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CONTRIBUTION OF HANARO IRRADIATION TECHNOLOGIES TO NATIONAL NUCLEAR R&D

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HANARO is a multipurpose research reactor located at the Korea Atomic Energy Research Institute (KAERI). Since the commencement of its operation in 1995, various neutron irradiation facilities, such as rabbit irradiation facilities, fuel test loop (FTL) facilities, capsule irradiation facilities, and neutron transmutation doping (NTD) facilities, have been developed and actively utilized for various nuclear material irradiation tests requested by users from research institutes, universities, and industries. 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. Based on the accumulated experience as well as the sophisticated requirements of users, HANARO has recently supported national R&D projects relevant to new nuclear systems including the System-integrated Modular Advanced Reactor (SMART), research reactors, and future nuclear systems. This paper documents the current state and utilization of irradiation facilities in HANARO, and summarizes ongoing research efforts to deploy advanced irradiation technology.

KEYWORDS : HANARO, Irradiation Test, Utilization Status, Contribution to National Nuclear R&D, Advanced Irradiation Technology

1. INTRODUCTION

The High Flux Advanced Neutron Application Reactor (HANARO) is an open pool type multipurpose research reactor with 30MW thermal power located at the Korea Atomic Energy Research Institute (KAERI) in Korea. Both general design features and detailed information about this reactor are available on the HANARO home page (http://hanaro.kaeri.re.kr). In an effort to boost the nation's research capability, HANARO was conceived and constructed in the 1980s using domestic reactor technology from KAERI [1]. HANARO has been operated 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. It is now being successfully utilized in areas such as fuel and material irradiation tests, neutron beam research, radioisotope production, neutron activation analysis, and neutron transmutation doping to meet industrial, academic, and research demands.

To support the national research and development programs for nuclear reactors and nuclear fuel cycle technology in Korea, various neutron irradiation facilities such as rabbit (small non-instrumented capsule) irradiation facilities, capsule irradiation facilities, and fuel test loop facilities have been developed and actively utilized for the irradiation tests requested by numerous users [2,3]. Continuing efforts to improve the capabilities and instrumentation of the facilities have been in progress at KAERI [4-6]. The irradiation facilities have been mostly utilized for the KAERI research projects related to the National Nuclear R&D Projects relevant to a commercial nuclear power reactor such as the ageing management and safety evaluation of the components. However, some irradiation tests were performed for scientific research of universities and for several commercial-based projects. Another research reactor that will specialize in radioisotope production and the demonstration of reactor design is under construction in Korea. Therefore, HANARO will specialize more on irradiation research. Based on its accumulated irradiation experience, HANARO has recently started new support of R&D relevant to new nuclear systems including power and research reactors.

In this paper, not only the status of HANARO irradiation facilities but also the utilization of the facilities and the prospect of development of the HANARO irradiation technology to support the National R&D Projects relevant to the present and future nuclear systems of Korea are described.

2. HANARO AND IRRADIATION FACILITIES

2.1 HANARO Reactor

In April 1995, KAERI completed the construction of a high performance multipurpose research reactor named HANARO which means, in Korean, “uniqueness”. The core features a combination of a light water cooled and moderated inner core and a light water cooled but heavy water moderated outer core. The inner core has 28 fuel sites and 3 test sites. Three test sites are hexagonal shaped and used for capsules, fuel test loop (FTL), and radioisotope (RI) production. The outer core consists of 4 fuel sites and 4 test sites, which are embedded in the reflector tank. There are several vertical test holes such as CT, IR1, IR2 (hexagonal type) and OR (cylindrical type) in the core of HANARO, and additionally, Large Hole (LH), Hydraulic Transfer System (HTS), Neutron Transmutation Doping (NTD) and Irradiation Position (IP) positions in the reflector region of the reactor for nuclear fuels and materials irradiation testing, RI production and Si doping, as shown in Fig. 1. Table 1 shows the characteristics of the reactor test holes for a fuel/material irradiation at HANARO [7]. The neutron flux of the vertical test holes varies markedly depending upon the location in the reactor core. The seven horizontal beam ports such as ST1, ST2, ST3, ST4, NR, CN and IR in the reflector region of the reactor are being actively applied for scattering and diffraction of neutrons, neutron radiography, and the out-of-core neutron irradiation facilities (Cold Neutron Reflection Facilities (CNRF), Boron Neutron Capture Therapy (BNCT) and dynamic Neutron Radiography (NR)).

