NEXT SOLUTIONS FOR ENGINEERING AND TECHNOLOGY

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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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Introduction (1)

- **Previous Works**
  - **MARS code has been coupled with the FRAPTRAN code to enhance the code with the state-of-the-art fuel rod model.**
  - **A LOCA was analyzed for OPR-1000 using the MARS-FRAPTRAN coupled code system**

- **Focus of the Present Study**
  - **Analyzing effects of cladding failure and other fuel model features on PCT during a LOCA using the MARS-FRAPTRAN coupled code**

Introduction (2)

- **LOCA Safety Criteria**

  ① Peak Cladding Temperature (PCT)
  ② Total oxidation limits

- **Objectives**

  - to ensure that the fuel rod claddings remain sufficiently ductile so that they do not crack and fragment during a LOCA (by ① and ②)
  - to ensure that the fuel cladding does not enter the regime of runaway oxidation and uncontrollable heat-up (by ①)

※ "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.

Introduction (3)

- **Cladding failure under PCT limit**
  - occurs in a certain percentage of the fuel rods during a LOCA
  - has not drawn much attention in the usual LOCA analyses
  - because a 100% fuel failure is assumed for the radiological consequence analysis in the US regulatory practices

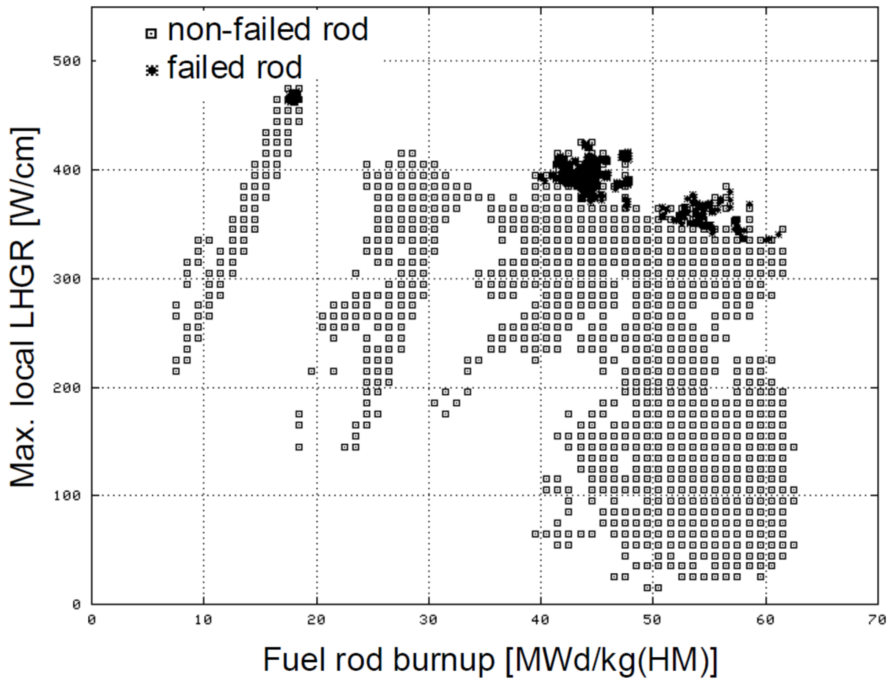
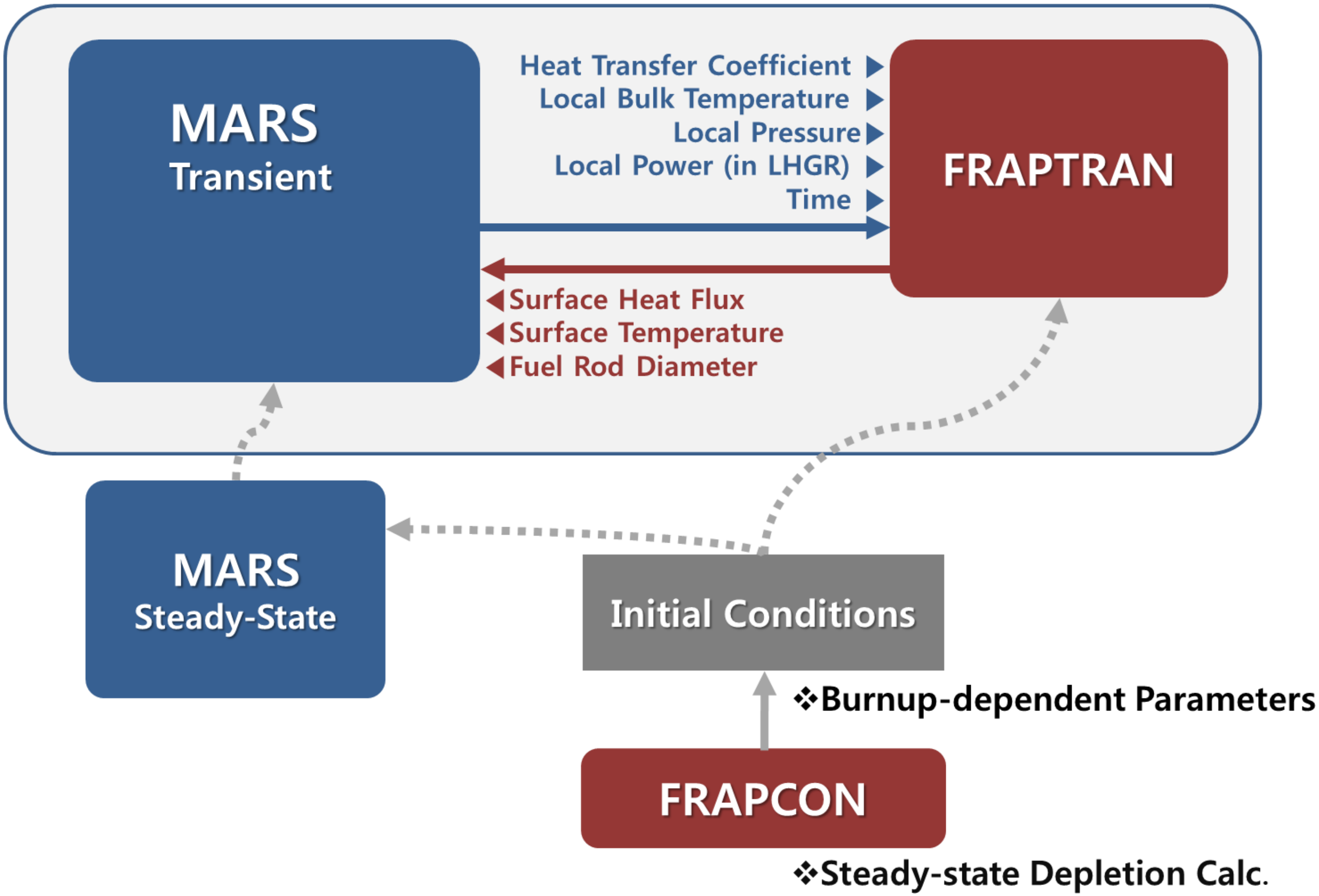


