Progress in high dpa irradiation testing at HANARO

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ABSTRACT

The High Flux Advanced Neutron Application Reactor (HANARO) is an open pool type multipurpose research reactor located at the Korea Atomic Energy Research Institute (KAERI) and has been operating as a platform for nuclear research in Korea. For the national research and development program on nuclear reactors and nuclear fuel cycle technology, numerous irradiation testing using various neutron irradiation facilities such as rabbit irradiation facilities, loop facilities, and capsule irradiation facilities have been performed at HANARO. Because the reactor uses U_3Si fuels of low enriched uranium of 19.75 w/o, it provides a peak fast flux of $2.1x10^{14}$ n/cm^2.s (E>1.0 MeV) at 30MW of maximum thermal power. It results in approximately 3 dpa (displacement for atom) of irradiation damage of Fe-based specimens per year. HANARO has recently been required to support national R&D projects requiring a much higher neutron fluence. To scope the user requirements for a higher neutron fluence, several efforts have been applied at HANARO. First, a long-term irradiation capsule technology of up to 3 dpa was developed and applied. The long-term irradiation capsule technology was scheduled to extend its capability up to 5 dpa for the irradiation of materials of future nuclear systems. The improvement in the capsule technology was based on a safety analysis and a design optimization of the irradiation capsule. However, for a higher neutron fluence exceeding 5 dpa, new capsule technologies including a new capsule design, flux-boosting, re-irradiation, and re-instrumentation are under planning at HANARO.

1. Introduction

The High Flux Advanced Neutron Application Reactor (HANARO), located at the Korea Atomic Energy Research Institute (KAERI) in Korea, has been operating as a platform for basic nuclear research in Korea, and the functions of its systems have been improved continuously since its first criticality in February 1995. To support the national research and development programs on nuclear reactors and nuclear fuel cycle technology in Korea, irradiation facilities have been developed and actively utilized for the irradiation tests requested by numerous users [1-3]. Most irradiation tests have been related to national R&D relevant to present nuclear power reactors such as the ageing management and safety evaluation of the components. HANARO has recently supported national R&D projects relevant to new nuclear systems including System-integrated Modular Advanced Reactor (SMART) and new research reactors [2].

Following the irradiation experience, the demand for neutron irradiation of materials of future nuclear systems is increasing rapidly at HANARO. The development of future nuclear systems such as VHTR, SFR, and fusion reactors is one of the most important projects planned by the Korean government. To effectively support national R&D, relevant to future nuclear systems, the development of advanced irradiation technologies is being preferentially developed at HANARO. In particular, irradiation technologies for a high dpa (displacement per atom) are inevitably required for the characterization of nuclear fuel and material performance of future nuclear systems. To scope the user requirements for a high dpa irradiation, several methods have been suggested and tested at HANARO.

In this paper, the status and on-going effort for a high dpa irradiation testing at

HANARO are described and discussed.

2. Irradiation at HANARO

2.1 HANARO and Irradiation Facilities

HANARO, a 30 MW open-pool type multipurpose research reactor, has been operated as a platform for nuclear researches in Korea since its first criticality in February 1995 [1]. Both the general design features and detailed information about this reactor are available on the HANARO home page (http://hanaro.kaeri.re.kr). Various neutron irradiation facilities, such as rabbit irradiation facilities, capsule irradiation facilities, loop facilities, and neutron transmutation doping (NTD) facilities, have been developed [2,3]. Figure 1 shows HANARO complex and the reactor core of HANARO with the irradiation facilities installed in the reactor core.

