IRRADIATION PERFORMANCE OF U_3Si LEU FUELS IN HANARO

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ABSTRACT

To verify the irradiation performance of the HANARO fuel at a high power and a high burnup, in-pile irradiation tests were performed. Two test fuels for a higher burnup irradiation and one test fuel for a higher linear heat rate had been designed and fabricated. All the test fuel assemblies were made of 6 fuel elements located in the outer ring of the hexagonal fuel assembly and 30 aluminum dummy elements. The test fuel assemblies were irradiated in the HANARO core. The maximum discharged burnup and linear power were 69.9 at% average and 85.5 at% peak with an 83 kW/m average and 121.6 kW/m peak, respectively. Detailed non-destructive and destructive PIE, such as the measurement of the burnup distribution, fuel swelling, clad corrosion, dimensional changes, fuel rod bending strength, micro-structure, etc., were performed. It was verified through the irradiation tests that the HANARO fuel maintains a proper in-pile performance and integrity even at a high power of 121 kW/m and up to a high burnup of 85 at%.

1. Introduction

HANARO is a light-water-cooled and heavy-water-reflected research reactor designed and operated at a full power of 30 MWth. The compact core results in a high power density and high neutron flux. The hybrid-type core is composed of an inner and outer core. The inner core, with a 0.5 m effective diameter and 1.2 m in height, has 23 hexagonal and 8 circular flow channels. Each hexagonal flow channel, formed by a hexagonal flow tube, is loaded with a hexagonal fuel bundle which has 36 fuel elements. The circular flow channel formed by a circular flow tube is loaded with a circular fuel bundle which has 18 fuel elements.

When the reactor operating license was issued for HANARO in 1995, the limitation for its rated power was imposed by the regulatory body, KINS(Korea Institute of Nuclear Safety). KINS required KAERI to obtain more fuel performance data at a higher linear rate which would prove fuel integrity[1]. To resolve this issue, fuel irradiation tests were performed in HANARO. To verify the irradiation performance of the HANARO fuel at a high power and burnup, in-pile irradiation tests were performed using the three test bundles.

Detailed non-destructive and destructive PIE(Post-Irradiation Examination), such as the measurement of the burnup distribution, fuel swelling, clad corrosion, dimensional changes, fuel rod bending strength, micro-structure, etc., were performed in the IMEF(Irradiated Material Examination Facility) located inside the HANARO boundary. The measured results were analyzed/compared with the predicted performance values

and the design criteria. It was verified that the HANARO fuel maintains a proper in-pile performance and integrity even at a high power of 121 kW/m and up to a high burnup of 85 at%.

2. Background

2.1 HANARO fuel

The HANARO fuel element is made of a cylindrical fuel meat and aluminum end plugs with finned aluminum cladding. The fuel meat of each fuel element consists of a dispersion of small particles of a high density uranium silicide(U_3Si) compound, in a continuous aluminum matrix. The driver fuel contains low-enriched uranium(less than 20 wt% U-235 in total uranium) in an U3Si inter-metallic compound dispersed in aluminum.

The fundamental fuel design requirements of an adequate fissile content, heat transfer capability, strength and dimensional stability are met for the KAERI's design and safety analyses. The design limits for a normal operation are for the T_{ONB}, fuel temperature, and temperature drop across the aluminum oxide layer. The safety limits for anticipated occurrences and accident conditions are MCHFR and the fuel temperature. Also the amount of swelling shall not be greater than 20 vol%.

2.2 Licensing Issues

For the verification of the fuel performance in the design stage of HANARO, KAERI relied on the AECL's experimental data. However, the maximum linear heat generation rate(LHGR) from the fuel element in the equilibrium conditions was quite close to the maximum value which had been experienced in the AECL's mini element irradiation tests. Thus KINS imposed a limitation for HANARO's rated power when the reactor operating license was issued. KINS required KAERI to obtain more experimental data at a higher linear rate which would prove the fuel integrity.

3. Irradiation Tests

3.1 Type-A Tests [2]

To verify the irradiation performance of the HANARO fuel at a high power and burnup, in-pile irradiation tests were performed. Two un-instrumented test fuel bundles(Type-A, KFH-051 and KFH-067) for a higher burnup irradiation were designed by KAERI and fabricated by AECL. The test fuel bundles were made of 6 fuel elements located in the outer ring of the hexagonal fuel assembly and 30 aluminum dummy elements as shown in Fig.1. The test fuel bundles were irradiated for 206 days(KFH-051) and 293 days(KFH-067) in the HANARO core. Type-A fuel bundles were discharged after a 69.9 at% average and 85.5 at% peak burnup, respectively.