FIG. 7. Example of a LOCA failure rate analysis (3.2% of all rods in the core fail).

※ "Fuel Cladding Failure Criteria," European Commission, Nuclear Safety and the Environment, pp. 99-114, September 1999.

Schemes of MARS-FRAPTRAN Coupling (1)



Schemes of MARS-FRAPTRAN Coupling (2)

- Feedback options from FRAPTRAN
  - volume feedback
  - heat feedback

- Volume feedback
  - cladding outer radius calculated by FRAPTRAN
    → outer radius and heat transfer area of the corresponding heat structure in MARS
    → volume and flow area of the boundary volume in MARS

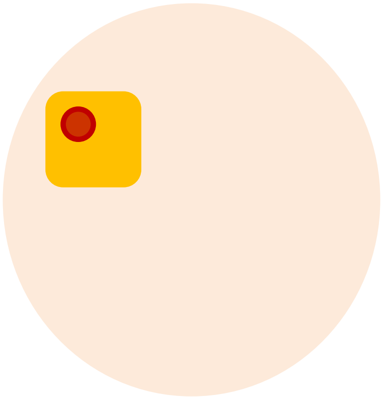
- Heat feedback
  - heat flux and surface temperature calculated by FRAPTRAN
    → replace those in MARS

Schemes of MARS-FRAPTRAN Coupling (3)

