*Transactions of the Korean Nuclear Society Autumn Meeting*
*Yeosu, Korea, October 25-26, 2018*

# PRIME for irradiation performance analysis of U-Mo/Al dispersion fuel

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## 1. Introduction

Since 1980, there have been the global efforts for research and test reactors to minimize the proliferation risk that was resulted by using high-enriched uranium (HEU) fuel. They were aimed at the conversion of those reactors operated by HEU fuel to alternative low-enriched uranium (LEU) fuels with the enrichment below 20% $U^{235}$.

Particularly, one of the promising candidates is U-molybdenum (U-Mo) alloy fuel of which U density is ~>16.4 gU/cm$^3$ for the conversion of HEU core in the high-performance research reactors. Developing and qualifying U-Mo fuel becomes critical for the success of the conversion of high-performance research reactors. A dispersion type fuel is widely used among several fuel forms for U-Mo. The dispersion fuel with a fueled zone where U-Mo fuel particles are dispersed in the Al matrix is denoted as 'U-Mo/Al dispersion fuel', and this fueled zone is referred to as 'fuel meat.'

The potential use of the U-Mo/Al dispersion fuel for those reactors has globally recognized since it has advantages of high uranium density and stable irradiation performance. However, while a number of irradiation tests were performed, few progresses on development and update of computational code for performance analysis of U-Mo/Al dispersion fuel have been achieved.

In this study, a new computational code, PRIME (**PR**ed**I**ction code for thermo-**ME**chanical performance of research reactor fuel), is present. PRIME was used to assess the irradiation performance of U-Mo/Al with thermo-mechanical coupling scheme which was verified. The code validation results are summarized, which were performed by using measurement data obtained from irradiated fuels.

## 2. Irradiation performance models

Irradiation performance models available for U-Mo/Al have been implemented in PRIME; U-Mo fuel swelling [1], interaction layer (IL) growth [2], fuel meat swelling [3], and pore formation at the IL-Al matrix interface [4]. All models were validated by using irradiated fuel plates. Since the fuel meat is composed of multiple components including U-Mo fuel particles, Al matrix, IL, and pores, irradiation behaviors of all components are interconnected complicately. The interrelations among irradiation performance models used in PRIME are summarized in Fig. 1.

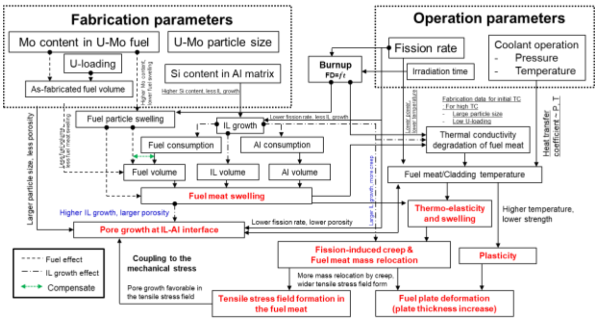



**Fig. 1 A schematic showing relationships among models for irradiation performance analysis for U-Mo/Al.**

The details for each model are available in the literature and references therein.

## 3. Code framework

It is known that dimensional changes in the plate width (or transversal) direction are constrained due to the typical plate loading configuration (see Fig. 2(a)). Therefore, the fuel plate deforms mostly in the thickness direction.

In the thermal response predictions, PRIME considers the heat transfer with convection in the plate width and thickness directions as shown in Fig. 2(b). A two-dimensional plane with the unit thickness was used as an analysis domain with the convective boundary condition with coolant conditions. No heat transfer through the plate axial (or length) direction is presumed because of very thin thickness of the fuel plate.

For the mechanical analysis, the generalized plane strain condition in the plate axial direction is assumed. By using the symmetric condition with respect to the plate centerline, only a half model of the fuel plate is modeled as shown in Fig. 2(c).

The calling sequence of the modules implemented in PRIME is shown in Fig. 3. The modules containing subroutines for the performance analysis were developed for the efficient maintenance and update of the code. Calling sequences are organized based on the sequence of the performance prediction; starting from the temperature calculation to the displacement and stress calculation. Independent material property libraries are called to compute required material properties which are dependent to the burnup or temperature.