3.2 High Power Irradiation Test [3]

Another test fuel bundle(KH99H-001) for the high power irradiation test was developed along with the localization plan of the HANARO fuel in KAERI. The high power test fuel bundle was composed of 3 pulverized and 3 atomized U_3Si fuels. The test assembly was irradiated during 173.7 reactor operation days in the CT hole with the highest neutron flux in the HANARO core. The reactor physics calculations showed an

average discharge burnup of 63 at%U-235, maximum local burnup of 77 at%U-235, average linear power of 83 kW/m and maximum linear power of 121.6 kW/m. Figure 2 shows the linear power distribution of the high power test bundle along with the burnup.

4. Post-Irradiation Examination

4.1 Visual Inspection

In the service pool of the HANARO, an under-water visual inspection system was deployed. Periodical examinations showed a good condition for the mechanical integrity of the test fuel bundles. One of the special findings was that some dark discolorations appeared at a relatively high heat flux. In the hot cell examination, it was confirmed that the dark discolorations in the under-water conditions were the white ones in the air conditions. And through the metallography of the irradiation sample, the above discolorations seem to be a kind of aluminum oxide layer caused by a local overheating.

4.2 Swelling

Uranium silicide dispersion fuels in aluminum swell due to irradiation. In the case of HANARO, a limit of 20% volumetric swelling had been set. Swelling had been conservatively estimated to be less than 1 vol% per 10 at% burnup at a terminal burnup in the AECL performance tests[4]. The meat diameter changes were measured from the micrographs by averaging several circumferential data or the cross-sectional area of the meat. But we could not confirm that the cut surface was not perfectly perpendicular to the axis of the fuel rod. Therefore we preferred immersion density measurements over diameter measurements for the core volume change assessments. Figure 3 shows the irradiation swellings of the test specimens with an increase of the burnup. Maximum swelling reached to an about 18 vol% in the KFH-067(1) sample. Thus we increased three times the sample size in the same bundle since the larger volume mitigates the linearly not-even distribution of uranium. These samples(KFH-067(2)) showed a good swelling performance lower than 10 vol% at the highest burnup.

4.3 Reaction Layer

The micrographs of the fuel cores revealed that a chemical reaction had occurred between the fuel particles and aluminum matrix as shown in Fig. 4. The reaction product was mainly confined to the peripheral regions of the fuel particles and was typically 5 μm thick after a 40 at% burnup and 20 μm thick after a 80 at% burnup as Fig. 5. A small amount of porosity was noted at the edges of some of the fuel particles.

4.4 Corrosion

An oxide thickness survey was done using each metallographic sample as illustrated in Fig. 6. The thicker oxides were created on the surfaces of the test fuel elements that had operated at high heat ratings or high burnups. The range of the oxide layers were typically from 10 to 80 μm along with the burnup as shown in Fig. 7. It was confirmed in the ANS (Advanced Neutron Source) corrosion test that the oxide film growth is dependent on the coolant water chemistry, and that a particularly sensitive increase is near pH 5[5]. Considering that the core coolant is controlled at pH 5.6 in HANARO, the thicker oxide layers than the expected ones seem to be caused by the water chemistry.

We could not find any evidence of a spallation of the oxide layer from the micrographs. The thick oxides do not threaten the cladding integrity and appear to have no detrimental effect on the fuel element performance.

5. Conclusions

The irradiation tests using the HANARO fuels were performed to verify the irradiation performance at a high power and burnup. The three test fuel bundles were used with 6 fuel elements located in the outer ring of the hexagonal fuel assembly. The maximum discharged burnup and linear power were 69.9 at% average and 85.5 at% peak with an 83 kW/m average and 121.6 kW/m peak, respectively. Through detailed non-destructive and destructive PIE, we could obtain the followings;

1) Some discolorations observed on the fuel surface were related to a kind of aluminum oxide layer caused by a local overheating.
2) Maximum swelling measured by the immersion density method was lower than 18 vol% at a terminal burnup and this value satisfies the design limit of a 20% volumetric swelling.
3) The thicker oxide layer than the expected one in the design stage appeared to be due to the water chemistry. But the thick oxides do not threaten the cladding integrity because there was no indication of a spallation in the micrographs of the oxide layers.
4) It was verified that the HANARO fuel maintains a proper in-pile performance and integrity even at a high power of 121 kW/m and up to a high burnup of 85 at%.

References

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[4] D.F.Sears et. al., "Post-Irradiation Examination of Prototype Al-64wt% U_3Si_2 Fuel Rods from NRU," Proceeding of International Meeting on Reduced Enrichment for Research and Test Reactors, Virginia, USA, 1994 September.