- **Multiple DLLs of FRAPTRAN**
  - **for more than one heat structure**
- **Node mapping file**
  - **specifies the heat structures in MARS corresponding to the fuel rods modeled by FRAPTRAN**
  - **pressure and temperature of the boundary volumes of the heat structures in the MARS input are provided as the boundary conditions for FRAPTRAN calculations**
- **Two results available**
  - **MARS also generates its own results for the heat structure, while FRAPTRAN produces its calculation results for fuel rods**
  - **two corresponding results is useful for evaluating the appropriateness of the coupled calculation results**
  - **MARS results in the one-way calculation are identical to the normal MARS calculation results without coupling**

Input Features for Analysis

- Reference scenario
  - A large-break LOCA for an OPR-1000 PWR



- Core Modeling
  - Two flow channels: hot and average with crossflow junction
  - Three heat structures: hottest rod, hot assembly, core average rod

- Power Data
  - OPR-1000 equilibrium core with 12 axial nodes
  - Radial peaking factor and the axial power distribution
  - Adverse conditions allowed for the normal plant operation

Results of One-Way Calculation (1)

- **No feedback**
- **Temperature results are identical to those of the MARS stand-alone calculation**

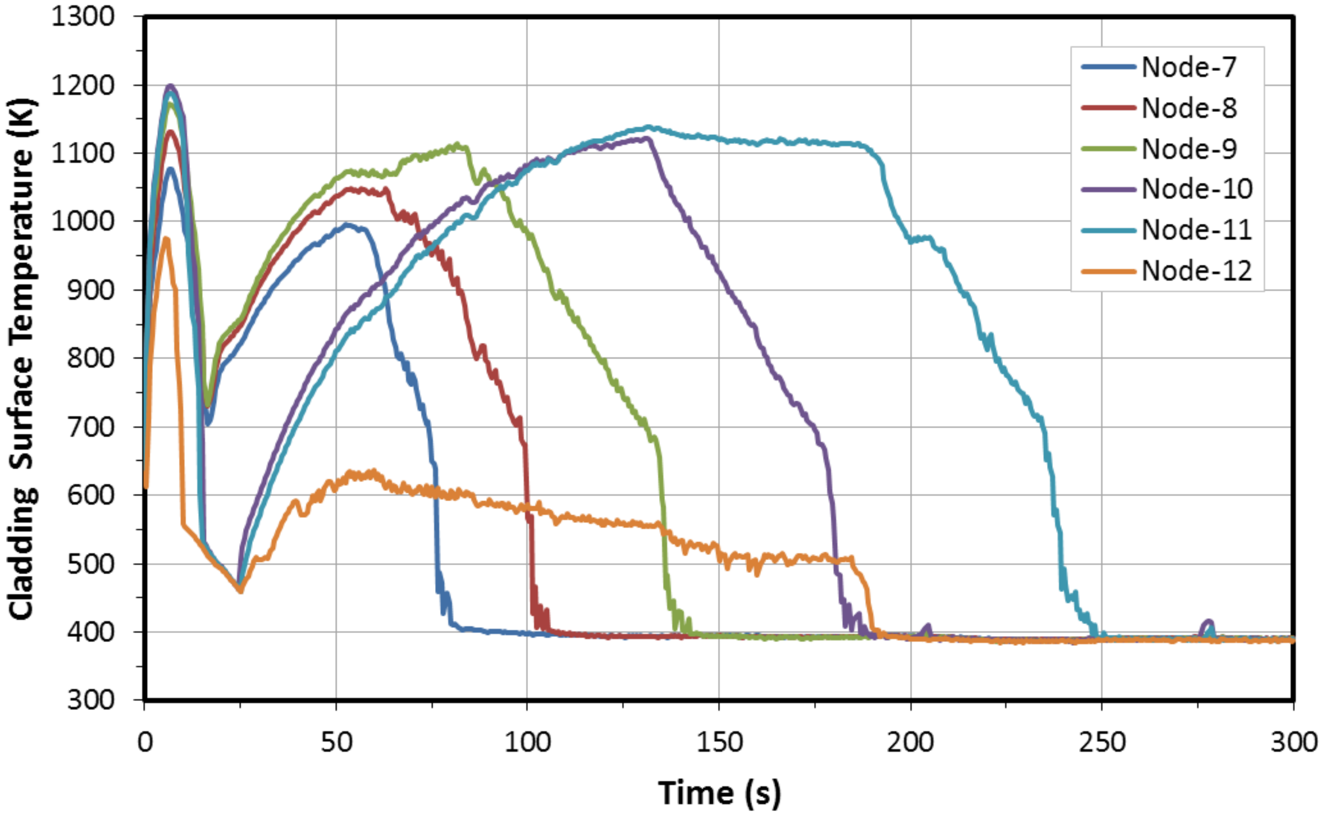


Fig. 2. Cladding temperature of MARS in the one-way calculation

Results of One-Way Calculation (2)

