Post Irradiation Examination on SMIRP-1 Fuel Rods

Jin Sik Cheon, B.O. Lee, C.T. Lee, J.H. Kim, B.G. Kim, J.H. Kim, S.J. Oh, K.H. Kim, H.M. Kim, B.O. Yoo, Y.H. Jung, C.B. Lee
Korea Atomic Energy Research Institute, 989-111 Daedeok-daero, Yuseong, Daejeon, Korea, 305-353

1. Introduction

KAERI initiated its program to develop SFR metal fuel technology in 2007. As an effort to validate the relevant fuel design and fabrication technologies, the first fuel irradiation test, SMIRP-1, was performed for 182 EFPD in HANARO. There were 12 rodlets which consist of 6 U-10Zr and 6 U-10Zr-5Ce slugs with T92 cladding [1]. Among them, four rodlets had a thin Cr layer which was electroplated. Subsequently the irradiated fuel rods were subjected to PIE at IMEF.

This paper summarizes the non-destructive and destructive test results of the fuel rodlets together with analyzing the fuel temperature based on the irradiation history.

2. Irradiation history

The irradiation rig accommodated 6 rodlets at each upper and lower positions, respectively. Each fuel rod was contained in a sealing tube. There was a gap between cladding and sealing tube to attain a temperature jump for the desirable cladding temperature.

Temperature at the cladding outer-surface depends on the fuel linear power which is presented in Fig. 1. Fuels experienced higher linear power at the lower position. The maximum linear power and burnup were 245 W/cm at BOL and 2.87 at% at EOL according to an as-run analysis. Using KAERI's fuel performance analysis code, MACSIS, cladding temperature and fuel centerline temperature were calculated to be 500 °C, and 628 °C, respectively. Thus fuel slugs were irradiated in the $\alpha+\delta$ regime with respect to time and location.

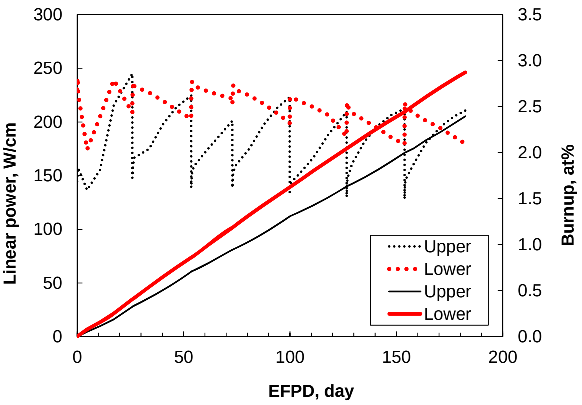

Fig. 1. Linear power as a function of EFPD.

3. Non-destructive tests

Cladding deformation was not measured by considering lower temperature and insignificant irradiation damage compared to irradiation conditions in a fast reactor. Gamma scanning measurements were made for all fuel rods. Cs isotopes are soluble in Na which is used for the gap material in the fuel rods. Thus Zr-95 and Ru-106 isotopes were employed as measures for the axial distribution of linear power and burnup, respectively.

Zr-95 and Ru-106 gamma intensities were found to have more or less uniform distribution. An example is shown in Fig. 2 for U-Zr-Ce. In some cases, there were locally steep variations that likely result from either fabrication porosity or a less uniform fissile distribution. Cs-137 is not distributed evenly and has a tendency of being displaced to the top of fuel column as previously reported in previous metal fuel tests [2].

Axial growth of the fuel slug was measured based on the gamma scanning results. U-Zr and U-Zr-Ce exhibits 12% and 10% anisotropic axial growth, respectively. These are slightly higher than those reported previously. This is thought to be related to a lower smeared density of 65% for SMIRP-1 fuel rodlets. In comparison, comparable metal fuels have a smeared density of 75%. Thus fuel rods with a wider gap have more room before fuel comes into contact with the cladding. In addition, the lower axial growth in Ce-bearing fuels might be caused by its brittle behavior as in the case of U-Pu-Zr fuel [2].

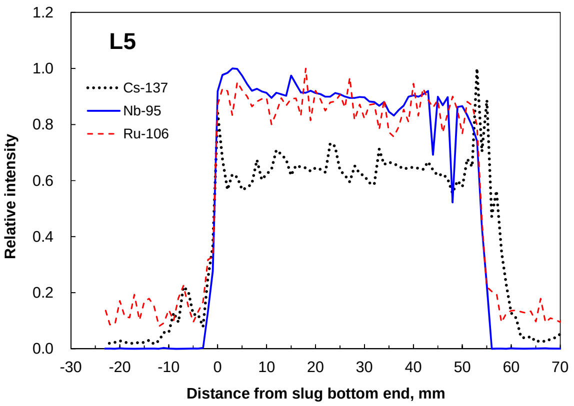

Fig. 2. Relative gamma ray intensity from the bottom of fuel slug (U-10Zr-5Ce).