At present, another research reactor that will specialize in radioisotope production and demonstrations of reactor designs is under construction in Korea. Therefore, HANARO will specialize more on the irradiation research of nuclear fuels and materials.

2.2 Irradiation Facilities at HANARO

Various neutron irradiation facilities such as the rabbit irradiation facilities, the loop facilities and the capsule irradiation facilities for irradiation tests of nuclear materials, fuels and radioisotope products have been developed at HANARO [2,3]. Among the irradiation facilities at HANARO, the capsule and rabbit systems have been used for the irradiation of nuclear materials, and the FTL was installed in IR1 by the end of 2008.

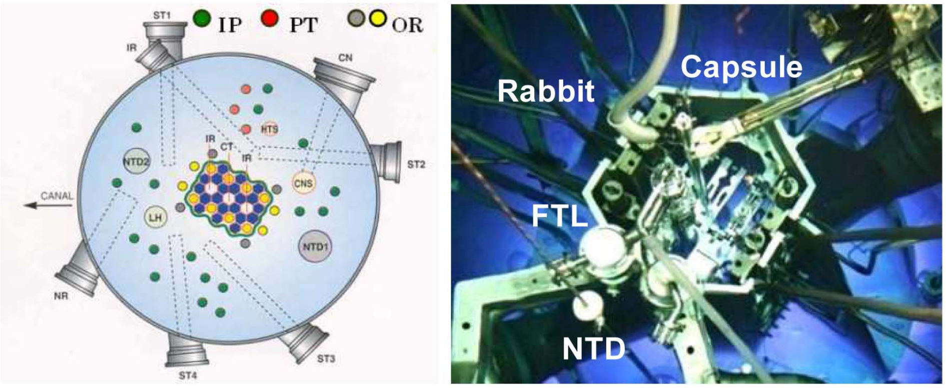

Fig. 1. Configuration and Photograph of the HANARO Core.

Table 1. Characteristics of the Test Holes for a Material Irradiation at HANARO

Location	*Hole*		Inside Dia. (cm)	Neutron Flux (n/cm^2. sec)		Remarks
	Name	No		Fast Neutron (>0.82 MeV)	Thermal Neutron (<0.625 eV)	
Core	CT	1	7.44	1.95×10^{14}	4.30×10^{14}	Fuel/material test Radioisotope production
	IR	2	7.44	$1.80/1.76 \times 10^{14}$	$3.83/3.80 \times 10^{14}$	
	OR	4	6.00	$1.92\sim2.01 \times 10^{13}$	$2.94\sim3.30 \times 10^{14}$	
Reflector	LH	1	15.0	7.35×10^{11}	9.72×10^{13}	Fuel/material test Radioisotope production
	HTS	1	10.0	1.72×10^{11}	8.82×10^{13}	
	IP	17	6.0	$1.43 \times 10^{9}\sim$ 2.17×10^{12}	$2.16 \times 10^{13}\sim$ 1.81×10^{14}	

The rabbit was originally designed for isotope production, but it can be used for the irradiation test of fuels and materials. Fig. 2 shows the typical rabbit (20 mm in diameter and 30 mm in length for specimen) inserted into the HTS hole. It is very useful for numerous irradiation tests of small specimens at a low temperature, below 200 °C, and neutron flux conditions.

The instrumented and non-instrumented capsules have been developed at HANARO for new alloy and fuel developments and the lifetime estimation of nuclear power plants (NPPs). For the development of an instrumented capsule system, the capsule related systems such as a supporting, connecting and controlling system were also developed. After locking the capsule in a test hole, the instrumented capsule is fixed by a chimney bracket and robotic arm supporting systems. Two sets of cantilever type robotic arm systems for the CT and IR2 test holes were installed at the location of the platform level of the reactor, which is 5.5 m in height from the bottom of the capsule, however, the in-chimney bracket is temporarily installed on the top of the reactor chimney for capsule irradiation tests. At the junction box system, heaters and thermocouples can be easily connected to, and separated from, the capsule controlling system before or after an irradiation test. The capsule temperature control system consists of three subsystems: a vacuum control system, a multi-stage heater control system and a man-machine interface system. After an irradiation test, the main body of the instrumented capsule is cut off at the bottom of the protection tube with the cutting system, and it is transported to the Irradiated Materials Examination Facility (IMEF) using a HANARO fuel cask.

