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Simulation of power ramp test in REGATE experiment by using FRAPCON3

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1. Introduction

The fuel performance is closely related with reactor safety and economy. Especially mechanical integrity of a fuel rod is very important design factor and most of fuel performance codes incorporate a mechanical model to evaluate the mechanical behavior of the fuel rod.

Up to now, although there are some limitations, almost fuel performance codes have adopted simplified analytical mechanical model to calculate strain and stress distribution of cladding. For example, FRACAS (Fuel Rod and Cladding Analysis Subcode) module which was implemented in the FRAPCON-3 is efficient mechanical analysis module during steady state and quasi-transient behavior of a fuel rod.

The purpose of this study is to understand a simplified analytical mechanics model and to increase a fuel performance analysis capability for R&D support.

In this work, we prepared in-pile test database including the base irradiation for power ramp test to simulate the power ramp test. Based on the simulation result of FRAPCON-3, the FRACAS module has been studied.

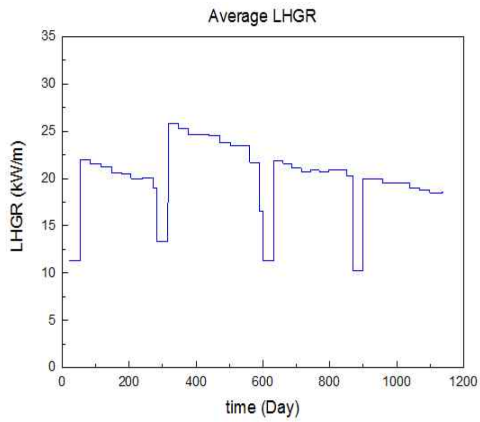
2. FRAPCON-3 Code

FRAPCON-3.4 is the latest version of NRC' s fuel performance code for the calculation of steady-state thermal-mechanical behavior of light-water reactor (LWR) oxide fuel rods for long-term and high burn-up. The code calculates the temperature, pressure, and deformation of a fuel rod as functions of time-dependent fuel rod power and coolant boundary conditions. The phenomena modeled by the code include 1) heat conduction through the fuel and cladding to the coolant; 2) cladding elastic and plastic deformation; 3) fuel-cladding mechanical interaction; 4) fission gas release from the fuel and rod internal pressure; and 5) cladding oxidation. The code contains necessary material properties, water properties, and heat-transfer correlations.

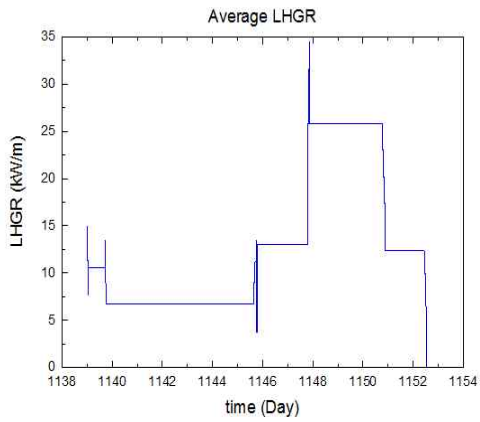
The mechanical model embedded in the code, the analytical (FRACAS) model or the finite element analysis (FEA) model, can be selected by the user. The FRACAS is the mechanical deformation subcode which is used in the FRAPCON codes to analyze the stresses and strains in the cladding of a fuel rod. At each time step, FRACAS uses the method of successive elastic solutions to obtain an elastic-plastic solution for the stresses, strains, and displacements in the fuel rod cladding at each load step. The cladding is modeled as a thin cylindrical shell with prescribed temperature, pressures, and radial displacement of the inside surface. The deformation of the fuel pellets caused by the stress is neglected, so called 'rigid pellet assumption'.

3. In-pile test data

For the simulation a in-pile test database REGATE experiment was prepared. This experiment deals with the study of fission gas release and fuel swelling during power transient at medium burn-up. The rod was base irradiated in Gravlines 5 PWR up to 47.415 MWd/kgM and then re-irradiated in the test reactor SILOE for experimental power ramp in Grenoble France.



(a) Linear heat generation rate history of base irradiation



(b) Linear heat generation rate history of power ramp

Figure 1. Power History of the Test Rod (REGATE L10)

Since the rod is initially a segmented rod (L10: 4.5 w/o UO_2 pellets, Zy4 stress relieved cladding, and 17x17 design), the re-fabrication process prior to loading in the test reactor was skipped. Figure 1 (a) and Figure 1 (b) show rod average linear heat generation rate (LHGR) history for steady-state and rod average LHGR for transient, respectively. In the steady state, it is assumed that axial profile of the test rod is flat according to database report. Figure 2 shows the axial profiles of the test rod for transient state against rod elevation.

