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Progress (II) on the 2nd Irradiation Test of the Metallic Fuel for SFR in the HANARO

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1. Introduction

In order to validate KAERI's SFR fuel design and fabrication technologies, the first fuel irradiation test, SMIRP-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. Now, the second irradiation test, SMIRP-2, was prepared. 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 U-10wt.%Zr and 6 rodlets 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. The compatibility with test hole of HANARO and its mechanical integrity was verified through an out-of-pile experiment using a mock-up of device. And then, the irradiation device, SMIRP-2, was assembled. After safety reviewing by the reactor safety committee for the irradiation testing in HANARO, the 2nd irradiation test, SMIRP-2, will be performed from the year 2018, and rodlets will be irradiated up to the maximum burnup of ~ 6 at.% in HANARO. Finally, PIE for SMIRP-2 will be finished in the year 2020. In this paper, the brief summary for the 1st irradiation results, the preparation of test rodlets and the irradiation device and the present status for 2nd irradiation testing were included.

2. First Irradiation Test and PIE

In 2012, the first 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. 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 calculated to be 245 W/cm at BOL and 2.44 at.% at EOL according to an as-run analysis. Using KAERI's fuel performance analysis code, MACSIS, maximum cladding temperature and fuel centerline temperature were calculated to be 452 °C, and 549 °C, respectively. The SMIRP-1 fuels were calculated to be 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].

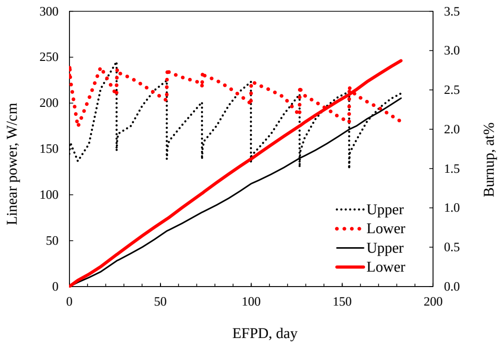


Fig. 1. Calculated linear power and burnup as a function of EFPD (Dotted lines; linear power, solid lines; burnup).

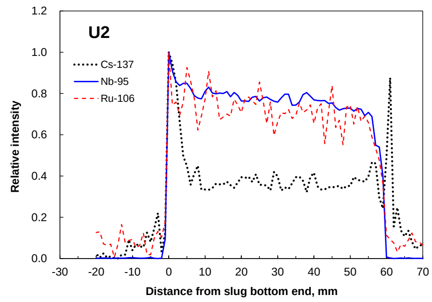
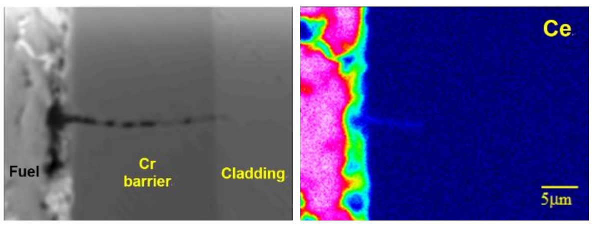


Fig. 2. Axial gamma scanning from the bottom of U-10wt.%Zr-5wt.%Ce fuel rod.



(a) (b)

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

3. Second Irradiation Test

3.1 Objectives

The objective of the second irradiation test, 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 first irradiation test, SMIRP-1. 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. Table 1 shows the configuration of fuel rodlets for the SMIRP-2 irradiation device. The fuel rodlets having the diameter same with PGSFR 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 Schedule

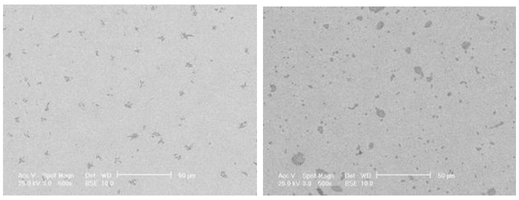
The SMIRP-2 irradiation testing in HANARO extends the irradiation condition of the SMIRP-1 test in terms of temperature, linear power, and burnup. The SMIRP-2 irradiation under normal operating conditions is planned to be complete with a maximum burnup of about 6 at.%. After approving for SMIRP-2 irradiation testing in HANARO by reactor safety review committee, the SMIRP-2 irradiation test is expected to be started from the year 2018 in the HANARO. Finally, PIE for SMIRP-2 will be finished in the year 2020.

4. Preparation of fuel rodlets and irradiation device for 2nd irradiation testing

4.1 Fuel rodlets

Two kinds of fuel slugs, U-10wt.%Zr and U-10wt.%Zr-4wt.%RE, slugs were 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. Graphite crucibles coated and quartz molds coated with Y_2O_3 were used. 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. And then, fuel slugs with diameters of 5.54 mm and 3.90 mm were cut to 50 mm and 25 mm (Fig. 5). And, Fig. 6 shows the fabricated U-10wt.%Zr and U-10wt.%Zr-4wt.%RE fuel rods for the 2nd irradiation test at the HANARO.

There are two kinds of sealing tubes. Their outer diameters were 8.52 mm and 6.62 mm with a thickness of 0.5 mm. Sealing tube was fabricated with Type 316L stainless steel, and contained the fuel rodlet. 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.



