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Development of thermal analysis module in the PRIME code

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1. Introduction

Under the auspice of the global program for the nonproliferation in the research reactors which utilize highly-enriched uranium (HEU) as a driving fuel, U-Mo/Al dispersion fuel has been developed successfully in U.S., Europe, and Korea. Particularly, the dispersion fuel that is composed of U-7wt% Mo fuel and Al-5 wt% Si matrix has been selected as the main driving fuel for Kijang Research Reactor (KJRR) in Korea, which implies that the commercialization of the U-Mo fuel can be accomplished shortly.

While an ample of irradiation tests have been performed, the development of a computational code to predict the irradiation performance and access its thermal and mechanical integrity of the U-Mo/Al dispersion fuel was not actively carried on. Several computational tools such as PLATE[1], DART[2], and MAIA[3] are available for the performance analysis with their features and advantages, but also less comprehensive prediction manners concerning both thermal and mechanical analysis.

The PRIME (PRedIction code for thermo-MEchanical performance of research reactor fuel) computational program is developed to support the qualification of the U-Mo/Al dispersion fuel by providing a preliminary assessment of the radio-thermo-mechanical performance of the fuel. It is a collection of the FORTRAN-based modules that are coupled dependently to each other. The PRIME code has capabilities to calculate the meat swelling distribution profile with consideration of fission-induced creep, and porosities by not only bubbles and pores formed both in the inside and outside of fuel particles.

In this paper, the code structure and implemented calculation scheme are introduced for the irradiation performance analysis in the PRIME code. In addition, the thermal performance analysis is demonstrated for dispersion fuels from RERTR-4 and RERTR-9 with available data, and the prediction results are compared to the measurement data for the verification.

2. General description of the PRIME

A performance analysis calculation scheme is developed by a combination of available prediction models for the irradiation behaviors of research reactor fuels, which were observed from in-pile tests. The calculation scheme was employed in the PRIME to access fuel performance with more accurate manner using radio-thermo-mechanically coupled the system to consider fuel particle swelling, interaction layer (IL) growth, pore formation, and creep-induced fuel deformation and mass relocation in the meat, etc.

A cross-section of the fuel plate is set to the analysis domain as shown in Fig. 1. The two-dimensional analysis was performed by the PRIME code for both thermal and mechanical responses for the given user-provided input data.

From the thermal response, temperature distribution from the Al cladding to the fuel meat is calculated with burnup-dependent material's thermal conductivity. Subsequently, the mechanical analysis is performed to calculate the strain and stress distribution in the fuel plate. A general code structure of the performance analysis code was shown in Fig. 2.

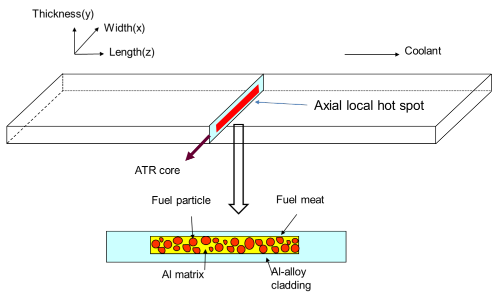


Fig. 1 A schematic of the cross-sectional area which is equivalent to the analysis domain in the PIME code.

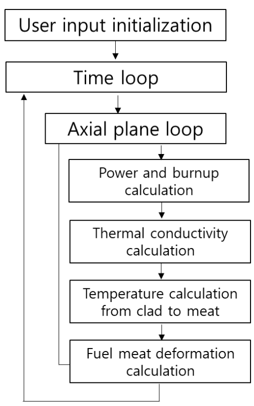


Fig. 2 A flowchart for the performance analysis in the PRIME code.

3. Model implemented in the PRIME

Several models are available to predict fuel performance prediction. They were developed based on in-pile data obtained by post-irradiation examination (PIE) of the dispersion fuel plates. These models include fuel particle swelling [4], IL growth [5], fuel meat swelling and creep [6][7], and pore formation at IL-Al interface [8]. Detail descriptions for the model are available in the literature and references therein.

Thermal and mechanical responses are calculated by using finite element method (FEM) for each analysis time step with the assumption of plane-strain condition.

4. Demonstration and verification of thermal performance analysis

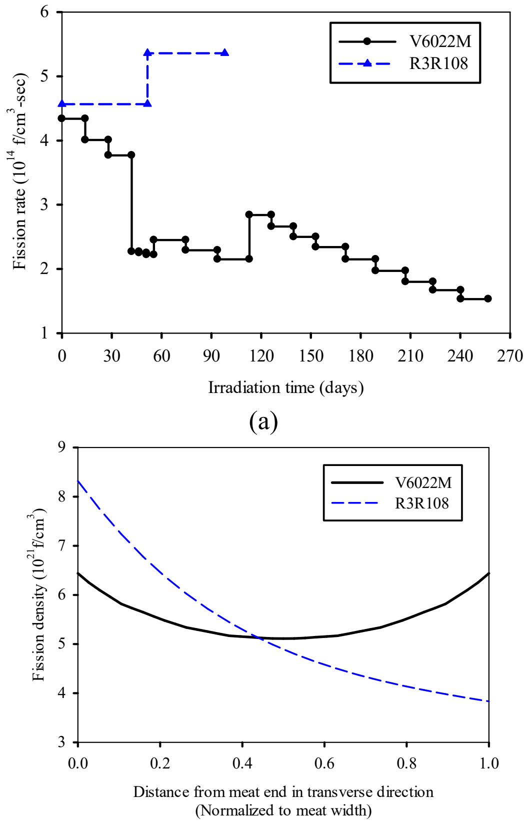
V6022M plate from RERTR-4 and R3R108 plate from RERTR-9 were used for the demonstration of the thermal performance analysis by PRIME code. Table 1 shows irradiation data that were used as input parameters for the analysis. The time-dependent fission rate and transversal power peaking profile were given as shown in Fig. 3.