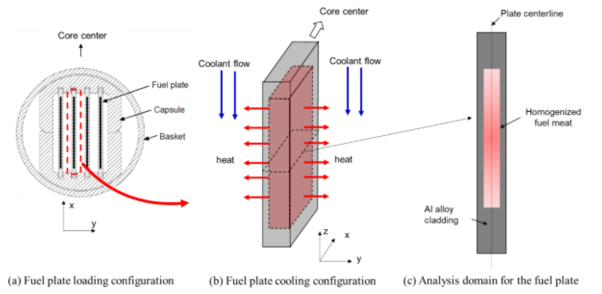



**Fig. 2 Schematics showing geometric configurations for irradiation performance analysis.**

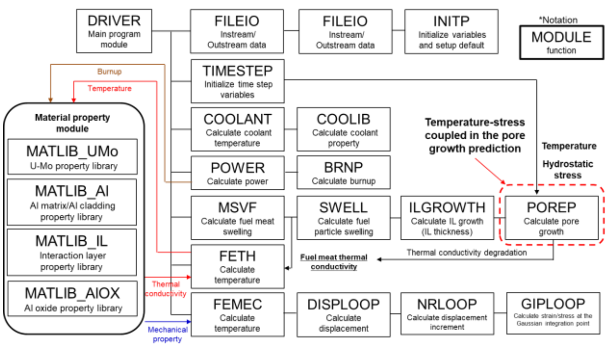



**Fig. 3 Calling sequence of the implemented modules in PRIME.**

Since not only elasticity, but also plasticity, creep, thermal expansion, and irradiation-induced swelling are considered, the mechanical equilibrium in the U-Mo/Al dispersion system includes the inelastic material behaviors. To solve this problem, PRIME has adopted the finite element method (FEM) to the inelastic analysis, which has been largely employed for the reliable and economic prediction of material response under conditions of extreme mechanical and thermal loading. The effective stress function (ESF) algorithm [5] is implemented in PRIME, which is the approach to solve the governing equations of inelastic constitutive behaviors as shown in Fig. 4.

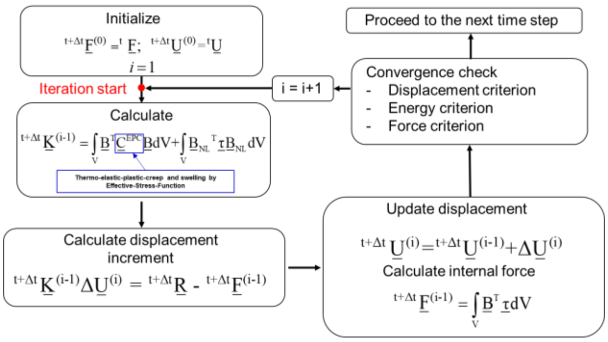



**Fig. 4 A schematic showing the finite element method with the effective-stress-function algorithm implemented in PRIME.**

## 4. Verification and Validation

### *4.1 Verification*

Verifications of PRIME for thermal and mechanical response prediction were performed. Fig. 5 shows the finite element model used in the verification of PRIME for thermal and mechanical response predictions. The homogenized fuel meat was used, and constant Al cladding oxide with 5μm-thickness was assumed.

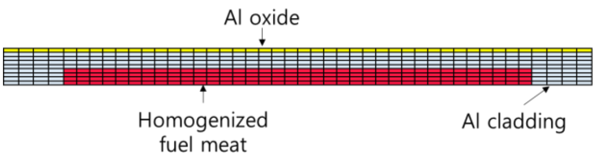



**Fig. 5 A finite element model generated by the PRIME for the verification of thermal response prediction.**

Three different transversal power peaking profiles were used to compare two-dimensional temperature distributions obtained from PRIME and ABAQUS commercial FEM package. Temperature contours with iso-temperature lines showed clearly that the temperature calculations by the PRIME were in good agreement with the results from ABAQUS as shown in Fig. 6.

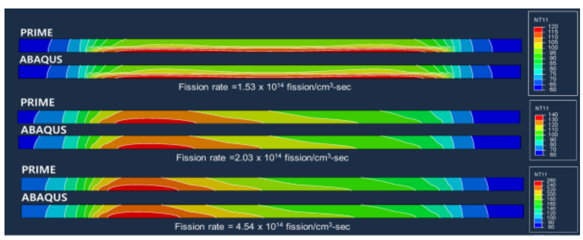



**Fig. 6 Comparison of temperature contours obtained from PRIME and ABAQUS for three different plates.**

In order to verify whether the stress integration is correctly computed for the mechanical response, the effective stress was compared at the peak-stress node located at the meat-clad interface where the magnitude of stresses is highest as a function of time. As shown in Fig. 7, PRIME predicted agreeable deformation of the fuel plate and computed the stress integration reliably.