(a) (b)

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

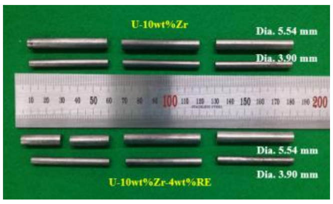


Fig. 5. Photography of final fuel slug after machining; U-10wt.%Zr (upper), U-10wt.%Zr-4wt.%RE (lower).

Fig. 6. Photography of fuel rodlets after welding of endcaps.

4.2 Irradiation device

The design of bottom parts and upper parts in SMIRP-1 irradiation device for SMIRP-2 was changed to improve the compatibility with test hole in HANARO and its structural integrity during an irradiation period [4-6].

As shown in Fig. 7, the assembling of SMIRP-2 with 12 rodlets was finished at the beginning of 2017. After confirming the design requirements [7], the compatibility with the test hole of HANARO [8], the irradiation performance of the fuel, and the safety analysis including ONB (Onset of Nuclear Boiling) and reactivity evaluation, the irradiation of SMIRP-2 will be started from the year 2018 in HANARO.

Fig. 7. Photography of assembled SMIRP-2 device.

4.3 Compatibility of irradiation device with test hole

The requirement for irradiation test in the test hole of HANARO core was confirmed through out-of-pile tests including the measurement of pressure drop and vibration at the top of the device, and an endurance test [5].

5. Preliminary performance analysis of fuel rodlets

The GENGTC and MCNP code systems have been employed to estimate the linear power of fuel. The linear power of fuel rodlet was estimated to be satisfied with the temperature of 650 °C on the inner cladding surface using GENGTC code [9]. And then, after predicting the linear power of fuel rodlet and the temperatures of coolant/sealing tube/cladding at normal and abnormal 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 [10-13].

Fig. 8 shows the anticipated linear power (W/cm) of fuel rodlets as a function of burnup (FIMA) during irradiation test of SMIRP-2. Linear power is near its peak at the beginning of irradiation due to the larger amount of fissile material present in the roldlets. The maximum linear power are estimated to 317 W/cm among the lower fuel rodlets, and to 509 W/cm among the upper fuel rodlets at the beginning of irradiation test, respectively. Fig. 9 shows the variation of the fuel temperature of upper rodlet (No. 9) and lower rodlet (No. 3) with the fuel burnup. The maximum centerline temperatures of the fuel of upper and lower rodlets are 773 °C and 666 °C, and the maximum cladding inner-wall temperatures of the fuel of upper and lower rodlets are 567 °C and 542 °C at the beginning of irradiation, respectively. That is, as shown in Fig. 9, these temperatures at the inner-wall cladding surfaces is too lower than 650 °C, the target temperature at the inner-wall cladding surfaces, for the 2nd irradiation testing. Now, in order to meet the target temperature at the inner-wall cladding surfaces of test rodlets, it is being reviewed that the thickness of Hf curtains around test rodlets will be thinned to increase the anticipated linear power of fuel rodlets. So, it is expected that the temperature at the inner-wall cladding surfaces of test rodlets will be maintained around 650°C during the period of irradiation testing.

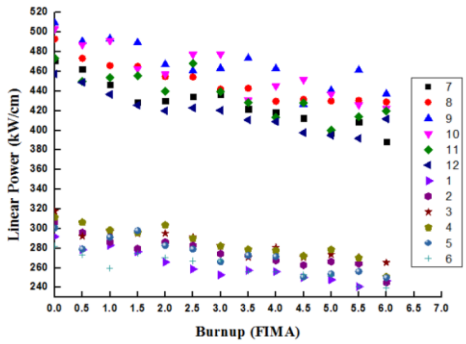


Fig. 8. Anticipated linear powers (W/cm) of fuel rodlets as a function of fuel burnup (FIMA) (Lower rodlets (fuel slug dia. 3.90 mm) No. 1-6, Upper rodlets (fuel slug dia. 5.54 mm): No. 7-12).

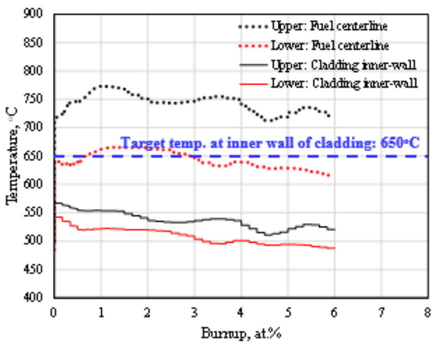


Fig. 9. Variation of the fuel temperature of upper and lower as a function of fuel burnup.

6. Summary

The SMIRP-1, was successfully performed for 182 EFPD in HANARO in 2012. The maximum 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. The SMIRP-1 fuels were calculated to be irradiated in the α+δ regime, which was confirmed by microstructural observation of PIE.

The SMIRP-2 test extends the irradiation condition of the SMIRP-1 test in terms of temperature, linear power, and burnup. Fuel slugs were cast using low-enrichment uranium (LEU) by the gravity casting method, and the fuel rodlets were fabricated for the HANARO irradiation test. Now, in order to meet the target temperature at the inner-wall cladding surfaces of test rodlets, it is reviewing that the thickness of Hf curtains around test rodlets will be thinned to increase the anticipated linear power of fuel rodlets. Performance analysis of fuel rodlets and safety analysis will be performed before installing the device into the test hole in HANARO core. The SMIRP-2 was prepared to start the irradiation test in HANARO from 2018.

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