Assessment of the Effects on PCT Evaluation of Enhanced Fuel Model Facilitated by Coupling the MARS Code with the FRAPTRAN Code

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1. Introduction

The MARS thermal-hydraulic system code has been coupled with the FRAPTRAN code to enhance the code with the state-of-the-art fuel rod model of the FRAPTRAN code. For demonstration, a large-break Loss-of-Coolant Accident (LOCA) of OPR-1000 reactor was analyzed using the MARS-FRAPTRAN coupled code system [1].

The principal objectives of the two safety criteria, peak cladding temperature (PCT) and total oxidation limits, are to ensure that the fuel rod claddings remain sufficiently ductile so that they do not crack and fragment during a LOCA. Another important purpose of the PCT limit is to ensure that the fuel cladding does not enter the regime of runaway oxidation and uncontrollable heat-up [2].

However, even when the PCT limit is satisfied, it is known that cladding failures may still occur in a certain percentage of the fuel rods during a LOCA [3]. In spite of this knowledge, fuel cladding failure has not drawn much attention in the usual LOCA analyses. This is largely because a 100% fuel failure is assumed for the radiological consequence analysis in the US regulatory practices.

In this study, we analyze the effects of cladding failure and other fuel model features on PCT during a LOCA using the MARS-FRAPTRAN coupled code.

2. Methods of Analyses

2.1 Schemes of MARS-FRAPTRAN Coupling

In the MARS-FRAPTRAN coupling calculations, MARS calls FRAPTRAN which have been modified in DLL (Dynamic Link Library) format. The fuel depletion code FRAPCON is used for initialization calculations. The general framework of MARS-FRAPTRAN coupled calculation is shown in Fig. 1.

MARS provides rod linear power, cladding surface heat transfer coefficient, coolant temperature and pressure as the boundary conditions for FRAPTRAN calculation. Depending on the user options, surface heat flux, cladding surface temperature, and cladding outer radius calculated by FRAPTRAN are fed back for the next calculation loop of MARS.

When the volume feedback option is ON, cladding outer radius calculated by FRAPTRAN are reflected in changes of outer radius and heat transfer area of the corresponding heat structure in MARS and changes in volume and flow area of the boundary volume in MARS. When the heat feedback option is ON, heat flux and surface temperature calculated by FRAPTRAN replace those calculated by the fuel model in MARS.

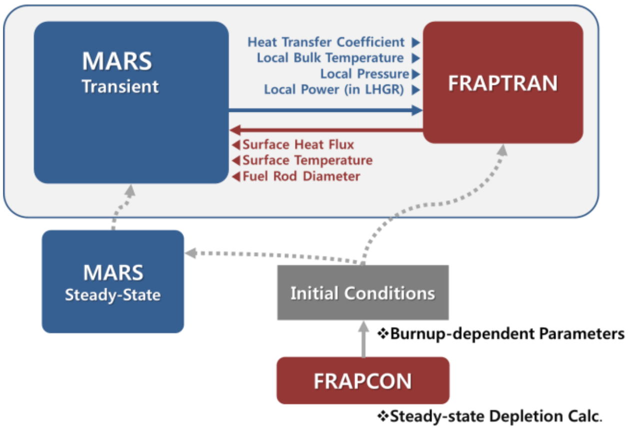

Fig. 1. Schematic diagram of the coupled calculation.

In this calculation frame, MARS is able to call multiple DLLs of FRAPTRAN for more than one heat structure. Heat structures of MARS, which are to be replaced by FRAPTRAN models in the coupled calculation, are designated in a node mapping file which specifies the heat structures corresponding to the fuel rods modeled by FRAPTRAN. Pressure and temperature of the boundary volumes for the selected heat structures specified in the MARS input are provided as the boundary conditions for FRAPTRAN calculations.

In the coupled calculation, while FRAPTRAN produces its calculation results for fuel rods, MARS also generates its own results for the heat structures corresponding to the fuel rod simulated by FRAPTRAN. Comparing these two corresponding results is useful for evaluating the appropriateness of the coupled calculation results.