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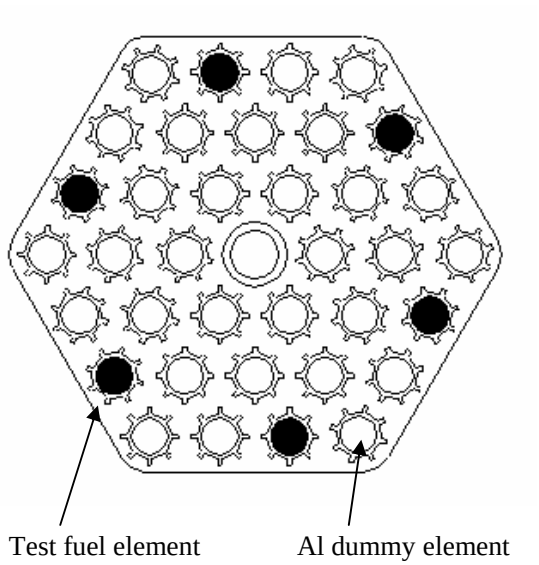

Fig. 1 Cross section of the irradiation test bundle

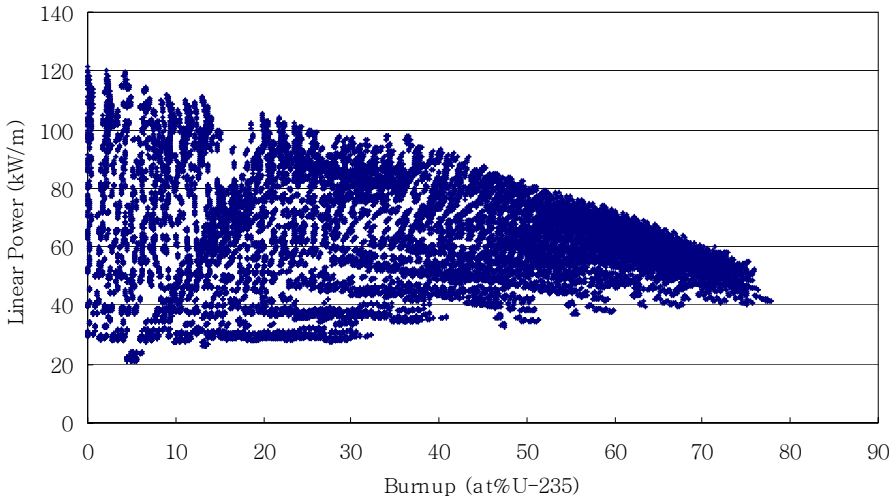

Fig. 2 Linear power distributions of the high power test bundle

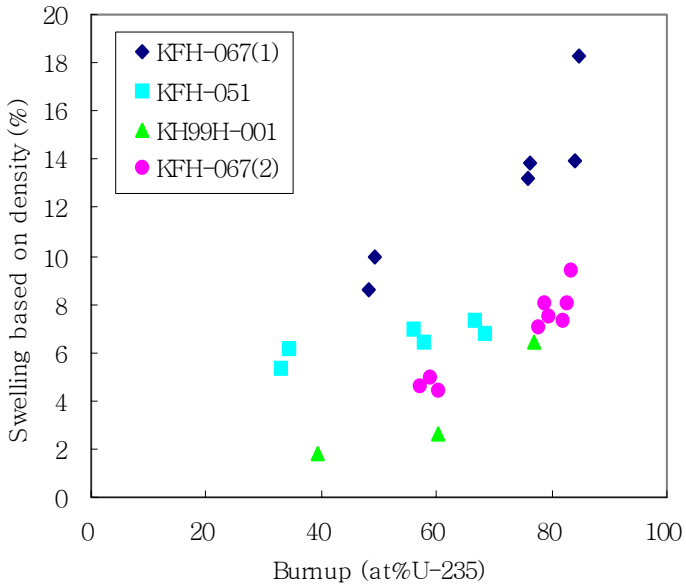

Fig. 3 Volumetric swelling measured by the immersion density method