4. Destructive tests

Recently, new equipment was installed in IMEF to measure the fractional fission gas release (FGR). This was developed to apply it to a fuel rodlet having an extremely small plenum. Nonetheless, problems appeared when some of the FGR measurements were made. Fig. 3 shows the fractional FGR of SMIRP-1 fuels, which turns out to be in good agreement with early experience. In addition, the ratio of Xe to Kr was measured. It remained in the range of 5.3 to 6.0, indicating that U-235 thermal fission is responsible. The ratio increases to more than 12 for Pu-239 when fission occurs in a fast reactor [3].

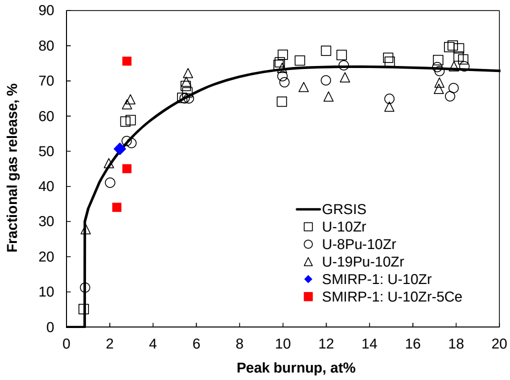

Fig. 3. Fractional fission gas release of SMIRP-1 fuels.

The microstructure of irradiated fuel slugs was observed. Fuel swelled to make contact with the cladding at a lower burnup of 2~3 at%. Low-temperature phase of U-Zr fuel swelled higher than the high-temperature one, leaving a swirled microstructure and containing irregular-shaped porosities and tearing. These characteristics are proof that the irradiation was undertaken at a temperature below 617 °C for phase transformation from $\alpha+\delta$ to $\alpha+\gamma_2$ [2]. There was not enough microstructural evidence in favor of the presence of fuel-cladding chemical interaction, which was likely to be caused by a low irradiation temperature.

Concentration profiles were measured across the whole cross-section of the fuel and especially around the interface between the fuel and cladding. Zr was observed to move against the temperature gradient as in the case of Pu in SFR MOX fuel. As the cladding was mostly not positioned to be concentric relative to the sealing tube, the Zr distribution was not symmetric with respect to the fuel center. In this case, the Soret effect is the sole mechanism for this phenomenon since there was no phase boundary in the fuels.

Lanthanides including Ce and Nd were seen to exist preferentially near the fuel-cladding interface. Moreover Ce was observed to be associated with porosities in the case of Ce-bearing fuel. This is quite similar to Am behavior in U-Pu-Zr-2.1Am-1.3Np [4].

The behaviors of Cr-plating barrier claddings were investigated. The thickness of the Cr barrier was in the range of 10 to 20 μm. There were observed some cracks which are regarded to initiate in the Cr barrier whose hardness is even higher than that of cladding material. It was seen that the crack grew up to 10 μm deep into both the fuel and cladding. It was revealed that such crack formation can be reduced substantially by adjusting the Cr-plating conditions, and the hardness of the Cr-layer can be controlled to be as low as that of the cladding [5].

Though examining EPMA concentration maps, Ce was shown to be more abundant near the cladding inner-surface in U-Zr-Ce than in U-Zr fuels. As shown in Fig. 4, the Cr barrier played a crucial role in protecting the lanthanide penetration into the cladding. However, a definite conclusion needs to be put aside due to its lower irradiation temperature until the second SFR fuel irradiation test at HANARO, SMIRP-2, is complete.

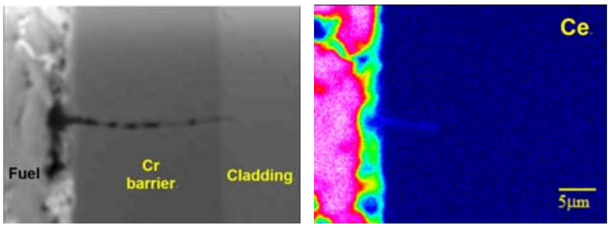

Fig. 4. SEM photography and EPMA Ce map at fuel-cladding interface for U-10Zr-5Ce.

5. Summary

SMIRP-1 fuels were irradiated in the $\alpha+\delta$ regime. This was estimated from an as-run analysis and confirmed by microstructural observation. Gamma scanning results showed that the axial burnup distribution was more or less uniform with local variations in microstructure and composition, and that there was slightly higher axial growth than the previous experience showed. Also, fractional fission gas release, and fuel constituent redistribution were consistent with the current understanding. The Cr barrier was excellent at protecting Ce diffusion into the cladding at lower temperature.

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