Table 1 Irradiation data used for the demonstration.

Parameter	Value	
Plate	V6022M	R3R108
Irradiation program	RERTR-4	RERTR-9
Fabrication data		
Plate dimensions (mm)	L 100 × W 25 × T 1.40	
Meat dimensions (mm)	L 81.3 × W 18.5 × T 0.64	
U-Mo fuel composition	U-10Mo*	U-7Mo*
Uranium loading (gU/cm^3-meat)	6	8
Average fuel particle size (μm)	65	65
Operation data		
Coolant inlet temperature (°C)	55.1	
Coolant pressure	23.1	
Irradiation day (EFPD)	257	98

* A value prior to Mo stands for Mo content in wt%.

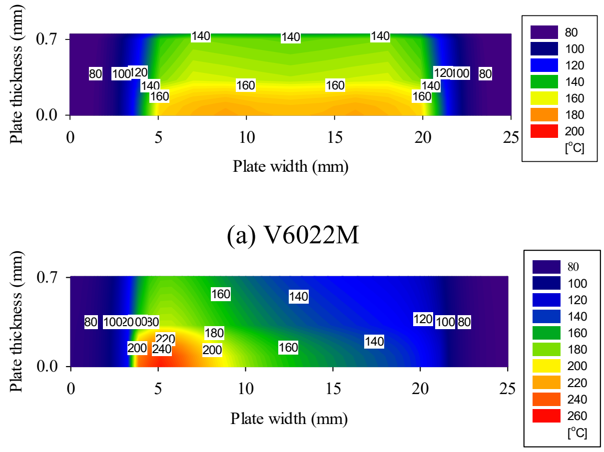
Fig. 4 shows the two-dimensional contour for plate temperature distribution. Maximum temperature was found at the location with highest power peaking factor. It can be demonstrated that user-supplied power peaking factor profile was employed in a well-defined manner.



(a)

(b)

Fig. 3 (a) Fission rate at different irradiation time and (b) transversal power peaking profile for the demonstration.

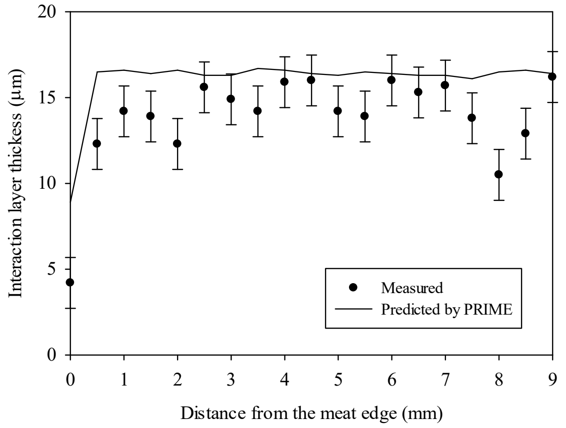


(a) V6022M

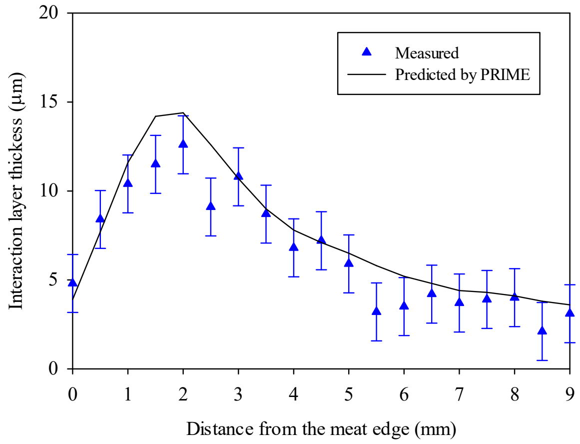
(b) R3R108

Fig. 4 Contours of two-dimensional temperature distribution at the beginning of the life.

Since no measurement data for the temperature of the irradiated plate were available, the temperature calculation was inevitably verified by comparing other temperature-dependent prediction results with the measurement data. Since IL growth is known to be thermal dependent, the measured IL thickness at the meat centerline was compared to the prediction results to verify the temperature calculation, as shown in Fig. 5.



(a) V6022M



(b) R3R108

Fig. 5 Comparison of the measured and predicted IL thickness for two plates at the meat centerline.

The IL thicknesses for V6022M were overally overpredicted, while those for R3R108 were in good agreement with the measured data. The overprediction in V6022M is probably due to the uncertainty in the IL growth model implemented in the PRIME code.

5. Summary

The development of the PRIME code is under progress for the performance analysis of the U-Mo/Al dispersion fuel. The computational framework for the PRIME code has been built with newly updated or developed models with studies on advanced fuel performance modeling.

The PRIME calculates irradiation-induced meat swelling with changes of meat constituent volume fractions by fuel particle swelling, interaction layer (IL) growth with fuel and Al matrix consumption, and pore formation at the IL-Al matrix interfaces. Two-dimensional temperature distribution and deformations due to the meat swelling and creep are also calculated based on the fission rate and coolant conditions.

The thermal performance analysis by using irradiation data for irradiated plates from RERTR tests was demonstrated in this study. The prediction results for temperature are physically reasonable by comparison between the measured and predicted IL thicknesses. The further verification of the prediction is in progress, and the status of PRIME code development is continuously updated.

Acknowledgement

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