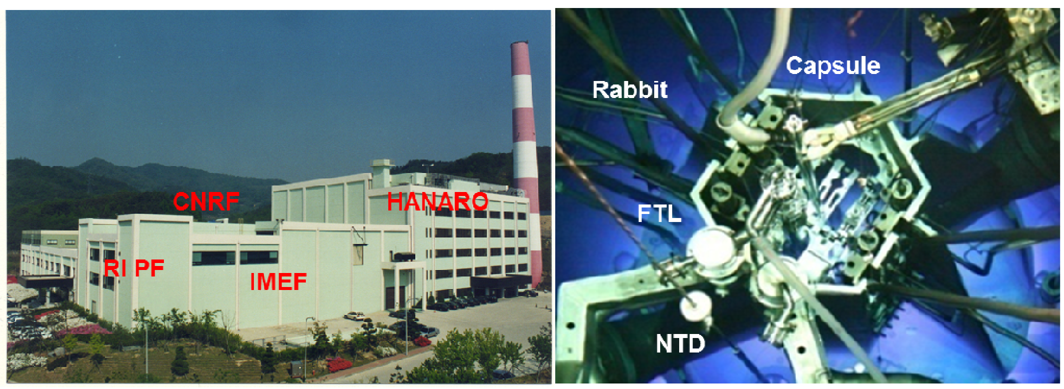

Figure 1. HANARO and reactor core with irradiation facilities

Irradiation technology at HANARO was basically developed for irradiation testing under a commercial reactor operation environment. Table 1 summarizes the current status of irradiation technology at HANARO compared with the advanced foreign technology.

Fields	KAERI	Worldwide	R&D Target	Remarks
Temp. (℃)	250～700	60～1000	60～1000	Irradiation
	±10	±3	±5	Accuracy
Fluence Accuracy	-	±20%	±20%	Thermal
	±20%	±10%	±10%	Fast
Flux ($n/cm^2.sec$)	$6x10^{12}$～$1.4x10^{14}$	No limit	$1.5x10^{9}$～$1.4x10^{14}$	E>1 MeV
Cycle (n/cm^2) Fluence (n/cm^2)	4 cycles (100 days)	No limit	20 cycles (500 days)	
	$<1x10^{21}$	No limit	$<5x10^{21}$	E>1MeV

Table 1. Status of irradiation technology of HANARO

After the Fukushima nuclear accident in Japan, Special Safety Inspections by the Nuclear Safety and Security Commission (NSSC) on HANARO were conducted. A part of the reactor building did not meet the seismic performance assessment standard of a magnitude 6.5 on the Richter scale (ground acceleration of 0.2 g). HANARO has been temporarily shut down for a safety reinforcement construction, which will be completed by March 2017. Reoperation of the reactor will be determined after a safety assessment by the NSSC.

2.2 Utilization of HANARO Irradiation Facilities

To support the national research and development programs on nuclear reactors and the nuclear fuel cycle technology in Korea, the irradiation facilities have been actively utilized for the irradiation tests requested by numerous users from research institutes, universities, and industries [2,3]. Among the irradiation facilities, the capsule is the most useful device for coping with the various test requirements at HANARO. Therefore, it has played an important role in the integrity evaluation of reactor core materials and the development of new materials through precise irradiation tests of specimens such as a reactor pressure vessel, structural materials of the reactor core, fuel assembly parts, and high technology materials at HANARO.
Most irradiation tests have been related to national R&D relevant to the present nuclear power reactors, such as the ageing management and safety evaluation of the components. HANARO has also supported national R&D projects relevant to the System-integrated Modular Advanced Reactor (SMART) and advanced research reactors. Based on the accumulated experience as well as the sophisticated requirements of users, HANARO has recently supported national R&D projects relevant to future nuclear systems such as the Generation IV (GEN-IV) and Fusion reactor programs. Among the six GEN-IV systems, Korea has participated in the VHTR (Very-High-Temperature Reactor System) and SFR (Sodium-Cooled Fast Reactor System) R&D programs. Figure 2 shows a typical contribution of neutron irradiation at HANARO for National Nuclear R&D Programs.