- **Fuel rupture occurs at 55.4 seconds at axial node 9**
- **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**

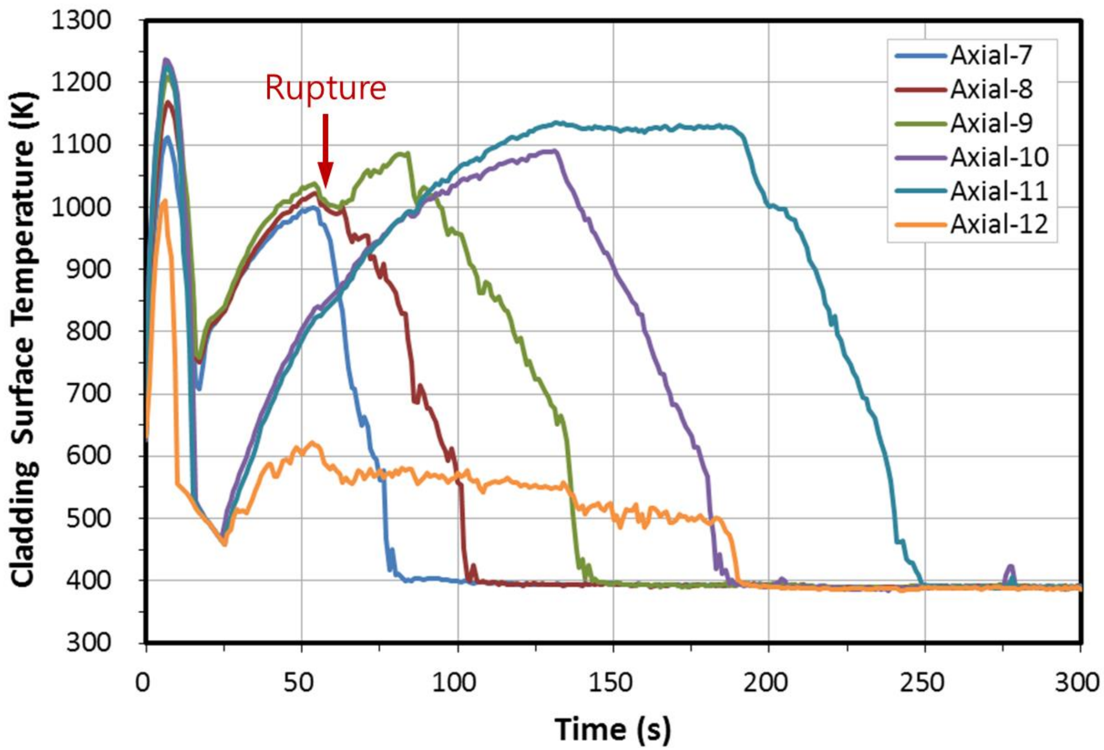
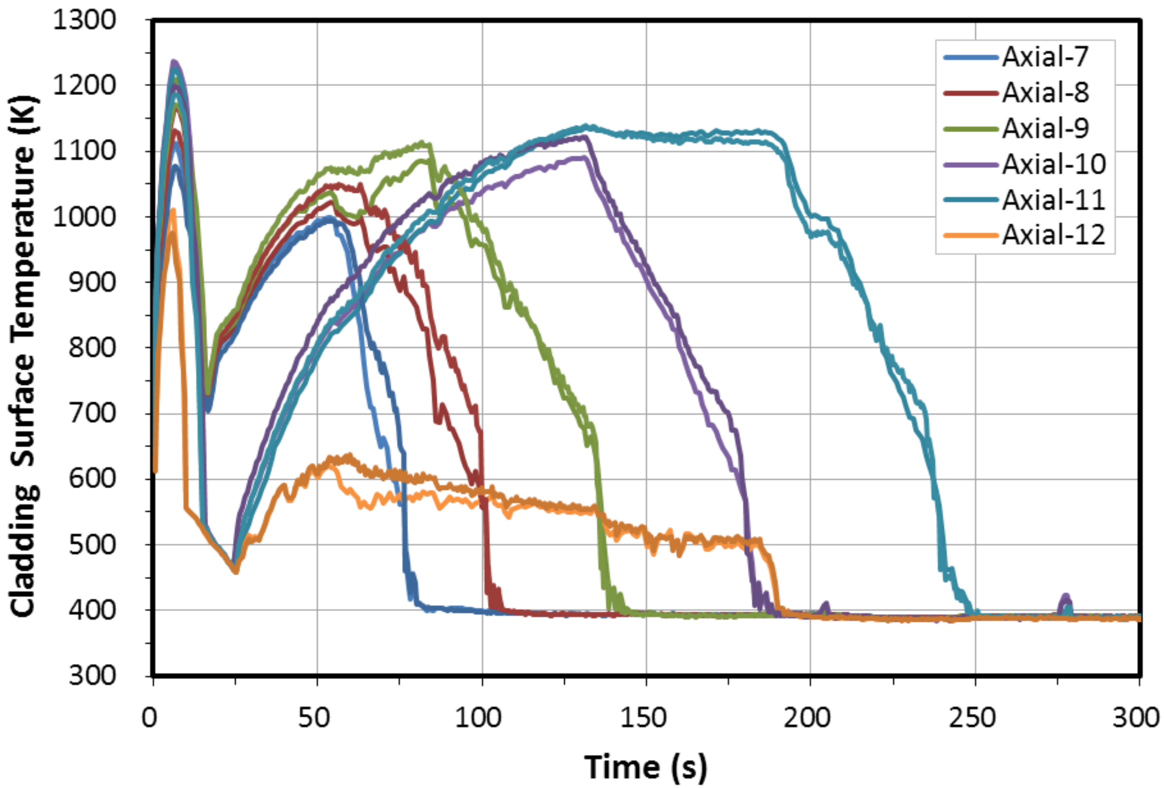