The FTL is a facility that can conduct fuel and material irradiation tests at HANARO. It is composed of an in-pile test section (IPS) and an out-of-pile system (OPS). The IPS in the IR1 irradiation hole can accommodate up to three pins of PWR or CANDU type fuels and has instruments such as a thermocouple, LVDT, and SPND to measure the fuel's performance during a test. The environment around the IPS is subjected to a high neutron flux (Thermal flux: 1.2×10^{14} $cm^{-2}s^{-1}$, fast flux: 1.6×10^{14} $cm^{-2}s^{-1}$). The FTL simulates commercial NPP operating conditions such as its pressure, temperature, flow, and neutron flux to conduct irradiation tests. The application fields of the FTL are nuclear fuel and material irradiation tests at the operating conditions of a commercial power plant, fuel burn up and mechanical integrity verification tests, irradiation data generation for a performance analysis model (PWR fuel, CANDU fuel and metallic fuel), technical improvement of a design and fabrication process for advanced fuel development, fuel rod irradiation testing for performance verification and more. The typical design pressure and temperature of the in-pile section of the FTL is 17.5 MPa and 350 °C, respectively. The commissioning of the FTL was performed from April 2007 to September 2009. At present, a cold test is being performed for long-term utilization. The FTL will be used for the irradiation tests of advanced fuels after completion of the commissioning.

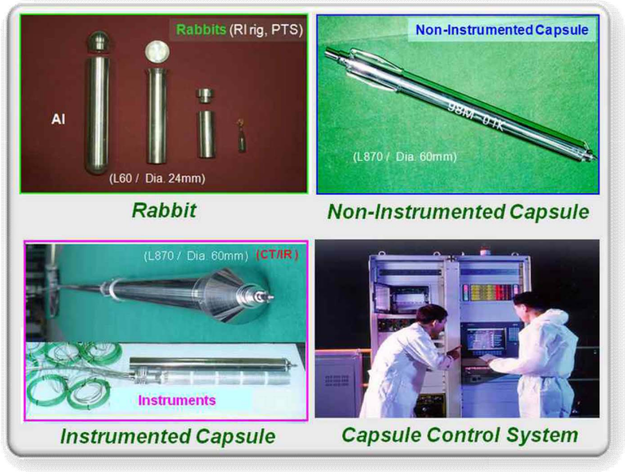

Fig. 2. Irradiation Rabbit, Non-instrumented Capsule and an Instrumented Capsule.

HANARO has two irradiation holes for neutron transmutation doping to manufacture high-quality n-type semiconductors. A semiconductor doped with neutrons has a much better dopant distribution compared to others made by conventional chemical doping methods, and is especially required for the effective use of high-power operating devices such as insulated gate bipolar transistors (IGBTs), integrated gate commutated thyristors (IGCTs), and gate turn off thyristors (GTOs). The demand for NTD silicon is increasing rapidly with the increase of wind, solar, and fuel cell energy systems; hybrid cars and hydrogen fuel cell engines; and devices to reduce electricity loss. A commercial NTD service for 5, 6 and 8 inch silicon ingots is being performed at NTD1 and NTD2, where the world's best quality products make up about 15% of the world market share as of 2012. New NTD facilities for a larger silicon ingot such as a 10 or 12 inch ingot are being planned in the new research reactor.

There are two facilities used for performing a post-irradiation examination (PIE) at KAERI. These are the Irradiated Material Examination Facility (IMEF) and the Post-Irradiation Examination Facility (PIEF). Detailed information about these facilities is available on the KAERI home page (http://www.kaeri.re.kr).

2.3 HANARO Irradiation Capsule

An irradiation capsule is an irradiation device that can be used to evaluate the irradiation performance of nuclear fuels and materials at HANARO. 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, reactor core structural materials, fuel assembly parts, and high technology materials at HANARO.

