HANARO Irradiation Testing Plan for CSBA-loaded Pellets and Accident Tolerant Fuel

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1. Introduction

When a safety of nuclear fuel is increased than before, a sustainability of nuclear power will be enhanced. For this reason, accident-tolerant fuel (ATF) is currently being actively developed and is expected to be applied to commercial power plants within a few years [1]. In Korea, several studies have been conducted to develop ATF with a goal of improving the safety of operating nuclear power plants [2-5]. A performance of developed nuclear fuel should be verified through in-reactor tests for the application of commercial nuclear power plant. Utilizing a research reactor is relatively easy method to investigate it. Therefore, we decided to conduct the test for developing fuels using HANARO, a unique research reactor in Korea.

This paper presents preparations for fuel irradiation test for a light water reactor. We plan to start the test within 2023. First, we selected test fuel candidates, and a rig was designed to carry out the test. In this test, a test method that sequentially checks the performances according to the burnup of test fuel will be applied. It is different from a conventional test method that can only observe the performance at target burnup. In addition, the behavior of test fuel was experimentally and analytically predicted. Therefore, detailed design will be performed based on this study in the future.

2. Test specimen and rig design

2.1 Test specimen

A HANARO test targeted nuclear fuel currently being developed by university and research institute in Korea. Korea Advanced Institute of Science and Technology (KAIST) is developing a centrally-shielded burnable absorber (CSBA) for boric acid-free or low-boric acid operation of nuclear power plants [2]. Since the CSBA is located in the nuclear fuel pellet, a high reactivity at the beginning of the cycle can be mitigated. The sintered body was successfully manufactured at the Korea Atomic Energy Research Institute (KAERI) [3], so it was decided to use it for HANARO test. A main interest is the formation of the reaction layer between CSBA and UO_2 during the irradiation and the diffusion of elements. To observe it, CSBA with two density contents will be tested. KAERI is developing Mo microcell UO_2 pellets [4] that can improve thermal conductivity and Cr or Cr/Al coated cladding tubes [5]. We also decided to conduct test for them. Table I shows the candidates for the HANARO test.

Table I: HANARO test specimen

Developing institution	Pellet	Cladding
KAIST	CSBA-loaded UO_2 pellets (high and low density CSBA)	Zircaloy-4
KAERI	UO_2 and Mo microcell UO_2 pellets (additionally containing Er_2O_3 or Gd_2O_3)	Cr or Cr/Al coated Zircaloy-4

2.2 Test rig

HANARO has conducted tests for a number of nuclear fuels [6-9]. Most of the tests used a method of performing the test by loading the test fuel into the static rig. When the burnup of test fuel is reached to target burnup, its performance is observed through a post-irradiation examination. However, the biggest issue in this test method is that the performance in the intermediate burnup before the target burnup cannot be observed, so the amount of data that can be obtained is limited. In the case of the large crystal grain pellet test that was irradiated from 2002 to 2011, a test was conducted to withdraw some of the test fuel rods in the middle of the test duration to overcome above disadvantages [10]. However, a replacement of test fuel rods was complicated because they needed much time and some equipment for it in a hot cell. In this test, an improved rig design was applied to replace the test fuel rods in the HANARO service pool. Fig. 1 shows the pictures of the verification test according to the design change of the rig. We confirmed that the test with improved design will be applied without any problems.

In this test, four test rods in a cluster are considered. In general, three test rods have been installed in the cluster for tests of light water reactor fuel [7, 10]. However, in the case of U-Zr metal fuel test at HANARO [8], since there is a history of testing six test rods in the cluster, it was evaluated that four test rods can be accommodated sufficiently. Fig. 2 shows the proposed arrangement of the test rods in the cluster of the test rig.

