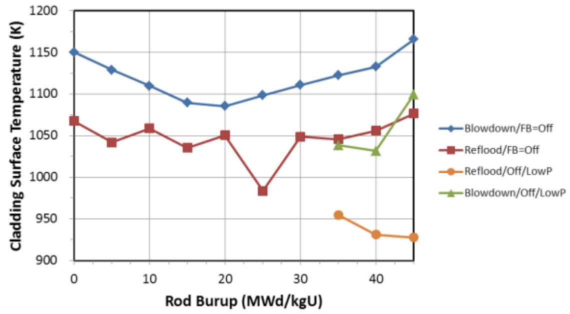

Fig. 7. Metal-water reaction energy.

As can be seen in Fig. 7, if the reduced linear power rate of the high fuel burnup range is considered, the blowdown and the reflood PCTs decrease significantly, and, in this analysis, they are lower than those at BOC.

4. Conclusions

A safety concern has been raised in which the PCT during LOCA is speculated to increase due to fuel thermal conductivity degradation as fuel burnup proceeds.

The MARS/FRAPTRAN coupled code was applied to assess the effect of burnup on PCT in LOCA analysis of a fuel cycle having fuels of various burnups.

Results of the analysis showed that the PCTs decrease until the fuel burnup reaches around 20 MWd/KgU and then increase afterwards, when the initial linear power rate is fixed. When the linear power rate of the fuel rod is reduced in the high burnup range as expected in actuality, the PCT decreases eventually. Although the fuel burnup tends to increase the PCT, the results show that the effect of reduced linear power rate on PCT can exceed that of burnup.

The results suggest that the PCT of LOCA analysis at BOC remains effective for the whole burnup range of the cycle. Further systematic studies are needed to draw more comprehensive conclusions on this issue.

REFERENCES

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