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Irradiation Testing of TRISO-Coated Particle Fuel in Korea

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Abstract – *In Korea, coated particle fuel is being developed to support development of a VHTR. At the end of March 2014, the first irradiation test in HANARO at KAERI to demonstrate and qualify TRISO-coated particle fuel for use in a VHTR was terminated. This experiment was conducted in an inert gas atmosphere without on-line temperature monitoring and control, or on-line fission product monitoring of the sweep gas. The irradiation device contained two test rods, one has nine fuel compacts and the other five compacts and eight graphite specimens. Each compact contains about 260 TRISO-coated particles. The duration of irradiation testing at HANARO was about 135 full power days from last August 2013. The maximum average power per particle was about 165 mW/particle. The calculated peak burnup of the TRISO-coated fuel was a little less than 4 atom percent. Post-irradiation examination is being carried out at KAERI's Irradiated Material Examination Facility beginning in September of 2014. This paper describes characteristics of coated particle fuel, the design of the test rod and irradiation device for this coated particle fuel, and discusses the technical results of irradiation testing at HANARO.*

I. INTRODUCTION

TRISO-coated particle fuel development is progressing favorably and therefore irradiation testing was planned to support a VHTR in Korea. The overall objectives of this irradiation test program are 1) to develop an irradiation device for irradiation testing of the coated particle fuels at HANARO, and the technology for PIE at KAERI; 2) to irradiate fuel developed in conjunction with the coated particle fuel process development for a VHTR in Korea, and to provide data supporting the development of an understanding of the relationship between fuel fabrication processes, fuel product properties, and irradiation performance; and 3) to prepare specimens for heat up testing under the simulated accident conditions [1-3]. The first irradiation test of TRISO-coated particle fuel has been carried out in HANARO. An irradiation device, which contains two separate test rods, was designed for the irradiation position and size, irradiation parameters (e.g., temperature and fluence). The irradiation test of TRISO -coated particle fuel in HANARO is performed with only passive temperature control and the experimental results will be determined after the irradiation by examination in a hot cell. This paper describes the design and fabrication of an irradiation device including TRISO-coated particle fuels, compacts and test rods for the irradiation testing in HANARO, and discusses the analytical results from the test, and the irradiation history.

II. TEMPERATUR EVALUATION OF SPECIMENS

Fig. 1 shows a schematic layout of two kinds of test rods embedded in the irradiation device: rod 1 contains nine compacts, and rod 2 has five compacts and eight graphite specimens. Each compact is a right circular cylinder nominally 8 mm in diameter, and 10 mm long, and the 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) were included to study the impact of graphite fabrication processing variables on graphite performance. These specimens were 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) were arranged between the fuel compacts in test rod 2, as shown in Fig. 1. The specification of the fuel compacts and graphite specimens that are being irradiated at HANARO is summarized in Table 1. The cladding tubes are approximately 16 mm in diameter and 150 mm in height including the plenum space.

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
- Spherocity (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

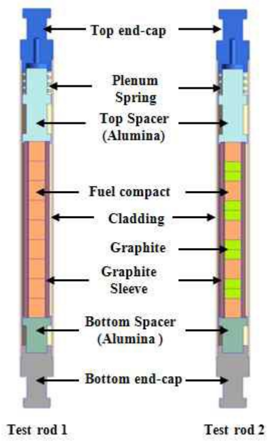


Fig. 1. Schematic layout of two kinds of test rods.

Binary mixtures of He and Ne gases, or He and Ar gases are typically used to control specimen temperatures during irradiation testing of nuclear fuel in research reactors. For example, during irradiation testing of HFR-EU1/HFR-EU1bis in HFR and AGR irradiation experiments in ATR, temperatures were controlled with on-line monitoring by using mixtures of He gas and Ne gas [4-7]. To achieve a fuel compact temperature of more than 1,000ºC at the beginning of the irradiation test at HANARO, rod 1 was filled up with a mixed gas of 30% He and 70% Ne. And, to achieve a temperature of 600ºC to 800ºC in the graphite specimens at the beginning of the irradiation test, rod 2 was filled up with a mixed gas of 10% He and 90% Ne. Temperatures were evaluated using COMSOL 4.3a [8]. During the BOC of the irradiation testing, the peak temperature of the fuel compact, which is axially located at the middle of test rod 1, is calculated to be about 1033ºC under the atmosphere of a mixed gas of 30% He and 70% Ne, and the peak temperature in test rod 2 is about 772ºC under the atmosphere of a mixed gas of 10% He and 90% Ne. The peak temperatures of the graphite sleeves in test rods 1 and 2 are estimated to about 800ºC and 580ºC, respectively.