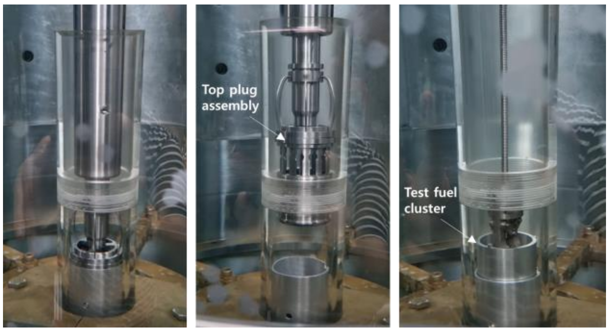

Fig. 1. Verification test to replace test fuel at HANARO service pool

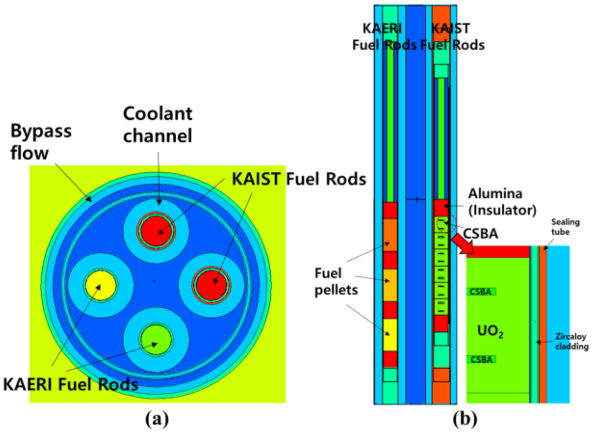

Fig. 2. Arrangement of test fuel rods: (a) horizontal view and (b) axial view

3. Performance Analysis

3.1 Heat generation rate of tests fuel rods

The most interesting concern for HANARO test is to control the linear power of the test fuel rod. It is adjusted by Hf shrouds installed in the rig. When the thickness of the Hf shroud is 0.9 mm, the average heat generation rate of CSBA-loaded pellets was evaluated by MCNP6 [11], which is shown in Fig. 3. We considered that lower and upper clusters are installed in the rig separately. The initial heat generation rate of the test rod at the lower cluster was high with low control absorber rod (CAR) height, but decreased toward the high CAR height. While the test rod at the upper cluster showed the opposite tendency. This is because a rod worth is very large according to the characteristics of HANARO, so it is greatly affected by the control rod. Therefore, it is necessary to consider the linear power of the lower test rod at the low CAR position and the upper test rod at the high CAR position to evaluate the safety of test conservatively. The linear power change of each test fuel rod according to the Hf thickness was also evaluated as shown in Fig. 4. Finally, the Hf shroud thickness will be determined after the target test temperature requirements is selected.

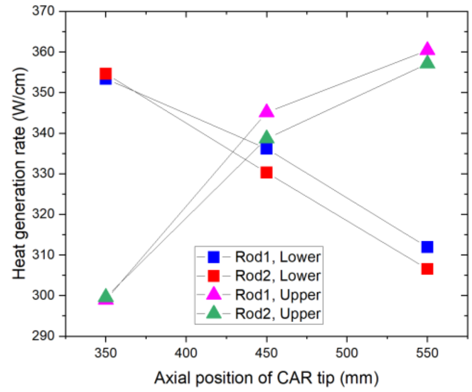

Fig. 3. Average heat generation rate of CSBA-loaded rods according to the axial position of control absorber rod (Hf shroud thickness: 0.9 mm)

