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

Preliminary Performance Evaluation of TRU Bearing Fuel Rod for Sodium-cooled Fast Reactor

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1. Introduction

As a part of developing technology to reduce the toxicity and volume of spent fuel, the preliminary design of the fuel rod (U-TRU-RE-Zr fuel slug with FMS (Ferritic-Martensitic Stainless) cladding) for Sodium-cooled Fast Reactor (SFR) is in progress at KAERI. The fuel slug composition of U-49TRU-5RE-25Zr (wt.%) was determined by taking into account the pyro-processing condition and the aspect of ensuring that the solidus temperature of the fuel slug is at least higher than 1,100 °C. The fuel rod is designed to maintain integrity during operational states. In order to assure this, fuel design criteria are established below the experimental limit at which actual fuel damage would occur, and it is proved that the fuel design criteria are satisfied through a fuel performance analysis.

In this work, fuel design criteria, performance evaluation methodology, and preliminary performance evaluation results of TRU bearing fuel rod by using LIFE-METAL code [1,2] which has been developed jointly with ANL are presented.

2. Fuel Design Criteria and Performance Evaluation Methodology

2.1 Fuel Design Criteria

In metallic fuels, a variety of physical phenomena occur at the same time: (1) there is a fuel-cladding mechanical interaction (FCMI) that exerts a mechanical load on the cladding due to fuel slug swelling, (2) a fuel-cladding chemical interaction (FCCI), (3) a decrease in the thermal conductivity of the fuel slug due to the generation of fission gas bubbles, and recovery due to sodium infiltration into open pores, and (4) fission gas release (FGR). The performance of the fuel rod is analyzed considering these phenomena, and the integrity of the fuel rod is evaluated by comparing the calculation results with the fuel rod design criteria: these are the fuel melting (approximately 1,100 °C for U-49TRU-5RE-25Zr), the cladding cumulative damage fraction (CDF < 0.05), and the cladding strain (total diametral inelastic strain < 1.0 %) [3].

2.2 Fuel Performance Evaluation Methodology

To demonstrate whether each design criterion is satisfied for all the rods of the core at any time, a fuel performance code is employed together with a fuel design methodology, which specifies how to use the code for design analysis.

The fuel rod design methodology ensures a fuel design procedure enough to have suitable margin by introducing conservatism by means of uncertainties. The uncertainties are reflected in the fuel performance models (cladding thermal conductivity, cladding thermal creep strain, FCCI and FGR), the as-fabricated fuel rod tolerances (cladding thickness), input neutronic and thermo-hydraulic conditions (fuel rod power and cladding temperature), etc. The root mean square method is employed to statistically combine the individual effects caused by model uncertainties and dimensional tolerances. The fuel performance model uncertainties are treated by taking an approximately 2σ level of confidence. Here, considering that the very conservative CDF limit was drawn with taking into account uncertainty in the cladding creep rupture data, a best-estimated creep rupture curve is used [4].

3. Performance Evaluation Results and Discussions

3.1 Fuel Rod Design Description

The fuel rod consists of a metallic fuel slug and FMS cladding. A preliminary schematic diagram of the fuel rod is shown in Fig. 1. The metallic fuel slug is a U-49TRU-5RE-25Zr alloy. In order to promote heat transfer, sodium fills the gap between the metallic fuel slug and cladding.

In the upper part of the fuel rod, there is a plenum that can accommodate the gas generated by fission. On the cladding outer surface, a wire is spirally wound, which maintains a gap between each fuel rod in the fuel assembly and allows the sodium coolant to flow through this gap.

The total length of the fuel rod is 2,140 mm and the outer diameter is 5.2 mm. The diameter of the fuel slug is 3.2 mm and the length is 800 mm. The thickness and inner diameter of the cladding is 0.75 mm and 3.7 mm, respectively. Since the threshold temperature of eutectic reaction between U-49TRU-5RE-25Zr fuel slug and FMS cladding is estimated to be less than 600 °C, the barrier of 50 μm thickness is applied on the cladding inner surface for preventing the eutectic reaction between fuel slug and cladding. HT9 wire with a diameter of 1.35 mm is wound on the outer surface of the fuel rod.