Fig. 3. Cladding temperature of FRAPTRAN in the one-way calculation

Results of One-Way Calculation (3)

- **Two results are generally similar, but the blowdown and the reflood peaks of the cladding temperature are slightly higher in FRAPTRAN results.**



Comparison of two results in the one-way calculation

Results of Feedback Calculation (1)

- **Volume and heat feedbacks ON**
- **Blowdown and reflood peak values are about the same but reflood quench timing is quite different from Fig. 2**
- **This difference is ascribed to the results of the feedback effects**

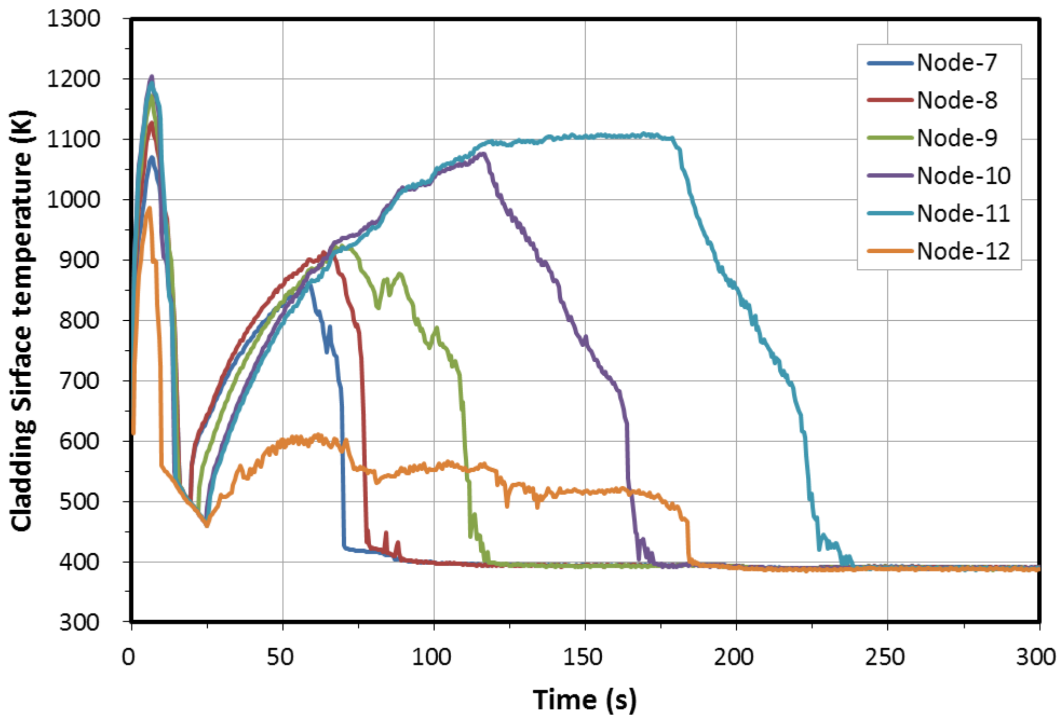


Fig. 4. Cladding temperature of MARS in the feedback calculation

Results of Feedback Calculation (2)

- **Quench time is about the same as Fig. 4**
- **Noticeable increase in cladding temperature**
- **Fuel cladding ruptures at 119.5 seconds at the axial node 11**
- **Start of steep increase of cladding temperature coincides with the fuel rupture**

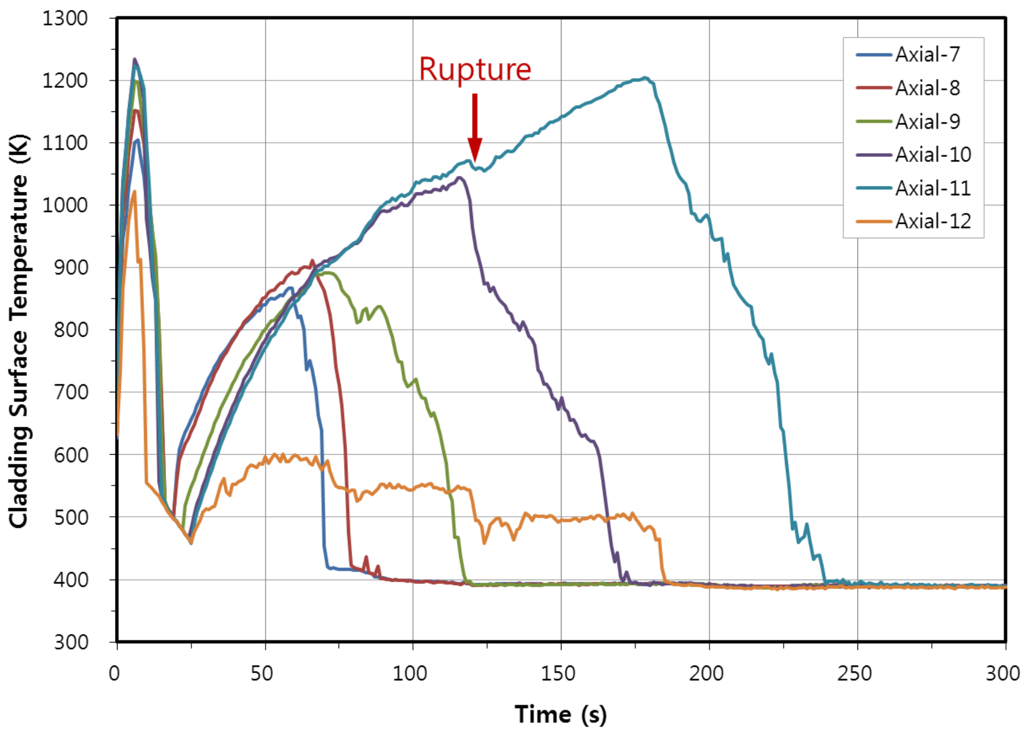


Fig. 5. Cladding temperature of FRAPTRAN in the feedback calculation

Results of Feedback Calculation (3)

- At cladding rupture, the gap gas pressure drops down to the surrounding coolant pressure
- Steam enters the gap after cladding rupture
- For rods whose cladding is calculated to rupture, the inside of the cladding is assumed to react after the rupture