2.2 Input Features for Analysis

A large-break LOCA for an OPR-1000 PWR reactor was selected as the reference scenario in this study [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 coupled to the FRAPTRAN fuel model.

The two flow channels, the hot assembly channel and the core average channel, cover the entire core flow channel and both are modeled using pipe component in MARS. Both the hottest rod and the hot assembly rod are entirely located in the hot channel and the average rods are located entirely in the core average channel. The two channels are connected using crossflow junctions provided by a multiple junction component.

The active core has 12 axial nodes of equal height. Power source data of an OPR-1000 equilibrium core 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. Fuel rod data is also representative of the fuels currently in use in OPR-1000 reactors.

3. Results of Analysis

3.1 Results of One-Way Calculation

In the one-way calculation, no feedback is provided to MARS from FRAPTRAN calculation, while FRAPTRAN uses the boundary conditions given by MARS as described in Section 2.1.

Fig. 2 shows the cladding surface temperature of the upper half of the hottest rod calculated by the MARS code in the coupled calculation for a LOCA. As there is no feedback from FRAPTRAN, the temperature results are identical to those of the MARS stand-alone calculation.

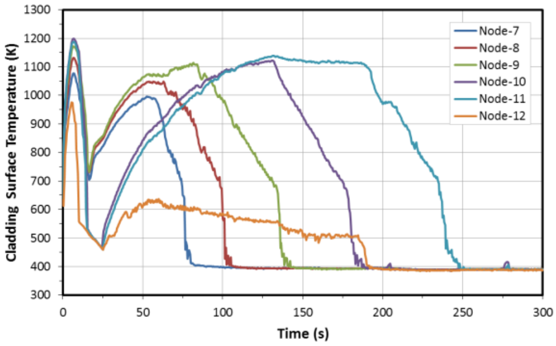

Fig. 2. Cladding temperature of MARS in the one-way calculation.

Fig. 3 shows the cladding surface temperature results of FRAPTRAN in the coupled calculation. Trend of the temperature behaviors is generally similar to that calculated by MARS. However, both the blowdown and the reflood peaks of the cladding temperature are slightly higher in FRAPTRAN results than those in MARS. In the FRAPTRAN calculation results, fuel rupture occurs at 55.4 seconds at axial node 9, as indicated by a red arrow in Fig. 3. The peak cladding temperature for node 9 is somewhat pronounced after the rupture. However, the peak reflood cladding temperature occurs at node 11 at a later time.

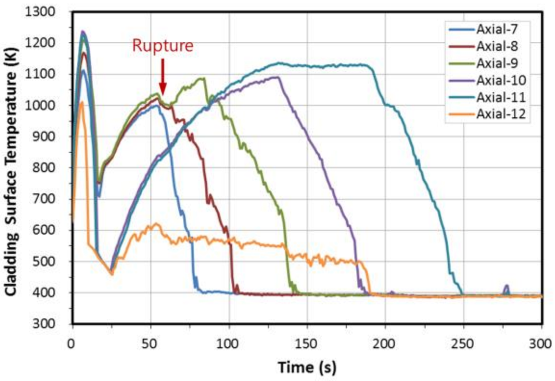

Fig. 3. Cladding temperature of FRAPTRAN in the one-way calculation.

3.2 Results of Feedback Calculation Case

In the coupled calculation with feedback, feedback variables can be optionally selected as described in Section 2.1. Fig. 4 shows the cladding surface temperature results of MARS for the same case as Fig. 2 but with the volume and heat feedbacks. Blowdown and reflood peak values are about the same but reflood quench timing is quite different from that of Fig. 2. This difference is ascribed to the results of the feedback effects.

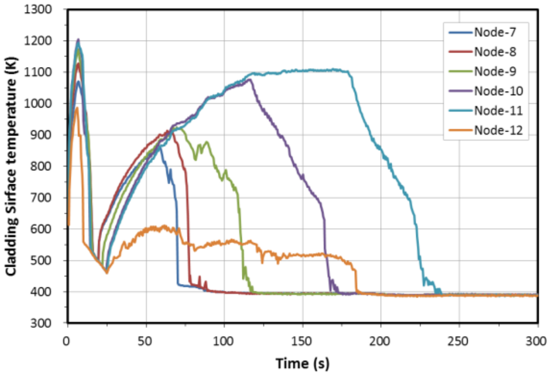

Fig. 4. Cladding temperature of MARS in the feedback calculation.