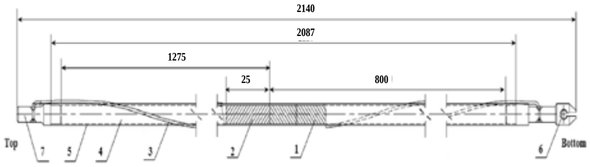

Fig. 1. Preliminary schematic diagram of the fuel rod: 1-fuel slug, 2-sodium, 3-wire, 4-plenum, 5-cladding, 6-lower end cap, 7-upper end cap

3.2 Irradiation Conditions for Performance Evaluation

Preliminary nominal irradiation conditions are summarized in Table I. Peak linear power and peak fast neutron flux is 302.6 W/cm and 6.34×10^{15} n/cm^2·sec, respectively. Effective fuel power days (EFPD) of the inner core is 435 and peak burnup is 22 at.%. Coolant inlet temperature is 390 °C and peak cladding mid-wall temperature is 580 °C. HT9 cladding is applied for the preliminary performance evaluation.

Table I: Preliminary nominal irradiation conditions

Peak linear power (W/cm)	302.6
Peak flux ($\times10^{15}$ n/cm^2·sec)	6.34
EFPD (inner core)	435
Peak burnup (at.%)	22
Coolant inlet temperature (°C)	390
Peak cladding mid-wall temperature (°C)	580

3.3 Performance Evaluation Results

The peak burnup of the limiting fuel rod for the inner core calculated by applying the fuel performance evaluation methodology is 24.3 at.%. The peak cladding mid-wall temperature is 617 °C, and the peak fuel slug centerline temperature is 677 °C (Fig. 2). Fig. 3 shows the CDF and total diametral inelastic strain of the cladding. As shown in the figures, the fuel rod design criteria of fuel slug centerline temperature (< 1,100 °C), cladding CDF (< 0.05), and cladding strain (< 1.0 %) are met.

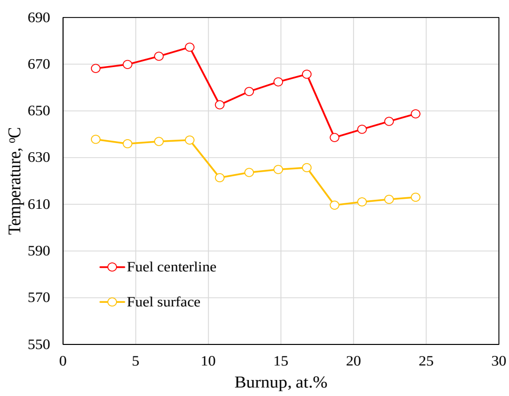

Fig. 2. Fuel slug temperatures at the fuel top position as a function of burnup.

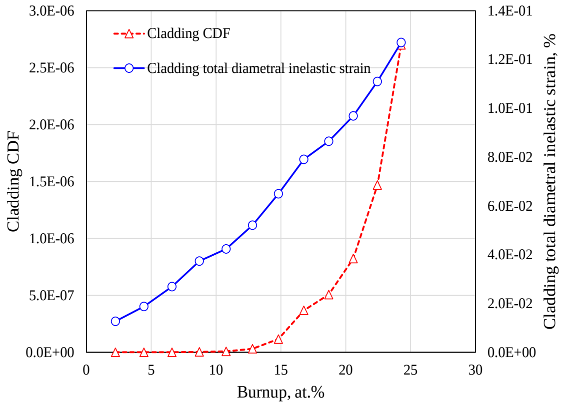

Fig. 3. CDF and total diametral inelastic strain of the cladding at the fuel top position as a function of burnup.

4. Conclusions

Fuel design criteria, performance evaluation methodology, and preliminary performance evaluation results of TRU bearing fuel rod for SFR were presented. Preliminary performance evaluation results met the fuel rod design criteria of fuel slug centerline temperature, cladding CDF, and cladding strain when the performance evaluation methodology was applied.

In near future, performance evaluation of TRU bearing fuel rod with more detailed irradiation conditions will be additionally carried out.

ACKNOWLEDGEMENT

This project has been carried out under the Nuclear R&D program by Ministry of Science, ICT & Future Planning.

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