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PIE Results of Irradiated TRISO-Coated Particle Fuel at HANARO

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1. Introduction

The first irradiation testing of TRISO (tristructural isotropic)-coated particle fuel and graphite was finished at the end of March 2014 at HANARO [1-4]. The overall objectives of the irradiation testing are to develop an irradiation device for an irradiation test of the coated particle fuels at HANARO, and the technology for PIE at KAERI; to irradiate fuel developed in conjunction with the coated particle fuel process development for a very high temperature reactor (VHTR) in Korea; to provide data supporting the development of our understanding of the relationship between the fuel fabrication processes, fuel product properties, and irradiation performance; and to prepare specimens for a heat up testing under the simulated accident conditions [5]. An irradiation device contained two kinds of test rods: one contains nine fuel compacts, and the other has five compacts and eight graphite specimens. The irradiation test of TRISO fuel in HANARO was conducted using only passive temperature control and post-irradiation examination (PIE) was performed. This paper describes the preparation of test rods for the irradiation testing at HANARO, the irradiation history, the analytical results (power, temperature and burnup of coated particle fuel and fluence for graphite specimens), and some results of PIE.

2. Design of Test Rods

There were two kinds of test rods in the irradiation device: test rod 1 contains nine compacts, and test rod 2 has five compacts and eight graphite specimens. Each compact is a proper cylindrical fuel compact, nominally 8 mm in diameter, and 10 mm in length, and graphite is nominally 8 mm in diameter and 5 mm in length [6]. Two graphite specimens (matrix graphite and structural graphite) are arranged between the fuel compacts in test fuel rod 2. These fuel compacts and graphite disks are loaded in graphite sleeves, which are nominally 8.6 mm in inner diameter and 90 mm in length. The cladding tubes are approximately 16 mm in diameter and 150 mm in height including the plenum space. The specifications of the fuel compacts and graphite specimens that were irradiated at HANARO are described in detail in Ref. 6.

A binary mixture of He gas and Ne gas, or He gas and Ar gas, is actually used to control the temperature of the specimen during irradiation testing of nuclear fuel in a research reactor. For example, during irradiation testing of HFR-EU1/HFR-EU1bis in HFR and AGR irradiation experiments in ATR, the temperatures were controlled through on-line monitoring using mixtures of He gas and Ne gas [7-10]. However, the irradiation testing of fuel compact and graphite specimens in HANARO was performed using only passive temperature control through a mixture of He gas and Ne gases.

For the fuel compact to reach a temperature above 1,000ºC at the beginning of the irradiation test at HANARO, rod 1 is filled with a mixed gas of 30% He and 70% Ne. In addition, wherever possible, to increase the temperature of the graphite specimens at the beginning of the irradiation test, rod 2 is filled with a mixed gas of 10% He and 90% Ne. During the BOC of the irradiation testing, the calculated peak temperature of the fuel compact, which is axially located at the middle of test rod 1, is calculated to be about 1033ºC under a mixed gas atmosphere of 30% He and 70% Ne, and the calculated peak temperature in test rod 2 is about 772ºC under a mixed gas atmosphere of 10% He and 90% Ne. The estimated temperatures of the radial distributions of the fuel compacts at the middle of each test rod, and the axial centerline distribution of each test rod were described in Ref. 6. The peak temperatures of the graphite sleeves in test rods 1 and 2 were estimated to be about 800ºC and 580ºC, respectively.