Fig. 5 shows the cladding surface temperature results of FRAPTRAN with the volume and heat feedbacks. Quench time is about the same as Fig. 4. However, a noticeable increase in cladding temperature is observed compared to the previous figures.

In this calculation, the fuel cladding ruptures at 119.5 seconds at the axial node 11 as shown in Fig. 5. The start of steep increase of cladding temperature coincides with the fuel rupture. When the cladding ruptures, the gap gas pressure drops down to the surrounding coolant pressure as shown in Fig. 6 and steam enters the gap. For rods whose cladding is calculated to rupture during the LOCA, the inside of the cladding is assumed to react after the rupture [5].

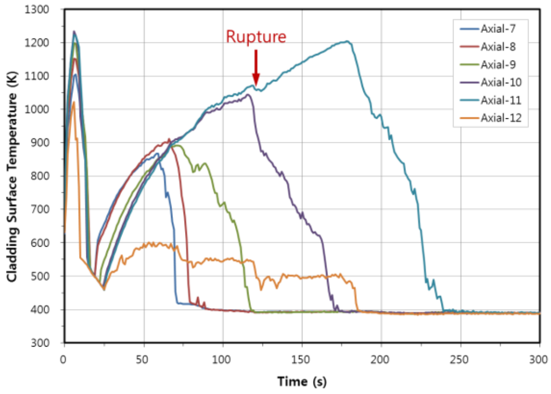

Fig. 5. Cladding temperature of FRAPTRAN in the feedback calculation.

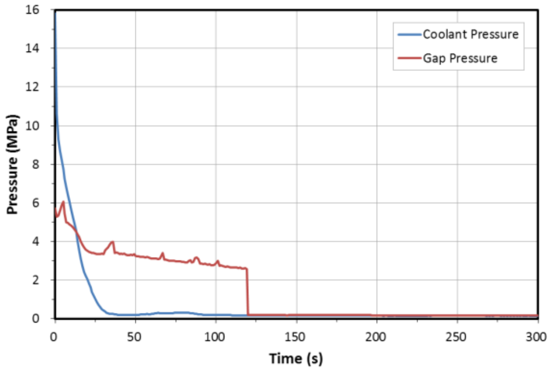

Fig. 6. Gap gas pressure vs. surrounding coolant pressure.

FRAPTRAN has a cladding oxidation model to calculate the metal-water reaction. In this study, Cathcart model is used for the metal-water reaction, which is known to be more accurate than the Baker-Just model for cladding temperature less than 1800K [6]. When the cladding temperature exceeds 1073K, the cladding oxidation model with Cathcart correlation is activated. The meatal-water reaction energy inside the cladding is added to the reaction energy outside of the cladding.

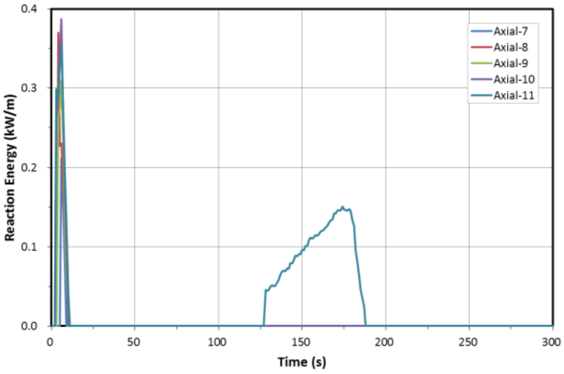

Fig. 7. Metal-water reaction energy.

Fig. 7 shows the metal-water reaction energy calculated by FRAPTRAN. This oxidation energy rate amounts to about 7 percent of the axial power from the decay heat in the fuel pellet of axial node 11. Upon analyzing the O_2 uptakes on the inside and outside of the cladding from the FRAPTRAN results, about a half of the reaction energy of the axial node 11 around 150 seconds is contributed by the oxidation inside the cladding after fuel rupture.