III. IRRADIATION SPECIMENS AND TEST RODS

III.A. Fuel particles and compacts

The 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. Fig. 2 shows cross-sections of TRISO-coated particle fuel and SEM micrographs of the coating layers. 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 1800ºC. 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 TRISO-coated fuel particles were distributed throughout the compact. Coated particle fuels and non-fueled region are clearly visible in the X-ray radiography.

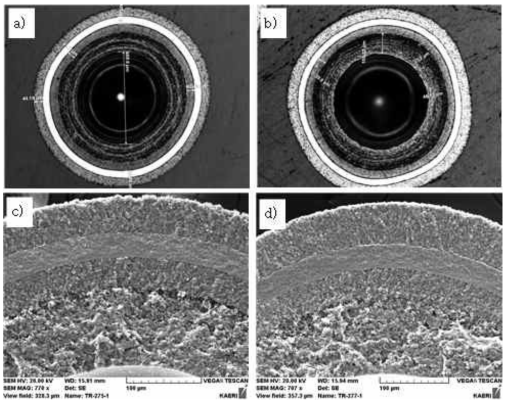
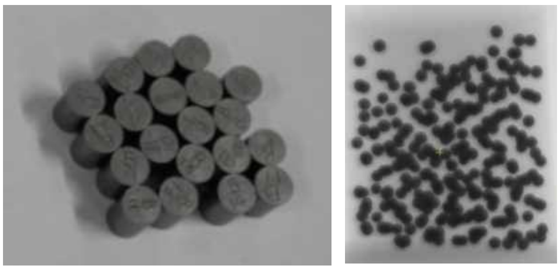


Fig. 2. Cross-section of TRISO fuel (a),b)) and SEM of coating layers (c), d)).



(a) (b)

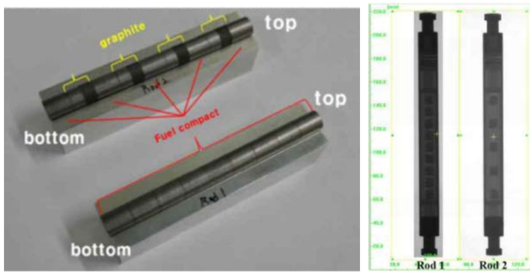
Fig. 3. (a) Fuel compacts and (b) X-ray image of a fuel compact.

III.B. Graphite specimens

Graphite specimens for this test have a cylindrical shape that is nominally 5 mm in length and 8 mm in diameter. Test rod 2 has two kinds of graphite specimens: one is 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.

III.C. Test rods

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. End-plugs of the test rods were welded, and then using X-ray radiography it was verified that the internal layouts of the fuel compacts, graphite specimens, and other parts had no problems. Fig. 4 (b) shows X-ray images of the assembled test rods 1 and 2 before welding pin holes onto the end-plug of the test rods. 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.

IV. SAFETY ANALYSIS FOR IRRADIATION TESTING

Before starting the irradiation testing of the device for coated particle fuel, the safety analysis was carried out to make sure of the compatibility with the test hole of HANARO and the irradiation performance of coated particle fuel. The following are required items for a safety review; hydraulic compatibilities with HANARO core, maximum surface temperature of test rod and maximum temperature of fuel compact under the hypothetical accidents, and the reactivity effect from loading the irradiation device into the test hole. According to the results of a safety review for irradiation testing [9], it complies with the design criteria of the test rod, and the criteria of an accident analysis of HANARO.

