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# The First Irradiation Testing of TRISO-Coated Particle Fuel and Graphite Specimens in HANARO

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## 1. Introduction

At the end of March 2014, the first irradiation testing of TRISO-coated particle fuel and graphite was finished in HANARO [1-5]. 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 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 [6]. An irradiation device contained two kinds of test rods; one contains nine fuel compacts, and the other has five compacts and eight graphite specimens. And then, the irradiation test of TRISO fuel in HANARO was performed with only passive temperature control and the experimental results will be estimated by PIE in a hot cell. This paper describes preparation of test rods including fuel compacts and graphite for the irradiation testing at HANARO, the irradiation history, and the analytical results; power, burnup for coated particle fuel and fluence for graphite specimens.

## 2. Temperature Evaluation of Specimens

Fig. 1 shows a schematic layout of 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 right cylindrical fuel compact nominally 8 mm in diameter, and 10 mm long, and graphite is nominally 8 mm in diameter and 5 mm long. For this irradiation testing, two different types of graphite (matrix graphite for compact and structural graphite for VHTR) are contained to study the impact of graphite fabrication processing variables of graphite performance. These are loaded in graphite sleeves, which are nominally 8.6 mm in inner diameter and 90 mm long. Two graphite specimens (matrix graphite and structural graphite) are arranged between the fuel compacts in test fuel rod 2, as shown in Fig. 1. 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 being irradiated at HANARO are summarized in Table 1.

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]. But, the irradiation testing of TRISO fuel compact and graphite specimens in HANARO was performed with only passive temperature control by using mixture gas of He gas and Ne gas.

Table 1. Characteristics of TRISO-coated particle fuel and graphite.

| Properties | Design value | Measured value | Remarks |
|---|---|---|---|
| **Kernel** | | | |
| - Diameter (μm) | 480 ± 30 | 477.84 | average |
| - Density (g/cm$^3$) | 10.65 ± 0.25 | 10.68 | average |
| - U-235 enrich. (wt%) | 4.5 ± 0.10 | 4.504 | Chemical analysis |
| - O/U ratio | 2.00 ± 0.01 | 2.003 | average |
| - Total uranium (wt%) | ≥ 87.0 | 88.13 | cal. value |
| - Sphericity (aspected ratio) | < 1.2 | ≤1.04 | average |
| **Coated fuel particle** | | | |
| - Buffer thickness (μm) | 95 ± 45 | 102.91 | average |
| - Buffer density (g/cm$^3$) | 1.00 ± 0.10 | 1.052 | average |
| - IPyC thickness (μm) | 40 ± 20 | 40.55 | average |
| - IPyC density (g/cm$^3$) | 1.85 ± 0.20 | 1.91 | average |
| - SiC thickness (μm) | 35 ± 10 | 36.08 | average |
| - SiC density (g/cm$^3$) | ≥ 3.18 | 3.182 | average |
| - OPyC thickness (μm) | 40 ± 20 | 46.3 | average |
| - OPyC density (g/cm$^3$) | 1.85 ± 0.20 | 1.88 | average |
| - Particle dia. (mm) | 0.90 ± 0.10 | 0.95 | average |
| - Anisotropic index | ≤ 1.03 | 1.018 | average |
| - Average wt. (g) | 0.001392 | 0.001392 | |
| **Fuel compact** | | | |
| - Compact mass (g) | 1.050 | 1.03 | average |
| - Mean U loading (gU) | 0.14 | 0.135 | average |
| - Diameter (mm) | 8.0 ± 0.2 | 7.98 | average |
| - Length(mm) | 10.0 ± 0.5 | 9.995 | average |
| - No. of compact(ea) | 9(rod1)/5(rod2) | 9(rod1)/5(rod2) | |
| - Volume fraction (%) | 20 | 19.75 | average |
| **Matrix graphite & structural graphite specimen** | | | |
| - Diameter (mm) | 8.0 ± 0.2 | 7.976 | average |
| - Length (mm) | 5 ± 0.2 | 5.028 | average |
| - No. of specimens(ea) | 8(rod 2) | 8(rod 2) | |
| - Density (g/cm$^3$) | 1.7 ± 0.1 | 1.771 | average |