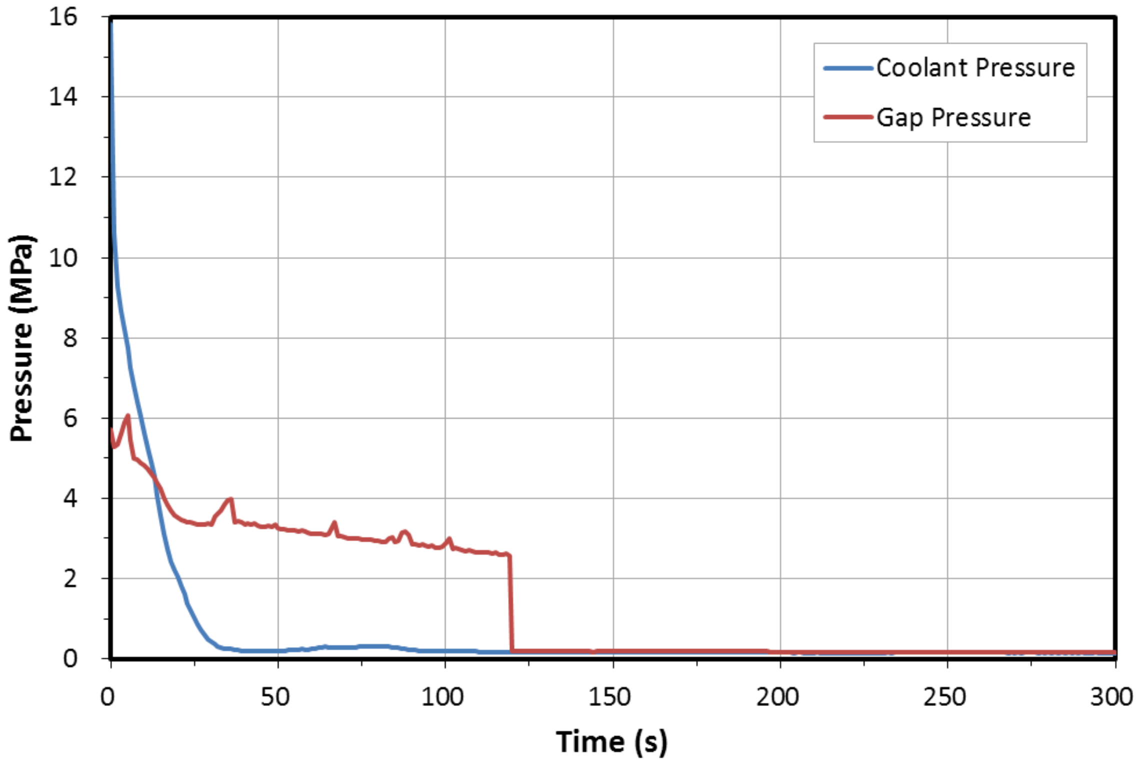


Fig. 6. Gap gas pressure vs. surrounding coolant pressure

Results of Feedback Calculation (4)

- Cladding oxidation model of FRAPTRAN
  - Calculates the metal-water reaction
  - Cathcart model is more accurate than the Baker-Just model for cladding temperature less than 1800K
  - 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

Results of Feedback Calculation (5)

- 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 O2 uptakes (kg/m2) and Oxide Thickness (mm) from the FRAPTRAN results, the values are about the same on the inside and outside of the cladding.
- 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.

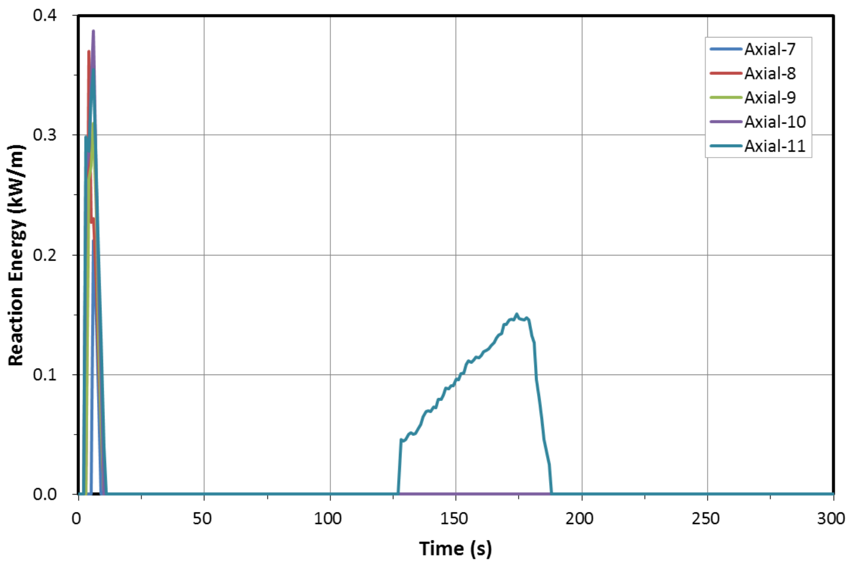


Fig. 7. Metal-water reaction energy

Results of Feedback Calculation (6)