V. IRRADIATION HISTORY

The irradiation testing was started in early August 2013 and continued to the end of March 2014 in the HANARO. The irradiation history of TRISO-coated particle fuel is shown in Fig. 5. The EFPD (Effective Full Power Days) was about 105 EFPD. The peak fuel compact power was 606 W, and the maximum particle power was 165 mW. And, the discharged burn-up was about 3.83 FIMA (Fissions per Initial Metal Atom). The PIE of irradiated TRISO-coated particle fuel started in September of 2014.

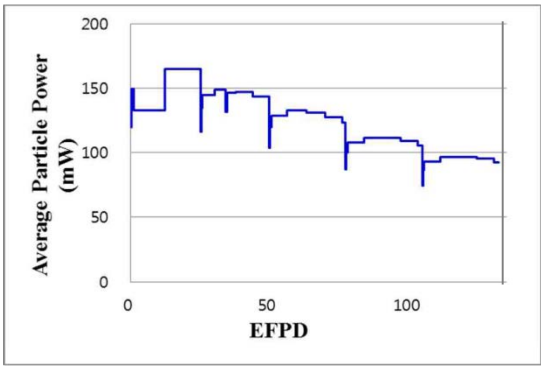


Fig. 5. Change of average power of TRISO-coated particle fuel during irradiation.

VI. SUMMARY

As outlined in this paper, KAERI has a plan to perform the irradiation testing of coated particle fuel at HANARO to support the development of a VHTR in Korea. The first irradiation testing is being carried out to demonstrate and qualify TRISO-coated particle fuel for use in a VHTR. The objectives of this irradiation testing are; 1) to provide data supporting the development of an understanding of the relationship between fuel fabrication processes, fuel product properties, and irradiation performance, and 2) to prepare specimens for heat-up testing under simulated accident conditions.

The irradiation device contains two 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. These test rods were irradiated in the HANARO core from August 2013, until March 2014. In addition, after a peak burn-up of about 3.8 FIMA and a peak fast neutron fluence of about 1.7×10^{21} n/cm^2 (E > 0.18 MeV), a PIE of the irradiated TRISO-coated particle fuel is being performed beginning in September of 2014.

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REFERENCES

[1] Bong Goo Kim, et al., "Preparation for Irradiation Testing of Coated Particle Fuel at HANARO", *Transactions of the Korean Nuclear Society Spring Meeting*, Gwangju, Korea, May 30-31, Korean Nuclear Society (2013).

[2] Bong Goo Kim, et al., "Irradiation Device for Irradiation Testing of Coated Particle Fuel at HANARO", *Nucl. Eng. Tech.*, Vol.45 No.7, 941 (2013).

[3] Bong Goo Kim, Byung Chul Lee, Moon Sung Cho, and Yong Wan Kim, Status on Irradiation Testing of TRISO Fuel in Korea, Transactions of the American Nuclear Society, Vol. 110, 767-769, 2014

[4] S. de Groot, K. Bakker, A.I. van Heek, M.A. Futterer, "Modelling of the HFR-EU1bis experiment and thermomechanical evaluation", *Nucl. Eng. Des.* 238, 3114 (2008).

[5] M. Laurie, M.A. Futterer, K.H. Appleman, J.M. Lapetite, A. Marmier, G. Berg, "JRC's on-line fission gas release monitoring system in the high flux reactor Petten", *Nucl. Eng. Des.* 251, 352 (2012).

[6] David A. Petti, S. Blaine Grover, Jon T. Maki, "Status of the First Advanced Gas Reactor Fuel Irradiation Experiment in the Advanced Test Reactor", *4th International Topical Meeting on High Temperature Reactor Technology HTR2008 (paper No. HTR2008-58024)*, Washington, D.C., USA, September 28 - October 1 (2008).

[7] S. Blaine Grover and David A. Petti, "Status of the NGNP Fuel Experiment AGR-2 Irradiated in the Advanced Test Reactor", *Proceedings of the HTR 2012 (paper No. HTR2012-3-029)*, Tokyo, Japan, October 28 - November 1 (2012).

[8] COMSOL AB., COMSOL Multiphysics Ver. 4.3a.

[9] B. G. KIM, et al., "Irradiation Test Plan of Coated Particle Fuel at HANARO", KAERI/TR-4875/2013, KAERI (2013).