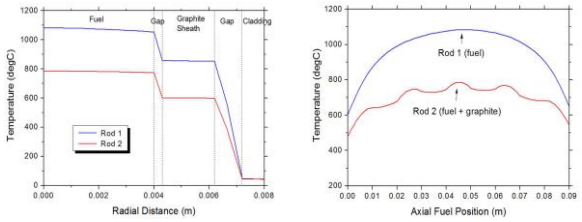
3. Fuel Compacts and Test Rods

TRISO-coated particle fuel is comprised of 480 μm nominal diameter LEU fuel kernels with an enrichment of 4.5 wt% U-235, and coated with TRISO coatings (i.e., a buffer layer, a layer of silicon carbide sandwiched between two pyrolytic carbon layers, IPyC, and OPyC) to make up the 900 μm nominal diameter TRISO-coated fuel particles. Each compact contains 263 fuel particles with a mean uranium content of approximately 0.14 grams. The particles were pressed into cylindrical compacts that were nominally 10 mm in length and 8 mm in diameter. Graphite specimens have a cylindrical shape that is nominally 5 mm in length and 8 mm in diameter. Rod 2 of the test rods has two kinds of graphite specimens: one is a matrix graphite of a fuel compact, and the other is the structural graphite used in a VHTR. Matrix graphite and structural graphite specimens are located between the fuel compacts in test rod 2, as described in Ref. 6.

4. Irradiation History

The irradiation testing of the test rods was started in early August 2013 and continued to the end of March 2014 in the HANARO.

The estimated power history of fuel compacts and particles, the calculated burnup of fuel compacts and particles, and the estimated fluence of graphite specimens in test rod 2 were described in detail in Ref. 7. Based on the above maximum power of the compacts, the temperature of the fuel compacts was evaluated. The maximum powers of the compacts in the middle of rod 1 and 2 are 491.6 W and 254 W, respectively. Fig. 1 shows (a) the radial temperature profile of test rods 1 and 2, and (b) the axial temperature profile across lateral cross sections of test rods 1 and 2. The highest temperatures of the compacts in the middle of rods 1 and 2 were estimated to be 1083ºC and 785ºC at 25.06 EFPD, respectively. Compared to the calculated maximum temperature of rods 1 and 2 before the irradiation test as shown in Ref. 6, these maximum temperatures are about 50ºC and 14ºC higher. In addition, the temperatures change slightly in the fuel and graphite sleeve and drop mostly in the gaps. The PIE of irradiated TRISO-coated particle fuel and graphite specimens began in September of 2014.



(a) (b)

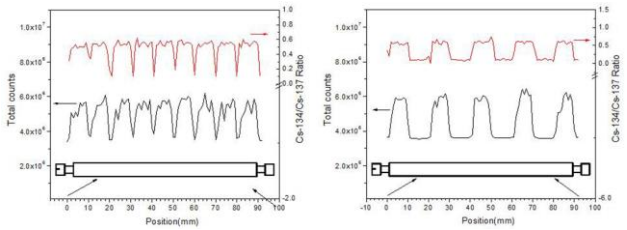
Fig. 1. Estimated maximum temperature distribution of test rods at maximum power after irradiation test; (a) Radial temperature profile, (b) Axial temperature profile.

5. PIE

5.1. Non-destructive test

5.1.1. Gamma scanning

Gamma scanning of two irradiated test rods (rod 1 and rod 2) was carried out following the disassembly of the irradiation device, and a visual inspection of the two test rods. No defects were found by a visual inspection of rods 1 and 2. Fig. 2 shows detailed scans including the ratio of Cs-134 to Cs-137 for the two test rods. The fuel compacts, non-fueled graphite specimens, and end caps of the test rods are clearly visible. In addition, the results of the gamma-scanning show an almost even distribution of burn-up regardless of the fuel location in the test rods.



(a) (b)

Fig. 2. Gamma scan details for (a) test rod 1 and (b) test rod 2.

5.1.2. X-ray observation on test rods

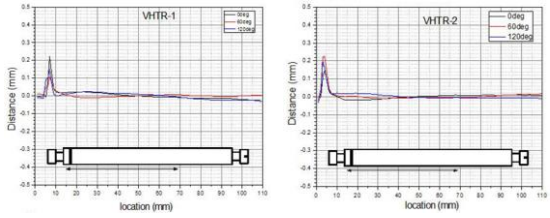
Fig. 3 shows an X-ray radiograph of the two test rods. The top of the rod is at the top of this figure. The radiograph provides some details of the condition of the rod components. The image clearly shows the shapes of the compacts and the distribution of the particles, as well as graphite in test rod 2. In addition, the diameter of the test rods can also be measured using a 3-dimensional solid implementation of the test rod images.