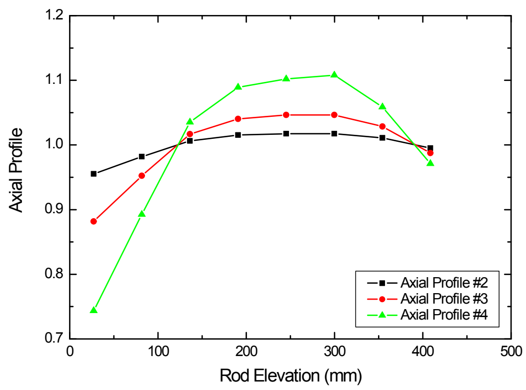


Figure 2. Axial profiles of the test rod for transient state

Calculation by FRAPCON3.4 for irradiation in the PWR was performed along an approximate power history of the rods. In the calculation, the characteristics of pellet and cladding such as dimensions, density, enrichment and so on are originated from the report of the test rod. For base irradiation in the commercial reactor, system pressure and inlet temperature are given. However, those conditions were slightly adjusted to match the given cladding temperature because all conditions of test reactor are not provided. To compare cladding outer diameter of each axial node after power ramp in PIE, the final time step was set as the cold state.

4. Results and discussion

In-pile data base by PIE includes oxide thicknesses of the test rod along the elevation, cladding outer diameter, fission gas release (FGR) after puncturing and EPMA of radial distributions of fission elements (Cs, Nd, O, Pu, U). Among them, this work used cladding outer diameter in order to evaluate FRAPCON mechanical model (FRACAS). In the case of corrosion data, oxide thicknesses of calculation results do not agree with those of measurement by PIE. It is because power profile of base irradiation does not represent real case. In addition, the discrepancy is not crucial in the view of mechanical behavior.

Figure 3 shows that cladding outer diameters of calculation result are compared with those of measurement. Line graph represents the measurement data along the elevation. Circle dots represent the calculation data after power ramp. Rectangular dots represent calculation data before power ramp. Through the comparison, it is clear that the mechanical module is over-estimated for the plastic deformation due to rigid pellet assumption. Before power ramp, the cladding outer diameter is smaller than the measurement by PIE because the cladding does not experience plastic deformation. After power ramp, the mechanical module of FRAPCON (FRACAS) predicts the larger cladding outer diameter in comparison with the measurement data. Whereas cladding experience only creep deformation as permanent deformation during base irradiation, the cladding of plastic deformation occurs during power ramp because the time is not enough to release stress by creep. Consequently, the comparison demonstrates that the FRACAS can be conservative in terms of strain. By the way, more case studies should be conducted with the in-pile data base to evaluate the FRACAS model. To improve calculation accuracy of the mechanical model in the fuel performance code, the advanced model should be developed.

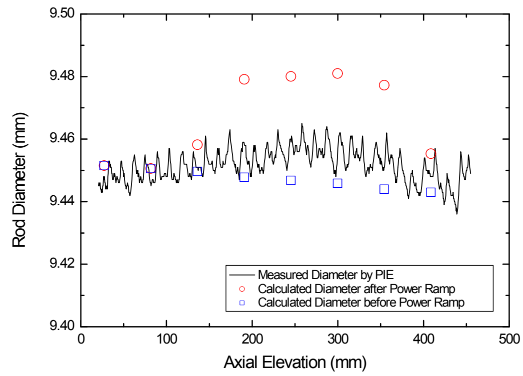


Figure 3. Comparison of cladding outer diameter from measurement, calculation result after power ramp, calculation result before power ramp

5. Conclusions

The fuel performance codes have adopted simplified mechanical model to calculate fuel strain and stress distribution. FRACAS module which was implemented in the FRAPCON-3 is efficient mechanical analysis module during steady state and quasi-transient behavior of a fuel rod. This study is to simulate the base irradiation for power ramp test and power ramp by FRAPCON 3.4. Based on the database of the test rod, its behavior has been calculated by FRAPCON. The calculation results show a good agreement against measurement results except cladding outer diameter.

The comparison shows that the FRACAS can be the conservative model because of rigid pellet assumption and analysis model characteristics. For the future, more case studies will be conducted to evaluate the mechanical module of FRAPCON.

Acknowledgement

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