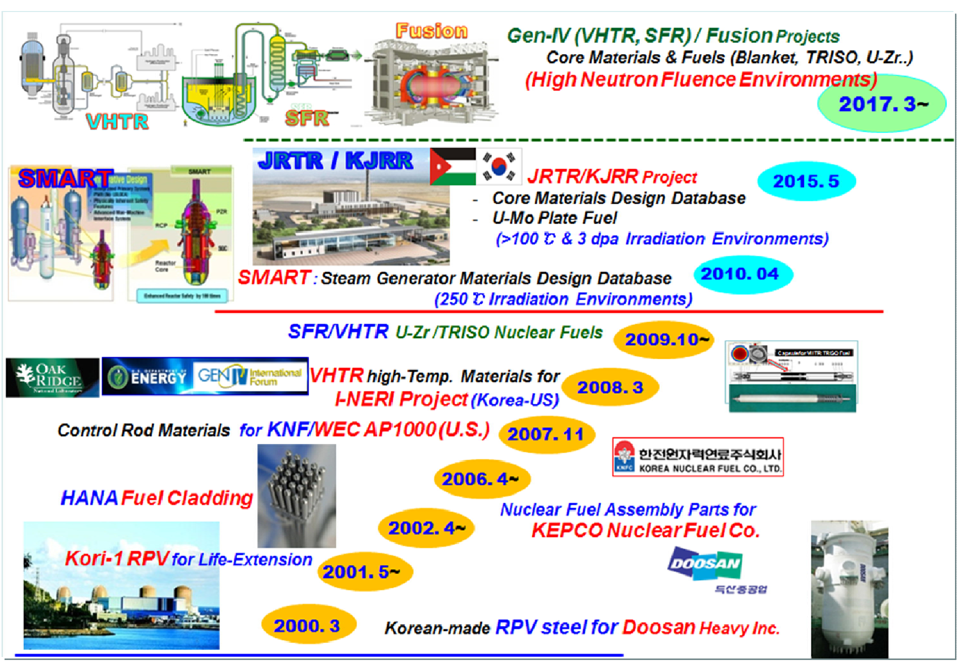

Figure 2. Typical Contribution of Neutron Irradiation at HANARO for National Nuclear R&D Programs

Because the reactor has not been in operation for more than two years, a number of irradiation testing requests from various users have been made. Owing to the limited test holes in the core of HANARO (CT, IR, OR, IP), there are currently two or three users waiting for neutron irradiation testing per test hole. Based on the importance and urgency of the user irradiation testing, an irradiation testing schedule at HANARO was determined. Although the IP test holes (having low neutron flux and temperature limit) are available for irradiation testing after reactor reoperation, the CT/OR test holes in the reactor core were already scheduled for more than three years after reactor reoperation.

3. Improvement of irradiation capsule for a higher neutron fluence

3.1 User requirements for a higher neutron fluence

The development of future nuclear systems such as VHTR, SFR, and Fusion reactors is one of the most important projects planned by the Korean government. The environmental conditions for these reactors are generally beyond the present reactor irradiation technology, particularly regarding a higher temperature and neutron fluence. Table 2 summarizes the requested irradiation testing from HANARO users up to March of this year.

	Specimen	Irradiation Temperature	Test Hole	Irradiation Cycle (dpa)	Year	User
1	Fusion Structural Mats (ARAA) (Fe-9Cr alloy)	300~350℃	CT	>8 (>5)	2017	KAERI
2	Fusion Structural Mats ARAA Welds	320℃	CT	>8 (>5)	2018	KAERI
3	Accident-Resistant Nuclear Fuel Cladding	300℃	CT	4~6	2017	KAERI
4	Cladding Alloys for PWRs	350~400℃	CT	2~4	2017	University
5	VHTR Reactor Core Mats	300~1,000℃	CT	8~24 (5~15)	2017	KAERI
6	Long Life SPND	300℃	OR	8~24	2017	KHNP
7	U-Mo Nuclear Fuel	-	OR	8	2017	KAERI
8	Epoxy, SiC Epoxy	~200℃	OR	8	2017	KAERI
9	Fission Mo Target	-	OR/IP	1	2017	KAERI
10	Th-based Nuclear Fuel	-	OR	8~24	2018	KAERI
11	SiC Composite	900~1,600℃	OR	>8	2018	KAERI
12	ENFMS (Instruments)	-	IP	1	2018	USERS Co.
13	SFR Structural Mat.s (ODS)	300～500℃	CT	>8 (>5)	2017	KAERI
14	SFR Fuel	-	OR	>16	2018	KAERI
15	Low Alloy RPV Mat.s	300℃	OR	2	2017	KAERI
16	Fuel Cladding	RT	CT	33 (17)	2017	KAERI
17	Mortar	RT	OR	1	2017	University
18	U-Mo Fuel	-	OR	>16	2018	KAERI-ANL