The same calculation was carried out with the metal-water reaction turned off for the hottest rod in order to evaluate the oxidation energy effects. The resulting cladding surface temperatures are shown in Fig. 8. Comparing Figs. 5 and 8, it can be seen that as much as 100K difference in the blowdown PCT can be caused by the metal-water reaction, about half of which occurs on the inside of the cladding after fuel failure.

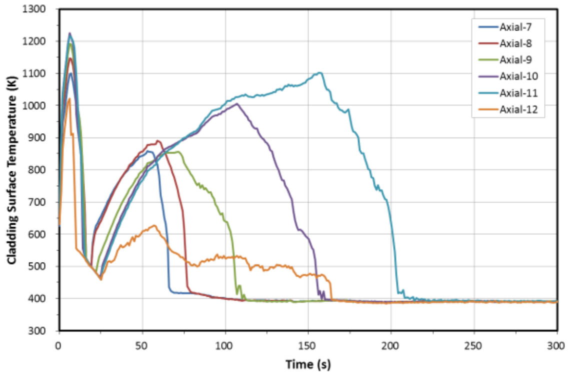

Fig. 8. Cladding temperature of FRAPTRAN without metal-water reaction.

It is, therefore, important to account for the metal-water reactions both inside and outside of the cladding. It is also important to include accurate cladding rupture models when evaluating the peak clad temperature in the reflood phase of LOCA.

The oxidation reaction energy peaks occur during the blowdown phase as shown in Fig. 7. Since fuel cladding is intact at this point of time, these are contributed solely by the oxidation reaction outside the cladding as a matter of course.

The blowdown peak is higher in Fig. 5 than in Fig. 4. It is conjectured that this is caused at least partly by the oxidation reaction energy shown in Fig. 7.

4. Discussions

MARS code has been coupled with FRAPTRAN code to extend fuel modeling capability. The coupling allows feedback of FRAPTRAN results in real time.

Because of the significant impact of fuel models on key safety parameters such as PCT, detailed and accurate fuel models should be employed when evaluating PCT in LOCA analysis. It is noteworthy that the ECCS evaluation models laid out in the Appendix K to 10CFR50 require a provision for predicting cladding swelling and rupture and require to assume that the inside of the cladding react with steam after the rupture [5].

The metal-water reaction energy can have significantly large effect on the reflood PCT, especially when fuel failure occurs. This effect is found to be more pronounced when the fuel failure occurs in the mid-range time of reflood.

Effects of applying an advanced fuel model on the PCT evaluation can be clearly seen when comparing the MARS and the FRAPTRAN results in both the one-way calculation and the feedback calculation.

As long as MARS and FRAPTRAN are used respectively in the ranges where they have been validated, the coupled calculation results are expected to be valid and to reveal various aspects of phenomena which have not been discovered in previous uncoupled calculations by MARS or FRAPTRAN. However, further efforts need to be exercised to validate the coupled calculation schemes proposed in this study.

REFERENCES

[1] H. C. Kim, et al., Enhancement of MARS with an Advanced Fuel Model by Coupling FRAPTRAN, Transactions of the Korean Nuclear Society Spring Meeting, May 12-13, 2016, Jeju, Korea.
[2] “Nuclear Fuel Behavior in Loss-of-coolant Accident (LOCA) Conditions,” NEA No. 6846, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, pp. 27-39, 2009.
[3] “Fuel Cladding Failure Criteria,” European Commission, Nuclear Safety and the Environment, pp. 99-114, September 1999.
[4] “MARS Code Manual, Volume IV: Developmental Assessment Report,” KAERI/TR-3042/2005, Korea Atomic Energy Research Institute, pp.222-228, 2009.
[5] Title 10, Code of Federal Regulations, Appendix K to Part 50-ECCS Evaluation Models, U.S. Nuclear Regulatory Commission, p.513, 2012.
[6] K. J. Geelhood, W.G. Luscher, J.M. Cuta, “FRAPTRAN 1.5: A Computer Code for the Transient Analysis of Oxide Fuel Rods,” NUREG/CR-7023, Vol. 1 Rev.1, Pacific Northwest National Laboratory, p.A.21, 2014.

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