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Performance Evaluation of the Metallic Fuel for the 2nd Irradiation Test in the HANARO

Bong Goo Kim*, Junehyung Kim, Seong Woo Yang, Jeong-Yong Park, ByoungOon Lee, and Jin-Sik Cheon
Korea Atomic Energy Research Institute, Daedeok-daro 989-111, Yuseong-gu, Daejeon, 305-353, Korea
*Corresponding author: bgkim1@kaeri.re.kr

1. Introduction

As a part of the performance verification tests for KAERI's metallic fuel design and fabrication technologies, the 1st fuel irradiation test, SMIRP-1 (Sodium-cooled fast reactor (SFR) Metal fuel IRradiation test Program-1), was successfully performed for 182 EFPD in HANARO [1-3]. There were 12 rodlets which consist of 6 rodlets of U-10wt.%Zr slugs and 6 rodlet of U-10wt.%Zr-5wt.%Ce slugs having a diameter of 3.7 mm with T92 cladding. Subsequently, PIE of the irradiated fuel rods was finished. The linear power was calculated to be 245 W/cm at BOL (beginning of life) and 220 W/cm at EOL (end of life). Now, the 2nd irradiation test, SMIRP-2, was prepared [4,5]. Compared with SMIRP-1 irradiation device, design of some parts in SMIRP-2 was modified. There are also 12 rodlets, the same as SMIRP-1, which consist of 6 rodlets of U-10wt.%Zr and 6 rodlets of U-10wt.%Zr-4wt.%RE(chemical composition of RE: 53wt.%Nd-25wt.%Ce-16wt.%Pr-6wt.%La) slugs having two kinds of diameter, such as 5.54 mm and 3.90 mm with three kinds of cladding, such as FC92B, FC92N, and HT9. SMIRP-2 will be irradiated from the end of 2019, and rodlets will be irradiated up to the peak burnup of 6 at.% (nominal) and maximum cladding inner-wall temperature of 650 ºC (considering uncertainty) in HANARO. Finally, PIE for SMIRP-2 will be followed. In this paper, the brief summary of the 1st irradiation results, the preparation of fuel rodlets and irradiation device for the 2nd irradiation testing, and the preliminary performance evaluation of rodlets were included.

2. First Irradiation Test (SMIRP-1) and PIE

In 2012, the 1st metal fuel irradiation test, SMIRP-1 was performed for 182 EFPD in HANARO [2]. There were 12 rodlets which consist of 6 U-10wt.%Zr and 6 U-10wt.%Zr-5wt.%Ce slugs with T92 cladding. Among them, four rodlets had the cladding with the electroplated Cr barrier of about 20 μm thickness. The cladding outer-wall temperature depends on the fuel linear power which is presented in Fig. 1. Fuels experienced higher linear power at the lower position. The peak linear power and burnup were calculated to be 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, maximum cladding inner-wall and fuel centerline temperature were calculated to be 452 °C, and 549 °C, respectively. The SMIRP-1 fuels were irradiated in the α+δ regime, which was confirmed by microstructural observation. As shown in Fig. 2, 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. Also, fractional fission gas release, and fuel constituent redistribution were consistent with the current understanding. Fig. 3 shows that the Cr barrier was excellent at protecting Ce diffusion into the cladding, although the test was performed at a lower temperature [1,3]. The discharged burnup was chemically determined to be 2.9 at.% by ^{148}Nd method [6,7].

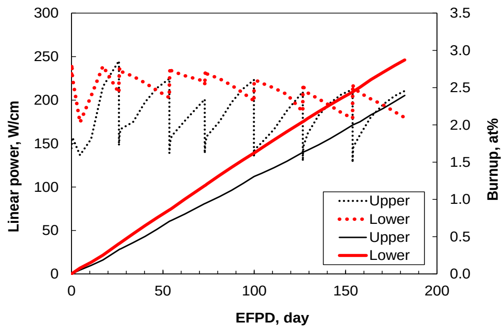

Fig. 1. Calculated linear power and burnup as a function of EFPD (Dotted lines; linear power, solid lines; burnup).