(a) (b)

Fig. 3. X-ray radiograph of test rods; (a) rod 1, and (b) rod 2

5.2.3. Diameter Measurement of test rods

The diameters of the two test rods were measured at 1mm along a length of 110 mm on the surface of the rods three times while rotating them by 60 degrees using LVDT, followed by the X-ray radiography of the two test rods. In addition, each test rod was rotated by 60 degrees. Fig. 4 shows the measured results. There are no differences in comparison with the as-built dimensions.



(a) (b)

Fig. 4. Measured diameter of test rods: (a) rod 1, and (b) rod 2

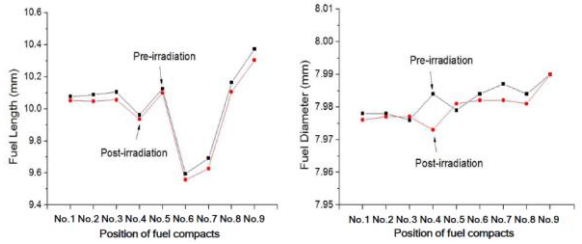
5.2. Destructive test

5.2.1. Fission gas

After laser piercing of each test rod, the fission gas was collected and analyzed. There were negligible amounts of Xe and Kr gases. That is, the fission gases were not released from the TRISO-coated particle fuels during the irradiation test.

5.2.2. Dimensional check of fuel compacts and graphite specimens

After the cutting of each test rod, compacts and graphite specimens were extracted from rods 1 and 2. The diameters and lengths of each compact and graphite disk were measured using a micrometer in a hot-cell. The lengths and diameters were measured three times for each specimen and averaged. Fig. 5 shows the dimensional changes of the fuel compacts in test rod 1. Slight decreases in length were observed in all of the fuel compacts, and slight changes were observed in diameter, but no obvious trends were discovered. Fig. 6 shows the dimensional changes of graphite specimens in test rod 2. Test rod 2 consisted of two kinds of graphite: M (matrix graphite and G (IG-110). Increases in diameter were observed in both types of graphite, and the matrix graphite showed a decrease in thickness, but the IG-110 showed no distinct changes in length.



(a) (b)

Fig. 5. Dimensional change of fuel compacts in test rod 1: (a) length, and (b) diameter.

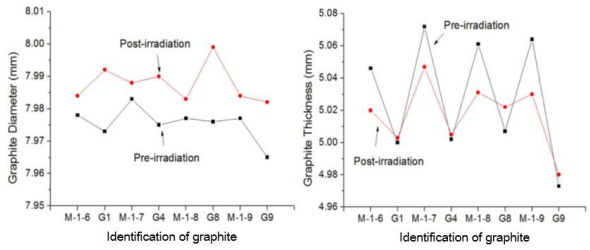
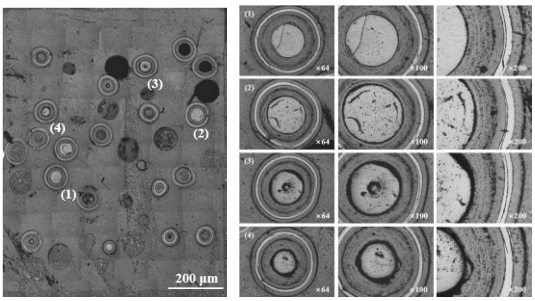


Fig. 6. Dimensional change of graphite specimens in test rod 2: (a) length, and (b) diameter.

5.2.3. Cross-sectional observations of fuel compacts and coated fuel particles

One of fuel compacts from test rod 1 was longitudinally cut to observe its microscopy. Fig. 7 shows a cross-sectional view of one of the fuel compacts of test rod 1. Due to preparation damage such as a falling out of the particles, the cracking of the coating layers, and the collapsing of the coating boundaries, the morphologies of the cross-section were not preserved. The techniques of hot cell cutting, grinding and polishing need to be developed to produce high-quality surfaces.