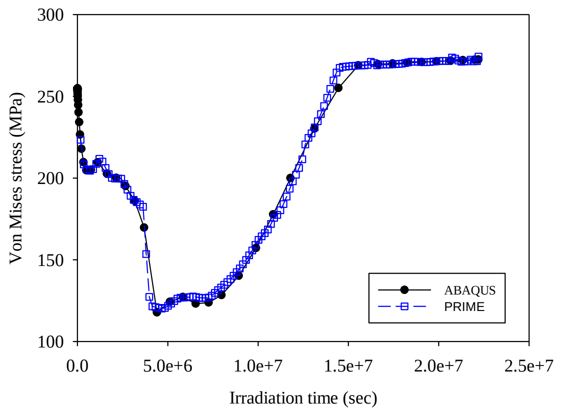



**Fig. 7 Comparison of FEA results from ABAQUS and PRIME mechanical solver for the effective stress as a function of irradiation time at the peak-stress node.**

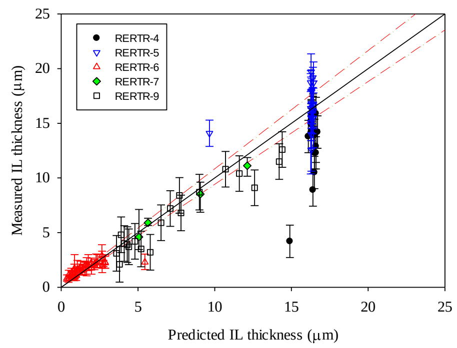
### *4.2. Validation*

The prediction results were compared to the PIE data from several different irradiation tests, including RERTR-4,-5,-6,-7,-9 [6], HAMP-1 [7], and E-FUTURE [8], to validate the prediction capability of the PRIME for the irradiation performance. The irradiation data for plates used in the benchmark are summarized in Table 1.

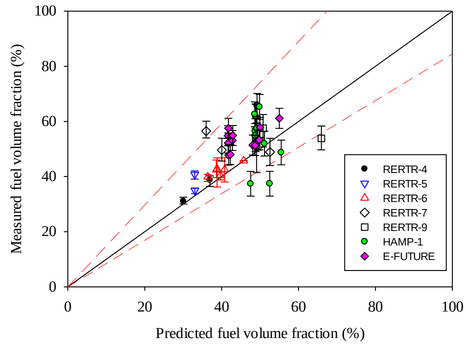
**Table 1 Irradiation test data for plates used in the validation.**

| Test | Plate ID | Irradiation Time (EFPD) | Meat U-loading ($gU/cm^3$) | Fuel meat composition | Particle size (μm) |
|---|---|---|---|---|---|
| RERTR-4 | V6022M | 257 | 6 | U-10Mo/Al | 65 |
| RERTR-5 | V6019G | 116 | 6 | U-10Mo/Al | 65 |
| RERTR-6 | R3R030 | 135 | 6 | U-7Mo/Al-5Si | 65 |
| RERTR-6 | R1R010 | 135 | 6 | U-7Mo/Al-0.9Si | 65 |
| RERTR-7 | R0R010 | 90 | 6 | U-7Mo/Al | 140 |
| RERTR-9 | R3R108 | 98 | 8 | U-7Mo/Al-5Si | 50 |
| HAMP-1 | KJM-8031 | 111.4 | 8 | U-7Mo/Al-5Si | 65 |
| HAMP-1 | KJM-6506 | 111.4 | 6.5 | U-7Mo/Al-5Si | 65 |
| E-FUTURE | U7MC6301 | 77 | 8.0 | U-7Mo/Al-6Si | 70 |

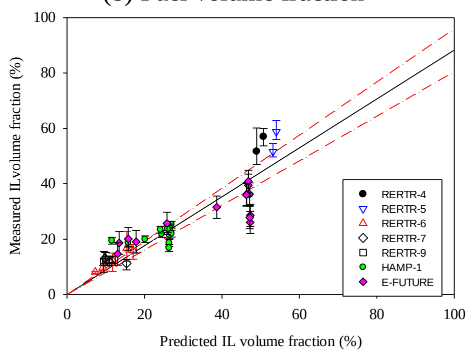
Validation for the thermal response for PRIME has been performed indirectly by comparison by IL thickness and meat constituent volume fractions at EOL from the measurement and prediction, because no measured data are available for fuel temperature. The PRIME predictions for IL growth and volume fractions for all constituent regarding plates used in the validation were in good agreement with the measured dataset as shown in Fig. 8.