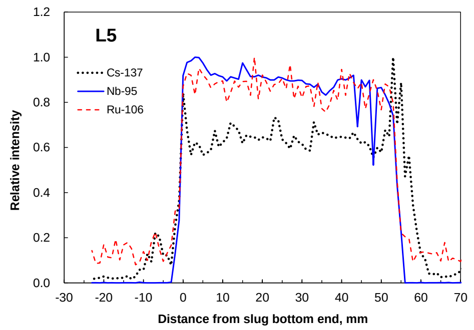

Fig. 2. Axial gamma scanning from the bottom of U-10wt.%Zr-5wt.%Ce fuel rod.

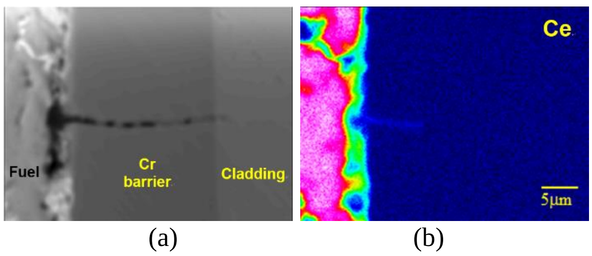

Fig. 3. (a) SEM image and (b) EPMA map at fuel-cladding interface for 10wt.%Zr-5wt.%Ce.

3. Second Irradiation Test (SMIRP-2)

3.1 Objectives

The objective of SMIRP-2 is to prepare for technologies to irradiate a series of fuels with the HANARO under a temperature, a linear power and a burnup higher than those of the 1st irradiation test, SMIRP-1. Table 1 shows the configuration of fuel rodlets for the SMIRP-2 irradiation device [5]. There are also 12 rodlets where two kinds of fuel slug, U-10%Zr and U-10%Zr-4%RE having a diameter of 5.54 mm and 3.90 mm. RE contains Nd, Ce, Pr and La as a representative of the rare earth elements to examine the level of impurities not harmful for fuel performance. And, there are three kinds of cladding, such as FC92B, FC92N and HT9. It is also intended to identify the characteristics of the Cr barrier which is being developed in order to suppress an inter-diffusion between the metal fuel and cladding [5].

The fuel rodlets having the diameter same with PGSFR (Prototype Gen-IV SFR) fuel rod are placed in the upper part of the rig. Each fuel rod was contained in a sealing tube. There is a gap between cladding and sealing tube to attain a temperature jump for the desirable cladding temperature.

Table 1. Configuration of the fuel rodlets in the irradiation rig.

Location	No.	Fuel	Cladding	Barrier (μm)	Remarks
Upper	1	U-10wt.%Zr	FC92B	-	
	2	U-10wt.%Zr- 4wt.%RE*	FC92B	Cr (20)	
	3	U-10wt.%Zr	FC92N	-	
	4	U-10wt.%Zr-4wt.%RE*	FC92N	Cr (20)	**
	5	U-10wt.%Zr	HT9	-	
	6	U-10wt.%Zr-4wt.%RE*	HT9	-	***
Lower	1	U-10wt.%Zr	FC92B	-	
	2	U-10wt.%Zr-4wt.%RE*	FC92B	Cr (20)	
	3	U-10wt.%Zr	FC92N	-	
	4	U-10wt.%Zr-4wt.%RE*	FC92N	Cr (20)	
	5	U-10wt.%Zr	HT9	-	
	6	U-10wt.%Zr-4wt.%RE*	HT9	Cr (20)	

* RE; 53wt.%Nd-25wt.%Ce-16wt.%Pr-6wt.%La
** Half of Cr barrier on the circumferential internal surface
*** Non-oxidized fuel slug (upper 25 mm) and oxidized fuel slug (lower 25 mm)

3.2 Testing schedule

The SMIRP-2 irradiation testing in HANARO extends the irradiation condition of the SMIRP-1 test in terms of temperature, linear power, and burnup. The SMIRP-2 irradiation under normal operating conditions is planned to be complete with a peak burnup of about 6 at.%. The SMIRP-2 irradiation test is expected to be started from the end of 2019 in the HANARO. And then, PIE is expected to be started in 2021.