(a) (b)

Fig. 7. (a) Cross-section of one of fuel compacts of test rod 1, and (b) enlarged views of (1), (2), (3), and (4) in (a).

To deconsolidate coated fuel particles from an irradiated fuel compact, two fuel compacts of test rod 2 were heated at 850°C from 5 h to 8.5 h in air. Then, the coated fuel particles without OPyC were obtained. A few of their particles were inspected using a micro X-ray system, YXLON 160kV, with a focus size of 1 to 5 μm. It took four images from zero to 270 degrees, generally. Fig. 8 shows a typical X-ray image of the particle from No. 5, shown in Fig. 4. The diameter of the kernel is 481.61 μm, and the average thickness of buffer, IPyC, and SiC is 96.73 μm, 38.09 μm, and 32.71 μm, respectively. Compared with those in Table 1, there are some differences. No damage to coating layers was observed from the 40 particles. A small radial gap partially between the kernel and buffer was observed where the buffer densified outward during the irradiation.

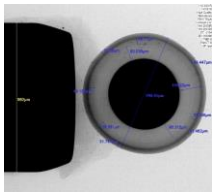


Fig. 8. Typical X-ray image of the particle

These loose particles were epoxy-mounted and polished to observe the microscopy by SEM and to investigate the fission product distribution in coated fuel particles by EPMA. Fig. 9 shows typical SEM images of loose irradiated particles. The most common observation was a radial gap between the kernel and the buffer as

observed in the X-ray images of the fuel particles. In addition, gaps between the buffer and IPyC were also observed. Next, the distribution of FPs in the coated particles was investigated. Fig. 10 shows elemental mappings of (a) U, (b) Pd, (c) Xe, and (d) Cs by EPMA from a cross-section of irradiated particle fuel. Most of the FPs were nearly retained in the kernel and not released. In addition, measurement of the discharged burnup of irradiated TRISO-coated particle fuel is under way by a chemical method.

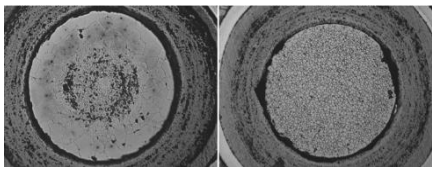
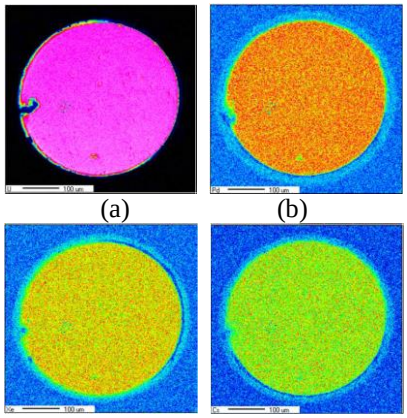


Fig. 9. SEM images of loose irradiated particles.



(a) (b)

(c) (d)

Fig. 10. EPMA images from kernel; (a) U, (b) Pd, (c) Xe, and (d) Cs.

6. Summary

As outlined in this paper, the first irradiation testing of TRISO-coated particle fuel was performed from August 2013 to March 2014 in the HANARO core to support the development of a VHTR in Korea. The fuel compacts were irradiated in an inert gas atmosphere without on-line temperature monitoring and control and without on-line fission product monitoring of the sweep gas.

The maximum power of the fuel compact was estimated to be 56 W at 25.06 EFPD, and the maximum power of the particle is 215.4 mW. In addition, the maximum discharged burn-up was about 37,344 MWD/MTU (3.99% FIMA) in the middle of rod 1. The maximum fluence of the graphite specimen in rod 2 was 2.99×10^{20} n/cm^2 (E > 0.18 MeV). In addition, a PIE of the irradiated TRISO-coated particle fuel was performed with the exception of the discharged burnup of TRISO fuel by chemical method.

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