

Finite Element Analysis of U-19Pu-10Zr Annular Metallic Fuel for SFR

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1. Introduction

Metallic fuels composed of U–Pu–Zr alloys are prominent candidates for sodium fast reactor (SFR) applications because of their high thermal conductivity, predictable swelling behavior, and excellent compatibility with liquid sodium coolant. In particular, HT-9 ferritic–martensitic steel is widely used as cladding material for its superior dimensional stability and corrosion resistance under irradiation.

Despite these advantages, metallic fuels exhibit considerably greater swelling compared to conventional ceramic fuels, which can lead to fuel–cladding mechanical interaction (FCMI) and plastic deformation of the cladding, potentially compromising fuel rod integrity. To alleviate this issue, annular metallic fuel designs have been proposed as an effective solution, offering additional space for fuel swelling and thereby reducing FCMI at high burnup conditions [1].

In this study, the thermo-mechanical behavior of an annular U–19Pu–10Zr metallic fuel rod encapsulated in HT-9 cladding is investigated using finite element analysis (FEA). The model is constructed based on the ABR-1000 fuel assembly design specifications, and the simulation results will be compared with outputs from the BISON code to assess the accuracy and reliability of the proposed approach.

2. Methods and Results

2.1 FEA Model Setup and ABAQUS Input Generation

This work aims to improve KAFKA [2], developed for Accident Tolerant Fuel (ATF) Light Water Reactor (LWR) fuel performance analysis based on the ABAQUS™ framework. In this study, a modified version of KAFKA for metallic fuel was developed to assess the thermo-mechanical behavior of metallic fuel and HT-9 cladding in an SFR environment. This was achieved by incorporating user-subroutines to account for the creep behavior of the materials and the volumetric swelling of U–19Pu–10Zr fuel under SFR operational conditions.

The material properties used in the simulation—including Young’s modulus, Poisson’s ratio, thermal conductivity, specific heat capacity, thermal expansion coefficient, and plastic deformation behavior—were adopted from the models described in the BISON Theory Manual [3]. Some of the important properties are shown in Fig.1.

2.2 Modeling and Constructing Boundary Conditions

The annular metallic fuel rod geometry was modeled in ABAQUS™ based on the specifications provided in a previous research [1], as illustrated in Fig. 2. The HT-9 cladding was defined with an outer diameter of 0.902 cm and an inner diameter of 0.778 cm, which matches the outer diameter of the annular U-19Pu-10Zr fuel. The inner diameter of the fuel was set to 0.522 cm, creating an internal annular void region. To represent the heat generation within the fuel, a body heat flux was implemented in accordance with the linear axial power distribution described in the reference, using the following equation:

$$q'''(W/m^3) = \frac{\text{Peak Linear Power}(W/cm) \times 100}{\text{Cross-sectional Area}(m^2)}.$$

The distribution was also fitted to a quadratic function, which was subsequently used to estimate the coolant temperature profile along the axial length of the fuel rod. The axial coolant temperature was derived using the energy balance equation,

$$q''(z)Pdz = \dot{m}C_p dT_m,$$

$$T_m(z) = T_{in} + \frac{A_{pin}}{\dot{m}C_p} \int_0^z (a\zeta^2 + b\zeta + c) d\zeta.$$

Film coefficient was calculated using the formula that is proposed by Lubarsky and Kaufman (1955)

$$Nu = 0.625Pe^{0.4} \quad [4]$$

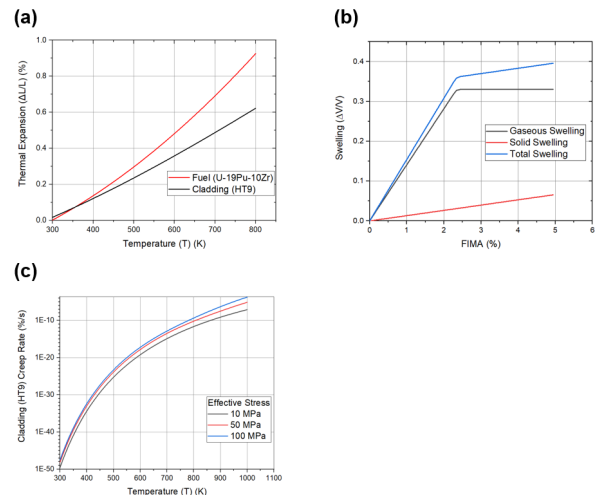


Fig. 1. Graphs of the (a) U-19Pu-10Zr fuel and HT-9 cladding thermal expansion, (b) fuel swelling, and (c) cladding creep rate according to the effective stresses of 10, 50, 100 MPa