19	VHTR Fuel	800~1300	OR	~40	2018	KAERI-JAEA

Table 2. Current user requirements for irradiation testing at HANARO

3.2 Design improvement of capsule for 3 dpa

There is a forced upward coolant flow in the core of HANARO. All of the inserted structures in the core including the irradiation capsule are required to satisfy the pressure drop criteria of 209 kPa at HANARO. Because of the up-stream of the coolant in the reactor, the instrumented capsule is fixed or supported at four points, which are the bottom and top of the main body, the top of the reactor chimney, and the site of the capsule robot arm. However, as the irradiation capsule is exposed to a very high pressure coolant flow of 19.6 kg/s during irradiation testing, it has been suspected to be vulnerable to vibration-induced fatigue cracking. Therefore, HANARO instrumented capsules have been limited to irradiation of within 1.5 dpa.
Recently, as part of the research reactor development project, irradiation testing of materials used as core materials in a research reactor, such as graphite, beryllium, and zircaloy-4, has been required for up to 3 dpa at low temperature (<100°C).
The source of stress causing the fatigue cracking is generally proportional to the vibrational displacement of the capsule. In addition, all of the inserted structures in the reactor core including the irradiation capsule are recommended to satisfy the vibration displacement criteria of 300μm owing to the design characteristics of HANARO. Therefore, the 'Reactor Safety Review Committee of HANARO' required a vibration and out-pile endurance testing for a newly designed capsule in the out-pile testing facility simulating the HANARO operating environment. Through out-pile performance and endurance testing of the capsule before HANARO irradiation testing in the HANARO out-pile test facilities, an optimized design of the capsule was determined [5]. By changing the material from STS 304 to STS 316L, and welding using an EB welding method fabricating the rod tip of the capsule, the endurance life of the rod tip of the capsule was greatly extended in the out-pile test. STS 316L was selected owing to its superior properties over STS 304 in terms of welding [6,7], EB welding is considered to have a narrow welding area than previous TIG welding, resulting in a less harmful distribution of residual stress in the welding area [8]. Based on the out-pile test results, an irradiation capsule was designed and successfully irradiated up to 3 dpa (equivalent to eight reactor operation cycles in HANARO) at low temperature (<100°C) at HANARO [9]. After the irradiation of 3 dpa, the rod tip of the capsule was also examined to see any occurrence of fatigue cracks or defects. No cracks or defects were found in the rod tip of the irradiated capsule. Therefore, the improved capsule design was proved to be safe for irradiation of up to 3 dpa at HANARO. The new capsule technology was successfully applied for neutron irradiation of the core materials (graphite, beryllium, and zircaloy-4) of research reactors as a part of the National Research Reactor Development Project.

3.3 Design improvement of capsule for 5 dpa

To effectively support the national R&D relevant to future nuclear systems, the development of advanced irradiation technologies concerning a higher neutron fluence than 3 dpa was required at HANARO. Based on the user requirements, the long-term irradiation capsule technology was scheduled to extend its capability up to 5 dpa, which is equivalent to irradiation testing for 15 cycles at HANARO. Although the design improved capsule was proved to be sound at up to 3 dpa, it still seems to be susceptible to fatigue cracking of the rod tip of the capsule for a higher dpa irradiation.

Actually, the improved rod tip failed after 203 days (equivalent to 3 dpa at HANARO) under the 110% accelerated condition of a normal reactor coolant flow [ ]. The fracture seems to have occurred at around the boundary of the weld end, and the fracture surface shows the typical appearance of a fatigue fracture described in the literature [10,11]. The failure of the rod tip was concluded to be caused by vibration-induced fatigue cracking during irradiation testing. The applied stresses on the rod tip were analyzed using the ANSYS program. The applied stresses on the rod tip can be classified into stresses based on the designed bottom spring, upward flowing coolant, capsule vibration, and residual stress of the welding. The maximal stresses due to the first three factors were estimated as 5.4 MPa, 132.9 MPa, and 161 MPa, respectively. These stresses do not exceed the known fatigue strength of stainless steels (~300 MPa [12]). Residual stress by welding is another possible stress, and is known to have occurred at up to about 300 MPa [13]. Therefore, the combination of these stresses can be sufficient to cause a fatigue failure of the rod tip of the capsule. Based on the failure analysis, another design of the rod tip of the capsule was made for 5 dpa irradiation, as shown in Figure 3. To decrease the applied stress on the rod tip, the diameter of the rod tip was increased from 8.0 to 9.0 mm, and the height of the tapered part of the rod tip was decreased from 0.5 to 0.2 mm. This results in a decrease of 22.6% of the applied stress under the same conditions. The gap between the rod tip and the bottom end guide, and the gap (gap 2) between the rod tip fixture guide and the bottom end guide, were decreased from 0.05 to 0.025 mm, and from 0.15 mm to 0.05 mm, respectively, to suppress the applied stress by constraining the vibration of the rod tip. The length of the rod tip was increased by 7 mm to position the weld part of the rod tip above the stressing position. This will eliminate the effect of the residual stress by welding fundamentally. The safety of the new capsule should be fully checked before irradiation testing. The out-pile performance and endurance testing was performed before HANARO irradiation testing. The new rod tip of the capsule was out-pile tested safely up to 450 days, which is equivalent to 5 dpa irradiation in the reactor.