4. Preparation of Fuel Rodlets and Irradiation Device for SMIRP-2

4.1 Fuel rodlets

There are two kinds of fuel slugs, U-10wt.%Zr and U-10wt.%Zr-4wt.%RE, as shown in Table 1, fabricated by an injection casting method. The lump of RE (53wt.%Nd, 25wt.%Ce, 16wt.%Pr, 6wt.%La) was used to fabricate U-10wt.%Zr-4wt.%RE alloy fuel slugs. The soundness, chemical and microstructural characteristics of the cast fuel slugs were also identified and analyzed. As shown in Fig. 4, SEM was used to study the microstructure of fuel slugs. It can be seen that the dark precipitate consisted of Zr or Zr-rich phases and were homogeneously distributed in microstructures of U-10wt.%Zr. It can be seen that the gray precipitate consisted of RE-rich phases, and they were also homogeneously distributed in microstructures of U-10wt.%Zr-4wt.%RE. The size of precipitates were various from few micrometers to 20~30 micrometers. However, the RE elements were not immiscible with the U-Zr base elements. Fig. 5 shows the fabricated U-10wt.%Zr and U-10wt.%Zr-4wt.%RE fuel rods for the SMIRP-2. A gap between the cladding and the sealing tube was 60 μm and charged with He gas with 1 bar. The sealing tube would act as an additional barrier to prevent sodium leakage to the coolant during a cladding failure.

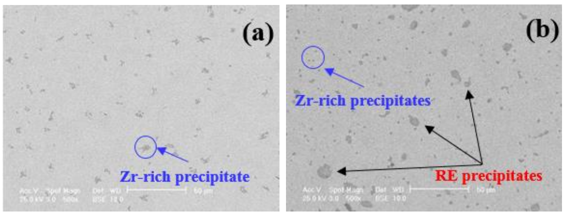

Fig. 4. Microstructures of fuel slugs; (a) U-10wt.%Zr, (b) U-10wt.%Zr-4wt.%RE (×500).

Fig. 5. Photograph of fuel rodlets after welding of endcaps.

4.2 Irradiation device

The design of bottom and upper parts in SMIRP-2 irradiation device was changed to improve the compatibility with test hole in HANARO and its structural integrity during an irradiation period [4,8,9]. As shown in Fig. 6, the assembling of SMIRP-2 with 12 rodlets was finished at the beginning of 2017. This assembly was also confirmed by the design requirements [10], the compatibility with the test hole of HANARO [11], the safety analysis including ONB (Onset of Nuclear Boiling) and reactivity evaluation at the end of 2017 [12].

Fig. 6. Photograph of assembled SMIRP-2 device.

5. Preliminary Performance Evaluation of Fuel Rodlets

The GENGTC and MCNP code systems have been employed to preliminarily estimate the linear power of fuel prior to the 2nd irradiation testing. The peak linear power of fuel rodlet was estimated to be satisfied with the temperature of 650 °C on the cladding inner surface using GENGTC code [13]. And then, after predicting the linear power of fuel rodlet and the temperatures of coolant/sealing tube/cladding at normal operating conditions, the fuel centerline temperature, cladding CDF (Cumulative Damage Fraction) and strain under normal operation condition were predicted using LIFE-METAL (L-M) code [14-16].

Fig. 7 shows the anticipated linear power and burnup of fuel rodlets as a function of EFPD during irradiation test of SMIRP-2 with considering linear power uncertainty (1.167). The peak linear power is near at the beginning of irradiation due to the larger amount of fissile material present in the rodlets. The peak linear power is estimated to be 423.5 W/cm among the lower fuel rodlets, and to be 645 W/cm among the upper fuel rodlets, respectively. The peak burnup was calculated to 7 at.%.