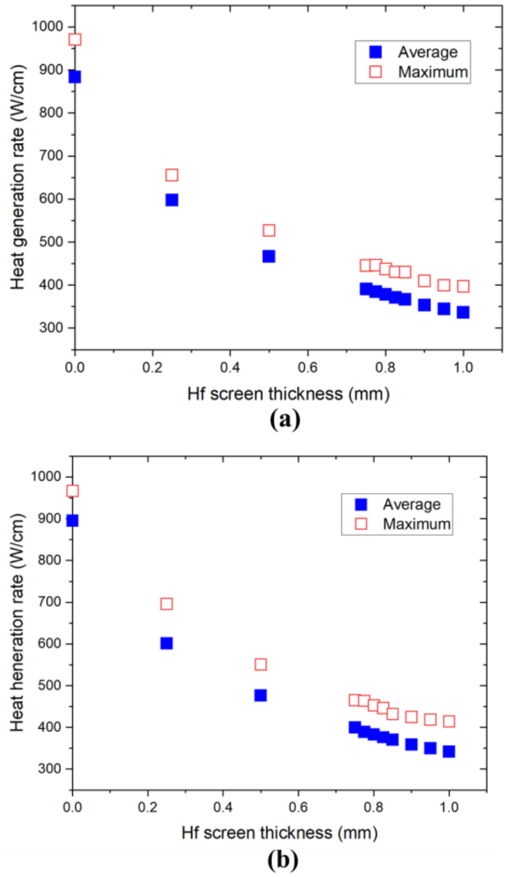

Fig. 4. Average and maximum heat generation rate of CSBA-loaded pellets according to the thickness of Hf shroud: (a) lower cluster (CAR height of 350 mm) and (b) upper cluster (CAR height of 550 mm)

3.2 Hydraulic test

Among the information required for the performance and safety analysis of the HANARO test, the important value is the cooling performance for test fuel rod. Therefore, we evaluated the cooling flow rate for the test rod using a test rig and dummy rods. The hydraulic test utilized a single channel test loop, which is an experimental facility that can simulate the hydraulic characteristics of an irradiation hole. When the test rig is installed in the irradiation hole, the cooling passage is divided into a passage contributing to the cooling of test fuel rod and a bypass passage flowing to the annular area between the outer surface of the rig and inside the irradiation hole, which does not contribute to cooling the test fuel rod. Fig. 2(a) shows the two flow passages. The flow rate of bypass passage is measured by a differential pressure gauge, so we evaluated the flow rate that contributes to the cooling of test fuel rod can be calculated by subtracting it from the total flow rate of the channel. When normal operation was considered with differential pressure of 209 kPa, the total flow rate of the channel was 7.4 kg/s, and the differential pressure of the bypass passage was about 48 kPa. The flow rate could be converted using the cross-sectional area in the annular flow passage and the properties of water. The estimated bypass flow rate was 1.83 kg/s. Therefore, the flow rate of the cooling water flowing through the cooling channel of one test rod was 1.32 kg/s and the coolant flow speed was about 8.02 m/s. The heat transfer coefficient for cooling the test fuel rod was estimated by the Dittus and Boelter equation [12]. The evaluated heat transfer coefficient was about 3.19 W/cm^2-sec.

3.3 Performance evaluation for HANARO test

FRAPCON-4.0 [13], which is widely used for fuel rod performance analysis, was used to analyze the performance of the HANARO test. Since FRAPCON-4.0 mainly targets the behavior in commercial reactors, the applied parameters are somewhat different with HANARO test. In the case of fuel rod in commercial reactor, the pin array geometry is the basic configuration, but in the case of HANARO, a single test rod is applied. Therefore, the thermal hydraulic parameters are different. For this test evaluation, it was decided to match the film heat transfer coefficient. For this purpose, the flow rate of coolant was arbitrarily adjusted. We considered that the maximum temperature of the center of the test rod will be lower than the maximum temperature in a commercial reactor (1,674°C) [14]. Table II shows the evaluation result according to the linear power. We expected that the final target linear power might be 440 W/cm to meet the above temperature requirement.

Table II. Test rod temperatures (°C) according to the linear power of test rod

linear power (W/cm)	300	350	400	450
Pellet center	1117.65	1315.75	1515.05	1709.25
Pellet side	507.35	544.35	572.25	591.55
Cladding inner	112.55	125.05	137.35	149.55
Cladding outer	67.05	72.45	77.75	83.15

4. Conclusions

The HANARO test was planned to evaluate the performance of nuclear fuel under development for the application at the commercial nuclear power plant in Korea. The test specimens are CSBA-loaded UO_2 pellets, Mo microcell UO_2 pellets, and cladding tubes coated with Cr or Cr-Al. The test rig was designed for that the test rod cluster can be replaced in the service pool to evaluate the performances according to the sequential burnup. The linear power of test rod according to the thickness of Hf shroud in the test rig was evaluated. The temperatures of test rod according to the linear power was evaluated based on the cooling performance examined from the hydraulic test. In the future, we will conduct a detailed design for the HANARO test. The test is scheduled to begin in late 2023.

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