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

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1. Introduction

Many countries are now pursuing the development of a nuclear-propulsion icebreaker for the exploration and development of the Arctic route. In Korea, the MINERVA project is now developing a non-refueling ultra-long fuel cycle (30+ years), lead cooled fast-flux microreactor named MicroURANUS.

Since the target heat generation rate of MicroURANUS is low, the reactor can be operated at a substantially low maximum fuel temperature of about 1000℃, ensuring the thermal safety of fuel and cladding. In addition, a fuel-cladding inverted concept [1] is considered for core design without a grid, which has the advantage of being free for the fretting, the most common cause of fuel failure incidents. However, there is no experience with this low operating temperature and inverted core design in conventional reactors. Accordingly, it is necessary to confirm the safety characteristics of the reactor design through thermal and mechanical analysis.

In this study, thermal and mechanical analysis of MicroURANUS fuel was performed using the finite element method. Steady-state thermal and static structural tool in ANSYS software was used for each analysis. Cladding-failure factors such as fission gas release, irradiation-induced swelling, and creep were evaluated with the temperature profile calculated in thermal analysis, and the results were used as input for mechanical analysis. Finally, a comprehensive safety evaluation was made on the safety criteria required for the naval nuclear reactors.

2. Methods and Results

Estimation was done for one fuel assembly, and geometry of the inverted core design is illustrated in Figure 1. The general fuel assembly design follows the inverted core concept: the coolant channel is inside the hexagonal UO_2 fuel pellet. Steel duct and cladding surround the fuel-coolant boundaries, and fuel-cladding gap space is filled with He gas.

Safety evaluation was performed sequentially, in linkage with thermal analysis, failure factor analysis, and mechanical analysis. The details of each procedure are described in the following sections.

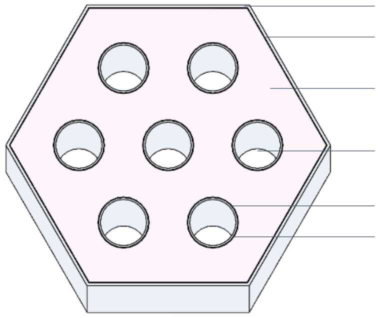

Fig. 1. The inverted core concept for MicroURANUS

2.1 Thermal analysis

First, we estimated the fuel assembly temperature for the unstrained case in ANSYS steady-state thermal module. The radial and axial temperature profiles were calculated from the inlet/outlet coolant temperature. Then the assembly was divided into 10 sections in a longitudinal direction, and the average cladding temperature was estimated in each section. The values were used as an input for failure factor analysis and deformation analysis.

2.2 Failure factor analysis

MicroURANUS adopted austenitic steel as a cladding and duct material, because austenitic steel shows better low temperature irradiation characteristics than that of ferritic/martensitic steel. It is necessary to investigate the failure factors that limit life for ultra-long cycle operation of more than 30 years. We estimated the fission gas release, irradiation-induced cladding swelling, and thermal /irradiation creep.

2.2.1. Fission gas release

During the reactor operation, insoluble noble gases are generated and released to the inner structure of fuel assembly and collected in the fission gas plenum. Fission gas release result in pressure buildup inside the fuel assemblies and may induce a duct deformation. FGR fraction was estimated by empirical correlation of burnup and temperature[2,3].

2.2.2. Irradiation-induced cladding swelling

For the cladding swelling estimation, empirical correlation derived from diametrical swelling data [4] of austenitic steel at low temperature was used. The dpa (displacements per atom) and fast-fluence of the reactor calculated from the core analysis were used in the swelling estimation.

2.2.3. Cladding creep

Thermal and irradiation creep of austenitic steel were estimated respectively. Yang's model [5] from the stainless steel creep data in the temperature range from 873K to 1023K was adopted for the thermal creep and Foster's model [6] from the stainless steel irradiation creep data from the EBR-II was adopted for irradiation creep. The total induced creep during the reactor operation was calculated from the creep rate and the time and was evaluated according to the safety criteria.

$$\dot{\varepsilon}_{thermal} = A\,[sinh(\alpha\sigma)]^n\ exp(-\frac{Q}{RT})$$
$$\dot{\varepsilon}_i = (B\,\sigma + C\,\sigma^3)\overline{E}\,\varphi$$
$$A = \exp\left(-6.885 \cdot \frac{10^7}{T^2} + \frac{186398}{T} - 77.6944\right)$$
$$B = 1.1932 \cdot 10^{-28}$$
$$C = 5.602 \cdot 10^{-33}$$

$\dot{\varepsilon}_{thermal}$: cladding thermal creep rate
σ: cladding hoop stress
α: material constant
n: material constant
Q: activation energy of deformation
R: gas constant
$\dot{\varepsilon}_i$: cladding irradiation creep rate
Φ: fast flux
$\bar{E}$: average neutron energy

2.3 Mechanical analysis

Lastly, we calculated the cladding deformation from the temperature and the failure factor estimation results. The thermal increase result in temperature, the pressure acting on the fuel assembly inner wall result in fission gas release in the plenum space, and the volumetric increases result in irradiation-induced swelling. We input each factor as an equation in ANSYS static structural module and calculate the bulging/bowing deformation.

3. Conclusions

Thermal and mechanical safety analysis of MicroURANUS was performed by linking the finite element method and empirical correlation. This analysis has significance in terms of the establishment of FEM-based safety evaluation methodology for a complex core design, and also the safety assessment of innovative MicroURANUS design. This study is expected to contribute to the improvement of the safety of lead-cooled fast reactors and inverted core design.

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