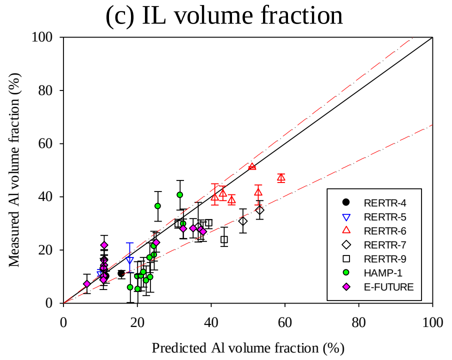

(a) IL thickness




(b) Fuel volume fraction



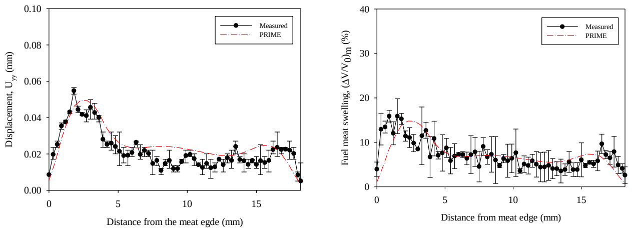

(c) IL volume fraction



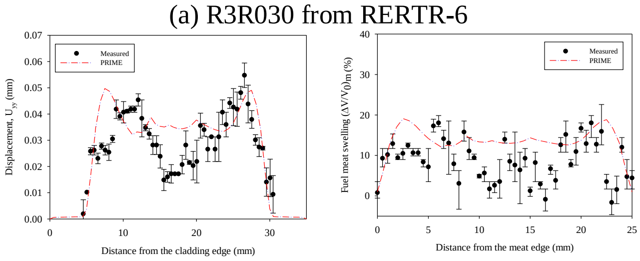

(d) Al matrix volume fraction

**Fig. 8 Comparison between the measured and predicted IL thickness and volume fractions of meat constituents (fuel, IL, and Al matrix) for the plates with 95% confidence intervals.**

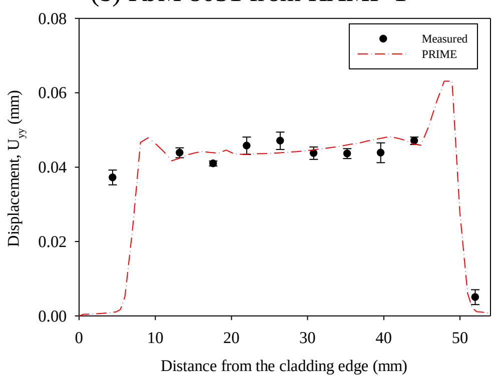
Mechanical responses for the plate were predicted in terms of the plate displacement in the thickness direction (i.e., plate thickness increase) and fuel meat swelling. and they were compared to the measurement data as shown in Fig. 9. Only displacement profile was available for E-FUTURE plate due to the lack of measured data. The prediction results were consistent with the measurement data.




(a) R3R030 from RERTR-6




(b) KJM 8031 from HAMP-1




(c) U7MC6301 from E-FUTURE

**Fig. 9 Comparison between measurement and prediction data of the displacement ($U_{yy}$) (left) and meat swelling (right) for benchmarked plates.**

## 5. Conclusion

The performance analysis code, PRIME, was developed by implementing models to predict two-dimensional steady-state irradiation behaviors of U-Mo/Al.

PRIME was successfully verified by comparing prediction results with ABAQUS solutions for the thermal and mechanical problems. Additionally, PRIME was validated by using irradiation data obtained from RERTR, HAMP-1, and E-FUTURE tests. In spite of large uncertainties from the measurement, PRIME predicted irradiation-thermal-mechanical response of U-Mo/Al reliably.

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