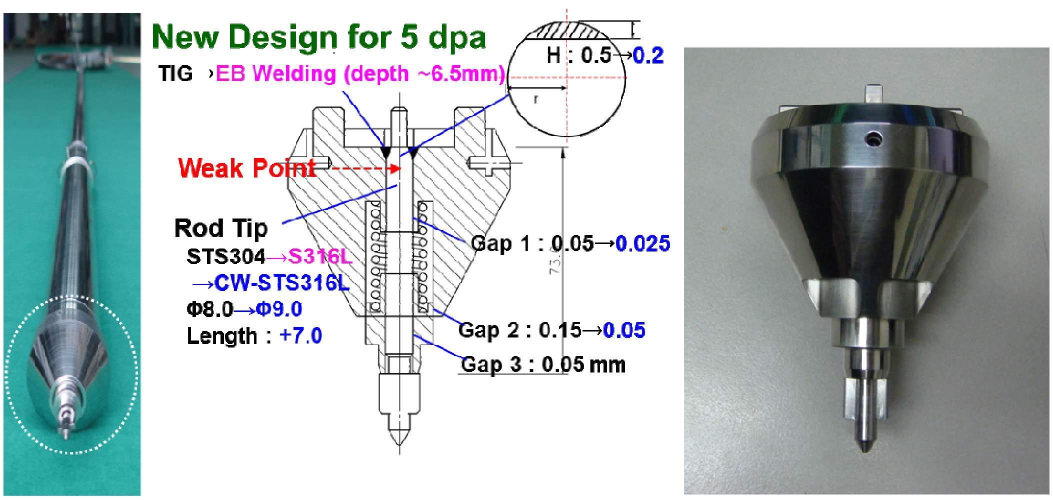

Figure 3. The improved design of the capsule bottom part for 5 dpa irradiation

3.4 Further R&Ds for a higher dpa irradiation

At up to 5 dpa irradiation, improvements of the capsule technology have been performed based on a design optimization of the irradiation capsule. However, for a higher neutron fluence exceeding 5 dpa, new capsule technologies including a new concept capsule, flux-boosting, re-irradiation, and re-instrumentation are under planning as the next 5-year R&D project starting from 2017 at HANARO. It will scope the user requirements for the National R&D on next-generation nuclear power plants.