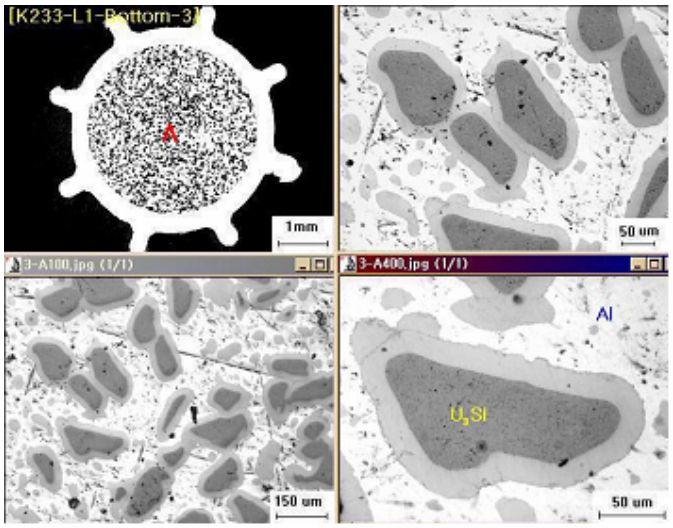

Fig. 4 Micrographs of the fuel particles and reaction layers

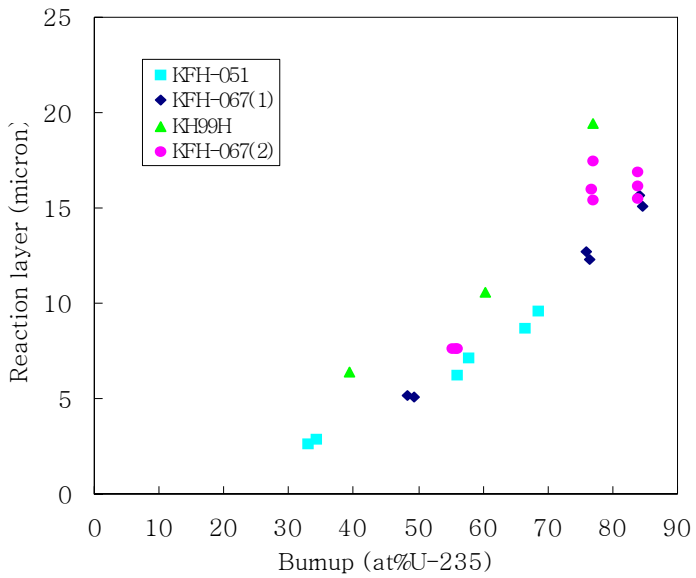

Fig. 5 Reaction layer thickness of the fuel particle

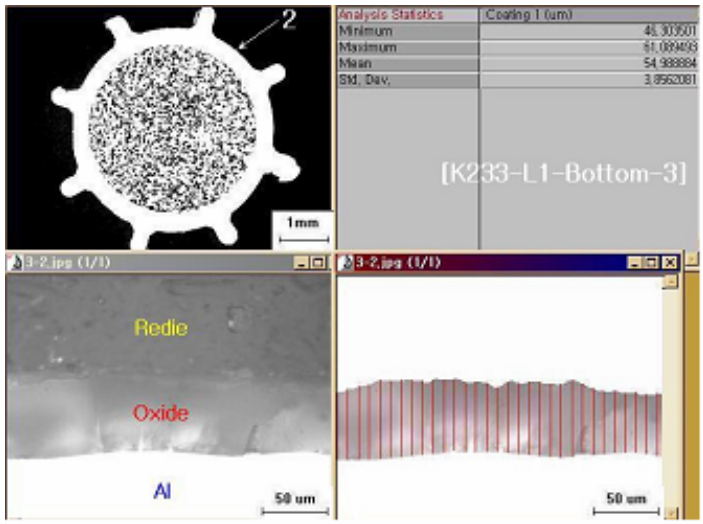

Fig. 6 Micrographs of the oxide layers on fuel surface

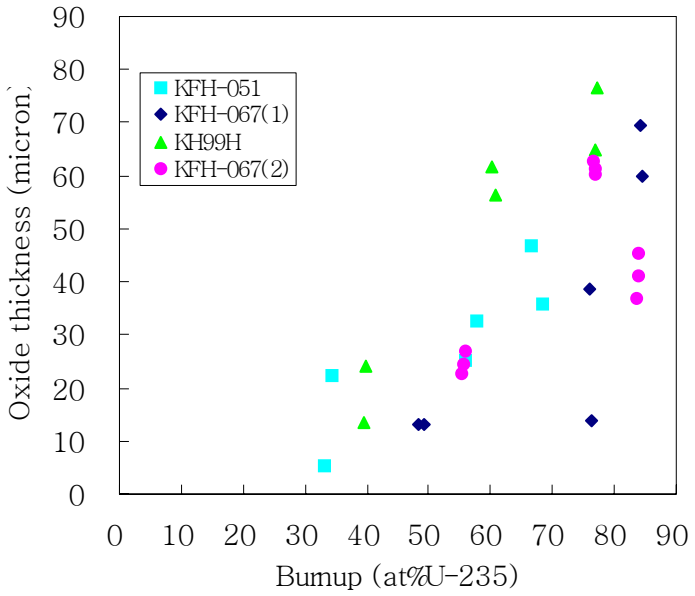

Fig. 7 Oxide layer thickness of the fuel cladding surface