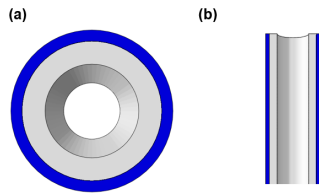


Fig. 2. Schematic of the (a) U-19Pu-10Zr fuel (gray) and HT-9 cladding (blue) seen from the top and (b) seen from the side

2.3 Calculation results

Fig. 3 presents the axial temperature distribution of the fuel and outer cladding in the annular metallic fuel rod under Hot Zero Power (HZIP) conditions, evaluated at 100,000 seconds after the onset of initial power ramp. The cladding temperature increases from approximately $\sim 380^\circ\text{C}$ to $\sim 520^\circ\text{C}$ along the axial direction, which closely follows the trend predicted by the BISON code, with a deviation of less than 6%.

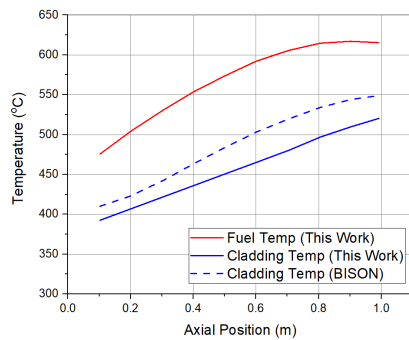


Fig. 3. Fuel and cladding temperature distribution

After 617 days of reactor operation, corresponding to an approximate burnup of 5%, the equivalent swelling strain of the fuel reached approximately ~ 0.38 . A notable inflection in the strain growth rate is observed around the 2% burnup mark, as depicted in Fig. 4 (a). As swelling progressed, the fuel thickness increased from 1.28 mm to 1.98 mm, as shown in Fig. 4 (b).

The cladding hoop stress, initially approximately 50 MPa, gradually decreased to about 20 MPa. It further dropped to approximately 10 MPa around the 2% burnup point, where the rate of swelling strain markedly diminished, as shown in Fig. 5.

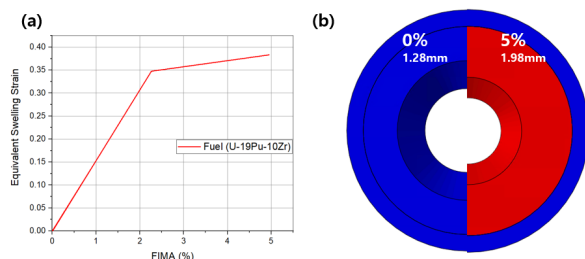


Fig. 4. (a) Graph of equivalent swelling strain with burnup, (b) Schematic of comparison between 0% burnup and 5% burnup condition.

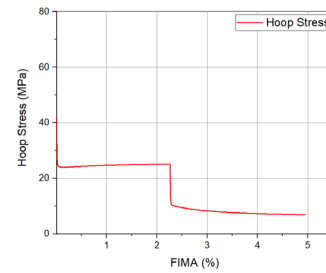


Fig. 5. Mid-region cladding hoop stress profile with burnup

3. Conclusion

In this study, the behavior of metallic fuel under sodium-cooled fast reactor (SFR) conditions was investigated, demonstrating that the annular fuel design significantly enhances the structural integrity of the fuel rod. The yield strength of typical HT-9 cladding at approximately 600°C is known to be around ~ 300 MPa [5], while the calculated hoop stress throughout irradiation up to 5% burnup remained below 40 MPa. Therefore, the HT-9 cladding withstands the mechanical loading with a significant margin of safety.

ACKNOWLEDGMENT

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