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Thermal-mechanical analysis of lead-cooled fast reactor fuel assembly with the inverted core design

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1. Introduction

A thermal-mechanical analysis was performed as part of the MINERVA project, which aims to develop a non-refueling ultra-long fuel cycle lead-bismuth eutectic cooled fast reactor (LFR) called MicroURANUS. MicroURANUS reactor has two distinct differences compared to conventional reactors. First, the reactor has a lower target heat generation rate, resulting in a lower reactor operation temperature range that contributes to ensuring the safety of the fuel system. Second, the fuel-cladding inverted core design [1, 2] offers the advantage of being free from fretting through a grid-free design.

Fuel and cladding material property models were constructed, including thermal properties such as thermal expansion and thermal conductivity, mechanical properties such as modulus and plastic deformation, as well as irradiation-induced characteristics such as swelling and fission gas generation. The safety analysis was performed by coupling the model with the finite element analysis software ANSYS. Finally, a reactor safety evaluation was performed by comparing the calculated results with safety criteria.

2. Methods and Results

In this section, the fuel performance parameters for safety analysis were described. Thermal properties, fission gas release (FGR), and mechanical deformation were analyzed. The general fuel assembly design follows the concept of fuel-cladding inverted core (Fig. 1)

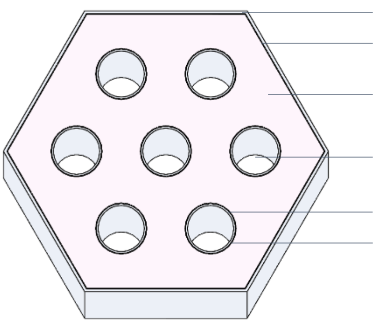

Fig. 1. The inverted core design option for MicroURANUS reactor (7 coolant channels case)

2.1 Thermal analysis

Fuel temperature was calculated at the average (34.09W/cm^3) and maximum (39.08 (BOL) ~ 50.91 (EOL) W/cm^3) power density, using the finite element method. The EOL maximum temperature is below 1000ºC, which is much lower than the melting point of UO_2 at the EOL burnup (2680ºC), and also lower than the operating temperature of European LFR ELSY (~1500ºC). This low temperature contributes to low FGR as well as low thermal creep.

2.2 Fission gas release analysis

The modified ANS4.5 model and the Forsberg-Massih model in the FRAPCON-4.0 LWR fuel performance code [3] were adopted for the FGR calculations. However, these models underestimate fission gas generation at below the threshold temperature, so an empirical formula as a function of burnup was used for low temperatures.

The analysis results showed very low fission gas generation of around 0.1 moles per assembly over a 40-year cycle, corresponding to a pressure increase of 0.517 MPa inside the plenum. The low fission gas generation due to the low operating temperature of the MicroURANUS reactor suppresses the plenum pressure increase, mitigating cladding hoop stress, which can be a life-limiting factor for the 40-year cycle operation.

2.3 Mechanical analysis

To analyze the mechanical deformation of the fuel-cladding inverted core using the finite element method, the following three steps were taken: 1) Fuel swelling was calculated using the low-temperature swelling model. 2) Fictitious thermal expansion coefficient [4] was determined considering the ratio of thermal expansion and fuel swelling, 3) Comprehensive deformation analysis using the finite element method.

The stress calculation results showed that the maximum stress occurs near the fuel-duct contact area due to the expansion. The outer duct experienced greater stress compared to the cladding surrounding the coolant channel. The contribution of stress due to thermal and swelling effects was about 6:4. At EOL, fuel experiences a local maximum stress of about 1.486 GPa, which is higher than the fracture stress of UO_2

(150~200MPa), and the maximum stress of the rod-type fuel (0.74 GPa). Therefore, fuel cracking is expected to occur, and the degree of cracking is expected to be greater than that of rod-type fuel.

For the thermal creep analysis, a cumulative damage function (CDF) analysis was performed. CDF results were extremely low (~10^{-12}, ~10^{-10} for the cladding and duct, respectively). This indicates that the thermal creep deformation of the cladding does not act as a safety limiting factor, compared to the cladding.

3. Conclusions

In this study, a steady-state fuel performance evaluation platform was constructed using 3D multi-physics models. The evaluation results showed a high thermal margin and a low generation of fission gas. The internal stress evaluation result revealed a higher stress distribution compared to the normal rod-type fuel. Additional analysis is required to evaluate the fuel cracking behavior. The CDF calculation result showed that deformation due to thermal creep is negligible in a 40-year reactor operation.

3D performance analysis methodology applicable to the LBE environment, fuel-cladding inverted core design, including the low-temperature region was established. The fuel safety was evaluated using this methodology. This study is expected to contribute to the improvement of the safety of lead-cooled fast reactors and inverted core designs.

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