Instrumented and non-instrumented capsules have been developed at HANARO for new alloy and fuel development and the lifetime estimation of NPPs. Extensive efforts have been made to establish design and manufacturing technology for a capsule and temperature control system, which should be compatible with HANARO's characteristics [2,3]. Up to now, material and fuel capsules have been developed and are being utilized for the irradiation testing of materials and nuclear fuel at HANARO, and creep and fatigue capsules are being developed to study the creep and fatigue behavior of materials under irradiation.

A typical HANARO irradiation material capsule consists of three main parts that are connected to each other: a protection tube (5 m), guide tube (9.5 m) and a capsule's main body. The main body including the specimens and instruments is a cylindrical shape tube of 60 mm in diameter and 1170 mm in length. The main body has five stages with independent micro-electric heaters, thermocouples and neutron fluence monitors to measure the temperature and the neutron fluences of the specimens, respectively. Heaters and thermocouples are connected to a capsule temperature controlling system through a guide tube and connection box system. A friction welded tube using STS304 and Al1050 alloys is introduced to prevent coolant leakage into a capsule during the capsule cutting process after an irradiation.

The fuel capsule is applicable to research into the irradiation characteristics of fuel pellets and to obtain the in-core performance and the design data of nuclear fuel at HANARO. The fuel capsule has also been utilized for the irradiation characteristics test of Direct Use of Spent PWR Fuel in CANDU Reactors (DUPIC) fuel and advanced PWR fuel pellets. The instrumented fuel capsule can be used to measure fuel temperature, internal pressure of a fuel rod, fuel deformation and neutron flux during a fuel irradiation test.

The creep and fatigue capsules were developed to obtain the creep and fatigue characteristics of nuclear materials during irradiation test. The loading stress needed for a test is applied on a specimen by a bellows system controlled by an external He gas pressure.

Based on a specimen's configuration and the basic design of a capsule, the reactivity effect, neutron flux, and gamma heating of specimens are calculated using MCNP code [8]. To compare the neutron flux of the specimens that are calculated by using the MCNP computer program before an irradiation test, two kinds of fluence monitors (F/Ms) are installed in the Al thermal media near a specimen (one F/M per stage) in a capsule. Monitoring wires of Fe, Ni, Ti, Nb or Ag are inserted in an Al tube. Nb-Ag and Fe-Ni-Ti wires are inserted for the measurement of the thermal and fast neutron fluences of the specimens, respectively. After an irradiation, the F/Ms are dismantled in a hot cell and the weight changes and gamma ray spectrum of the wires are measured to obtain a neutron spectrum. The fast neutrons (E>1.0 MeV) obtained using the SANDII code are known to be located within about a 20% error range of the theoretical values calculated by the MCNP code. The temperature of the specimens during an irradiation is initially increased by the gamma heating and then roughly adjusted to an optimum condition by a gas control system and then finally adjusted to a desired value by a micro-electric heater. After the irradiation tests, the displacement per atom (DPA) and activation of the irradiated specimens are also evaluated using the SPECTOR [9] and ORIGEN2 codes [10], respectively.

The irradiation temperature of the specimens is preliminary analyzed using the GENGTC [11] and ANSYS codes [12]. Because the gamma heating rate varies along the vertical position of the reactor core, a gap adjustment between the capsule parts is very important to maintain a uniform temperature of the specimens over the region. Because of the complicated configuration of the specimen, a gap adjustment between the capsule parts is performed based on the expected temperatures obtained by the GENGTC code.

Table 2 summarizes the current status of irradiation technology at HANARO compared with the advanced foreign technology.

Table 2. Status of Irradiation Technology of HANARO

Fields	KAERI	Worldwide	R&D Target	Remarks
Temp. (ºC)	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 Fluence (n/cm^2)	4 cycles (100 days)	No limit	20 cycles (500 days)	
	<$1x10^{21}$	No limit	<$5x10^{21}$	E>1MeV

3. UTILIZATION OF HANARO FOR NUCLEAR R&D

As HANARO represents multipurpose research reactors, it plays a major role in nuclear technology development and the utilization of radiation technology in Korea. Owing to its stable operation and the buildup of various research results, as well as the support of the government for the reactor, more research demands for the utilization of HANARO are arriving. One of the major uses of the HANARO reactor focuses on its irradiation service.