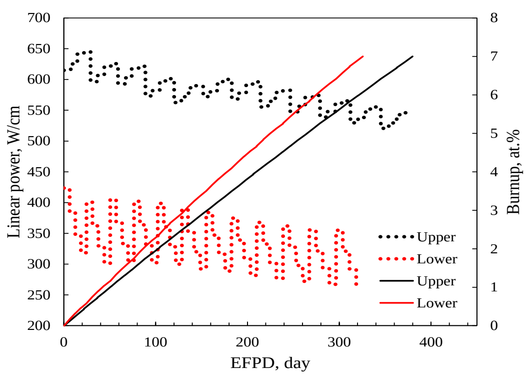

Fig. 7. Variation of the fuel centerline and cladding inner-wall temperature of upper and lower rodlets as a function of fuel burnup.

Fig. 8 shows the variation of the fuel centerline and cladding inner-wall temperature of upper rodlet (C) and lower rodlet (D) (Fig. 9) with the fuel burnup. The maximum fuel centerline temperatures of upper and lower rodlets were calculated to be 891 °C and 795 °C, respectively. And the maximum cladding inner-wall temperatures of upper and lower rodlets were calculated to be 649 °C and 650 °C at the beginning of irradiation, respectively. These temperatures at the BOL are the same as 650 °C which is the target maximum cladding inner-wall temperature for the 2nd irradiation testing.

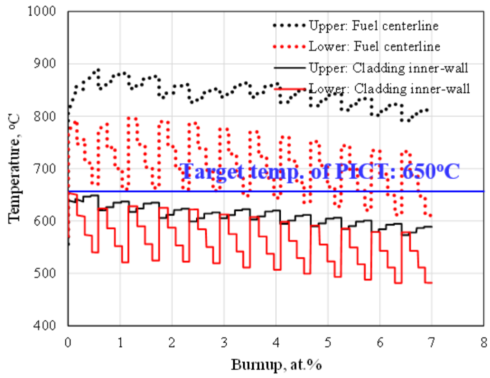

Fig. 8. Variation of the fuel centerline and cladding inner-wall temperature of upper and lower rodlet as a function of fuel burnup.

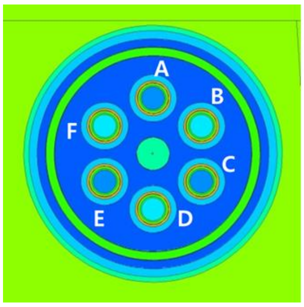

Fig. 9. Position of fuel rodlets for the calculation.

The fission gas release, rod internal pressure, cladding inner-wall wastage, cladding hoop stress, cladding strain, and cladding CDF were also evaluated. The calculation results of cladding strain and CDF showed that the integrity of fuel rodlet can be maintained during the 2nd irradiation testing.

6. Summary

The SMIRP-1, was successfully performed for 182 EFPD in HANARO in 2012. The peak linear power was calculated to be 245 W/cm at BOL. The SMIRP-1 fuels were irradiated in the α+δ regime, which was confirmed by microstructural observation of PIE. The discharged burnup was chemically measured to be 2.9 at.%.

The SMIRP-2 test extends the irradiation condition of the SMIRP-1 test in terms of temperature, linear power, and burnup. The followings were preliminary evaluated:

i) The preliminary peak linear power with uncertainty was estimated to be 423.5 W/cm among the lower fuel rodlets, and to be 645 W/cm among the upper fuel rodlets at BOL, respectively. The peak linear power of fuel rodlet was estimated to be satisfied with the temperature of 650 °C which is the target maximum cladding inner-wall temperature of the 2nd irradiation testing. The peak burnup was calculated to 7 at.% at EOL.

ii) The maximum fuel centerline temperatures of upper and lower rodlets were calculated to be 891 °C and 795 °C, respectively.

iii) The fission gas release, rod internal pressure, cladding inner-wall wastage, cladding hoop stress, cladding strain, and cladding CDF were also evaluated. The calculation results of cladding strain and CDF showed that the integrity of fuel rodlet can be maintained during the 2nd irradiation testing.

The SMIRP-2 was prepared to start the irradiation test in HANARO from 2019. PIE is expected to be started in 2021.

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