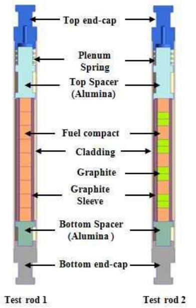
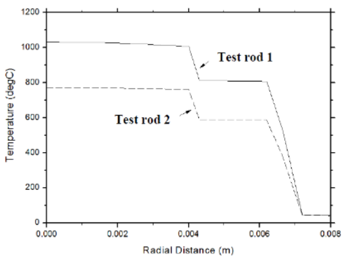
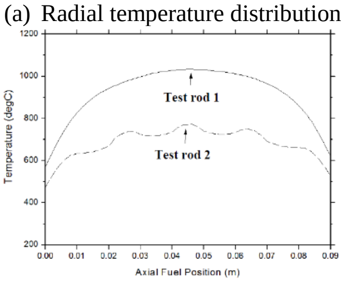



Fig. 1. Schematic layout of two kinds of test rods

To reach the temperature of fuel compact above 1,000℃ at the beginning of the irradiation test at HANARO, rod 1 is filled up with a mixed gas of 30% He and 70% Ne. In addition, to increase the temperature of 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 1033℃ under a mixed gas atmosphere of 30% He and 70% Ne, and the calculated peak temperature in test rod 2 is about 772℃ under a mixed gas atmosphere of 10% He and 90% Ne as shown in Fig. 2. Fig. 2 shows (a) radial temperature distributions of fuel compacts at the middle of each test rod and (b) axial centerline temperature distribution of each test rod [6]. The peak temperatures of the graphite sleeves in test rods 1 and 2 were estimated to be about 800℃ and 580℃, respectively. These temperatures were evaluated using COMSOL 4.3a [11].




(a) Radial temperature distribution

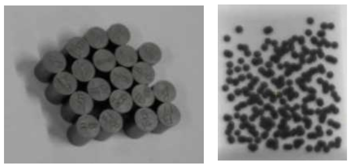



(b) Axial temperature distribution

Fig. 2. Temperature distribution of test rods.

## 3. Irradiation Test Rods

The TRISO-coated particle fuel is comprised of 480 μm nominal diameter LEU fuel kernels with an enrichment of 4.5 wt% U-235, 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. Fig. 3 (a) shows images of the fuel compacts heat-treated at 1800℃. As shown in this figure, the particles were pressed into cylindrical compacts that were nominally 10 mm in length and 8 mm in diameter. The compacts are well-formed, with no apparent cracks or chips. In addition, the X-ray radiograph in Fig. 3 (b) shows that the driver-fuel particles were distributed throughout the compact. Coated particle fuels and a non-fueled region are clearly visible in the X-ray radiography.

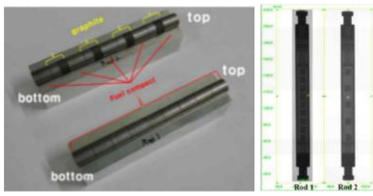


(a) (b)

Fig. 3. (a) Fuel compacts and (b) X-ray image of a fuel compact.

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 shown in Fig 4.

Fig. 4 (a) shows photographs of the fuel compacts and graphite specimens for rods 1 and 2 before inserting in the graphite sleeve. These specimens are inserted into test rods 1 and 2, respectively. Fig. 4 (b) shows X-ray images of the assembled test fuel rods 1 and 2 before welding pin holes onto the end-plug of the test rods. It was verified that the internal layouts of the fuel compacts, graphite specimens, and other parts had no problems. In addition, after injecting mixed gas through the pin holes at the end-plug of test rods 1 and 2, pin holes were also welded. The integrity of the welded parts, end-plugs, and pin hole, was confirmed through PT test and He-leak test.




(a) (b)

Fig. 4. (a) Fuel compacts and graphite specimens and (b) X-ray images for test fuel rods 1 and 2.

## 4. Irradiation History

The irradiation testing of test rods was started in early August 2013 and continued to the end of March 2014 in the HANARO. During the first irradiation testing of TRISO-coated particle fuel and graphite specimens, the power history from 89 cycle to 93 cycle of

HANARO operation (~132 EFPD) is shown in Fig. 5. Fig. 6 and 7 shows estimated power history of fuel compacts and particles in test rod 1 and rod 2, respectively. Fig. 8 shows calculated burnup of fuel compacts and particles in test rod 1 and rod 2. And, Fig. 9 shows estimated fluence history of graphite specimens in test rod 2. The PIE of irradiated TRISO-coated particle fuel and graphite specimens is being performed from September of 2014.