- **Same calculation was carried out with the metal-water reaction turned off in order to evaluate the oxidation energy effects.**
- **About 100K difference in the blowdown PCT is caused by the metal-water reaction, about half of which occurs on the inside of the cladding after fuel failure**

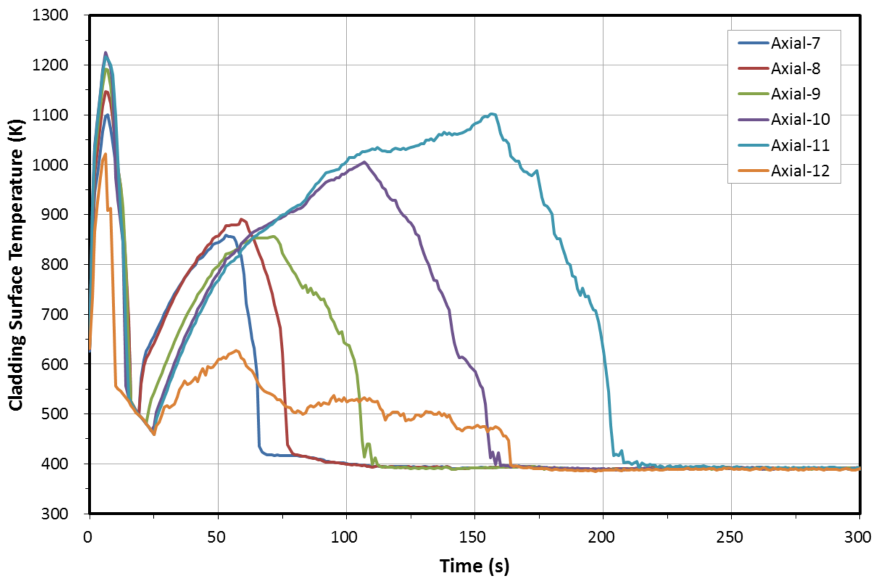
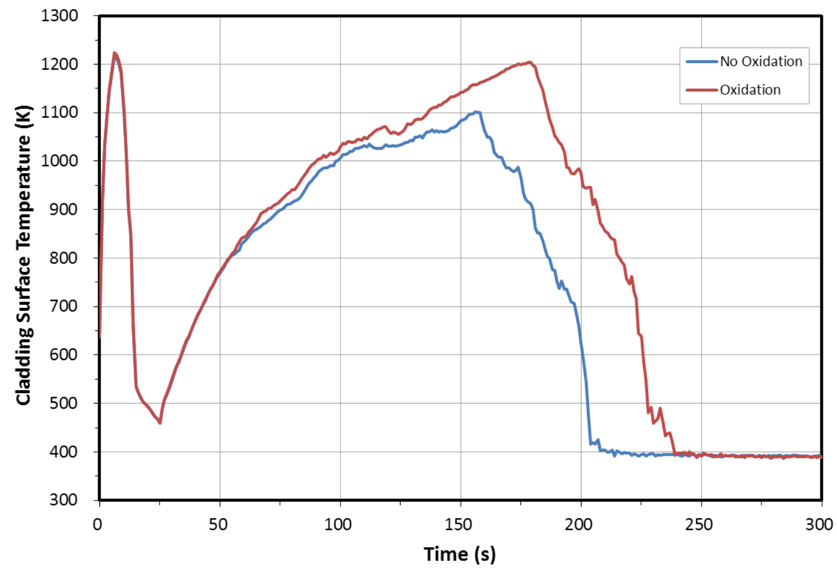


Fig. 8. Cladding temperature of FRAPTRAN without metal-water reaction.



Comparison of Node 11

Results of Feedback Calculation (7)

- **Important to account for the metal-water reactions both inside and outside of the cladding**
- **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 FRAPTRAN calculation than in MARS. This is contributed at least partly by the oxidation reaction energy.**

Discussions

- **MARS coupled with FRAPTRAN extends fuel modeling capability.**
- **Detailed and accurate fuel models should be employed when evaluating PCT in LOCA analysis.**
- **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**
- **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**
- **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**

Thank You