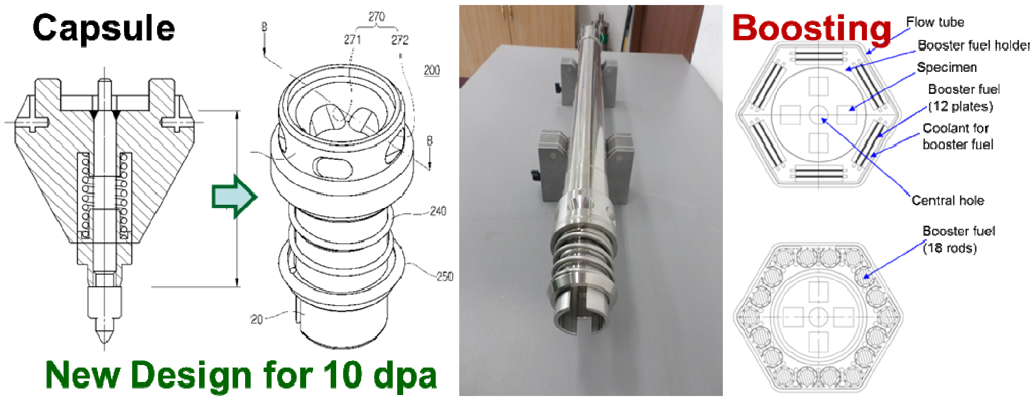

Figure 4. The design improvement of the capsule for a higher neutron fluence

4. Conclusions

Several R&D efforts for higher neutron irradiation have been conducted to satisfy the user requirements at HANARO. At first, a long-term irradiation capsule technology of up to 3 dpa was developed at HANARO. For an extended endurance life of the rod tip of the irradiation capsule, susceptible to a vibration-induced fatigue cracking, the material of the rod tip was changed from STS 304 to STS 316L, and the welding method was also changed from TIG welding to EB welding. The newly designed capsule was successfully applied for neutron irradiation of the core materials (graphite, beryllium, and zircaloy-4) of research reactors up to 3 dpa of irradiation as a part of the National Research Reactor Development Project. To scope out the user requirements for the irradiation of materials of future nuclear systems, more improved long-term irradiation capsule technology of up to 5 dpa is under development. The second improvement of the capsule technology has been performed based on a safety analysis and a design optimization of the irradiation capsule to reduce the applied stress on the venerable rod tip of the capsule. However, for a higher neutron fluence exceeding 5 dpa, new capsule technologies including a new concept capsule, flux-boosting, re-irradiation, and re-instrumentation are under planning as the next 5-year R&D project starting from 2017 at HANARO.

Acknowledgements

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References

1. K.N. Choo, et. al., “Material Irradiation at HANARO, Korea,” Research Reactor Application for Materials under High Neutron Fluence, IAEA-TECDOC-1659, 2011, IAEA.
2. K.N. Choo, et. al., "Contribution of HANARO Irradiation Technologies to National

Nuclear R&D," *Nuclear Engineering and Technology*, **46**, 4, 501 (2014).
3. M.S. Cho, et al., "Material Irradiation by Capsules at HANARO," *Nucl. Technol.*, **193**, 330 (2016).
4. B.G. Kim, et. al., "Design and Fabrication Report on Capsule (11M-19K) for Out-pile Testing of Research Reactor Materials at HANARO," KAERI Report, KAERI/TR-4610/2012 (2012).
5. J.M. Keisler, er al., "Statistical models for estimating fatigue strain-life behavior of pressure boundary materials in light water reactor environments," *Nucl. Eng. Des.,* **167**, 129 (1996).
6. D. Harish Kumar, et al., "A review on critical aspects of 316ln austenitic stainless steel weldability," *Int. J. Mat. Sci. App.*, **1**, 1 (2012).
7. Jiamin Sun, et al., "A comparative study on welding temperature fields, residual stress distributions and deformations induced by laser beam welding and CO_2 gas arc welding," *Materials and Design*, **63**, 519 (2014).
8. S.W. Yang, et. al., "The Irradiation Test Report for Research Reactor Materials at HANARO," KAERI Report, KAERI/TR-5494/2014 (2014).
9. K.N. Choo, et. al., "Development of a Low-Temperature Irradiation Capsule for Research Reactor Materials at HANARO," *Nucl. Technol.*, **195**, 213 (2016).
10. G.F. Vander Voort, "MACROSCOPIC EXAMINATION PROCEDURES FOR FAILURE ANALYSIS," *Metallography in Failure Analysis*, p. 60, James L. McCall and P.M. French, Ed., Plenum Press, New York and London (1978).
11. R. Avilés, et al., "Influence of low-plasticity ball burnishing on the high-cycle fatigue strength of medium carbon AISI 1045 steel," *Int. J. Fatigue*, **55**, 230 (2013).
12. Sergei A. Shipilov, "Solving some key failure analysis problems using advanced methods for materials testing," *Eng. Failure Analysis*, **14**, 1550 (2007).
13. J. Sun et al., "A comparative study on welding temperature fields, residual stress distributions and deformations induced by laser beam welding and CO_2 gas arc welding," *Materials and Design*, **63**, 519 (2014).