The maximum power of fuel compact is estimated to be 56 W at 25.06 EFPD, and the maximum power of particle is 215.4 mW in rod 1. And, the maximum discharged burn-up is about 37,344 MWD/MTU (3.99 FIMA ((Fissions per Initial Metal Atom)). In rod 2, the maximum power of fuel compact is 50 W, and the maximum power of particle is 197.5 mW. The maximum discharged burn-up was about 35,698 MWD/MTU (3.81 FIMA ((Fissions per Initial Metal Atom)). And, the maximum fluence of graphite specimen was $2.99\times10^{20}$ n/cm$^2$ (E > 0.18 MeV). Now, based on the above maximum power of compacts, the temperature of fuel compacts is being evaluated. Finally, the irradiation performance of fuel compacts and graphite specimens will be evaluated after carrying out PIE.

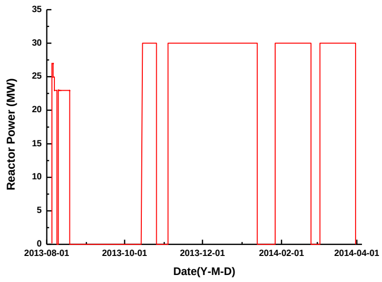
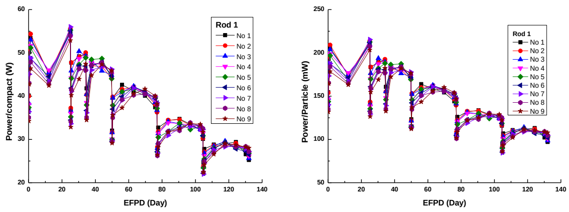
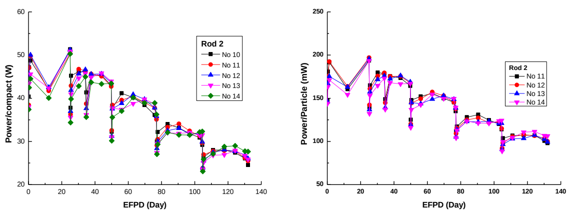



Fig. 5. HANARO power history for TRISO Fuel Irradiation



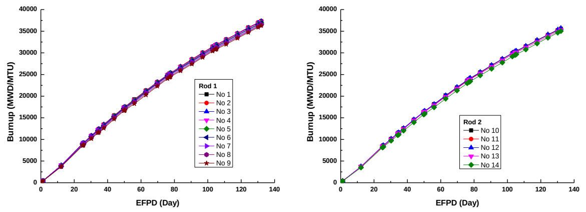

(a) (b)

Fig. 6. Estimated power history of (a) fuel compacts and (b) particles of test rod 1




(a) (b)

Fig. 7. Estimated power history of (a) fuel compacts and (b) particles of test rod 2.




(a) (b)

Fig. 8. Calculated burnup of fuel compacts in (a) test rod 1 and (b) test rod 2.

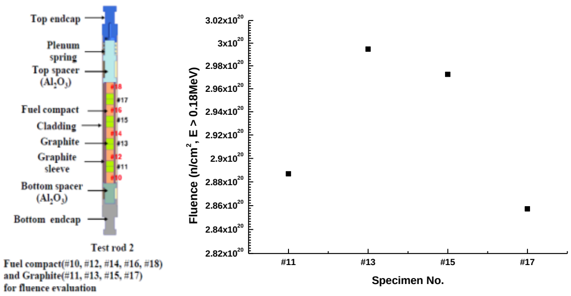



Fig. 9. Estimated fluence of graphite specimens in test rod 2.

## 5. Conclusions

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. There were two kinds of test rods, one contains nine fuel compacts, and the other has five compacts and eight graphite specimens. The fuel compacts are 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 fuel compact is estimated to be 56 W at 25.06 EFPD, and the maximum power of particle is 215.4 mW. And, the maximum discharged burn-up is about 37,344 MWD/MTU (3.99 FIMA). The maximum fluence of graphite specimen in rod 2 was $2.99\times10^{20}$ n/cm$^2$ (E > 0.18 MeV). In addition, a PIE of the irradiated TRISO-coated particle fuel is being performed from September of 2014. And then, the irradiation performance of fuel compacts and graphite specimens will be evaluated.

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