The irradiation facilities of HANARO have been actively utilized for various nuclear fuel and material irradiation tests requested by users from research institutes, universities, and industries. Fig. 3 shows the trends of the irradiation specimens and the time requested by users. The increasing trends of the irradiation tests were recently disturbed by the installation of the CNRF and FTL. Since 1995, 12,000 specimens from research institutes, nuclear industry companies and universities have been irradiated at HANARO for 123,000 cumulative hours using the developed capsule and rabbit irradiation systems. One of the major irradiation fields is the support of national research and development program relevant to the commercial nuclear power reactor such as ageing management and the safety evaluation of its components. Another field is the progress of science and technologies (fundamental research, future nuclear systems). Fig. 4 shows a typical contribution of neutron irradiation at HANARO for the National Nuclear R&D Programs. Based on its accumulated experience and the sophisticated requirements of users, HANARO has recently started a new support of R&D relevant to new nuclear systems including SMART and future nuclear systems of VHTR and SFR. To effectively support R&D relevant to new nuclear systems, the development of advanced irradiation technologies concerning irradiation test temperature and instrumentation is being preferentially developed at HANARO.

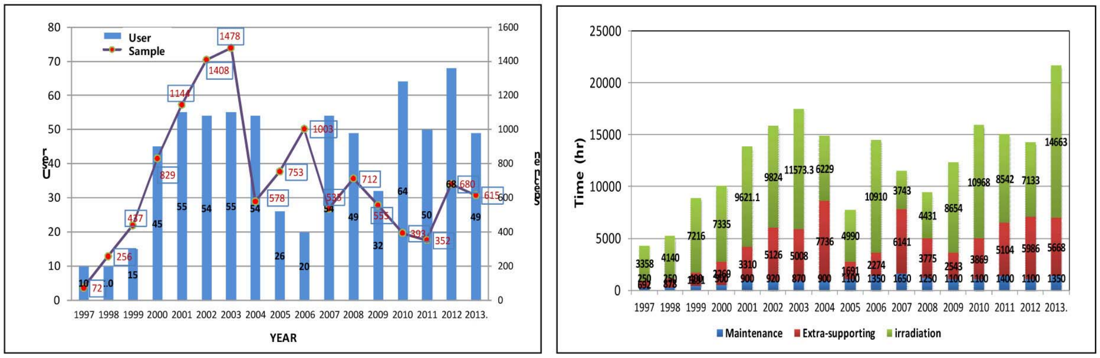

Fig. 3. Annual Trends of HANARO Users, Samples, Irradiation Times.

Fig. 4. Typical Contribution of Neutron Irradiation at HANARO for the National Nuclear R&D Programs.

3.1 Contribution of HANARO to the R&D of Commercial Reactors

The national R&D program on nuclear reactors and nuclear fuel cycle technology in Korea requires numerous in-pile tests at HANARO. Most irradiation tests at HANARO have been related to R&D relevant to commercial nuclear power reactor ageing management and the safety evaluation of its components. The capsules were mainly designed for the irradiation of a reactor pressure vessel, reactor core materials, and Zr-based alloys. Most capsules were made for KAERI R&D, but some capsules have been applied to several commercial-based irradiation tests relevant to the lifetime extension of the current nuclear power reactor Kori-1, new alloy and fuel developments with Doosan Heavy Industry Company (DHI) and KEPCO Nuclear Fuel Company (KNF), and control rod material evaluation in cooperation with Westinghouse Electric Company in the US. The archive material of the reactor pressure vessel of the Kori-1 reactor, which is the first NPP in Korea, was irradiated and evaluated to support the lifetime extension of the reactor, and the neutron irradiation performance of the Korean-made commercial RPV materials was also evaluated at HANARO. Several fuel irradiation capsules were designed and irradiated at HANARO to improve the nuclear fuel cycle technology of power and research reactors, and were also irradiated for an evaluation of the neutron irradiation properties of the nuclear fuel assembly parts fabricated by KNF.

3.2 Contribution to the SMART Project

The SMART is one of the most advanced small and medium sized reactors (SMRs) in the world [13]. There has also been a growing interest in small and medium sized reactors in developed countries that have deregulated their electricity market, under a call for flexibility in power generation. The Korean government decided to develop the system as a new growth engine, and to obtain the standard design approval on SMART from the Korean licensing authority by 2011. In order to fundamentally eliminate the possibility of a large break loss of coolant accident, major components of the reactor coolant system such as the pressurizer, the reactor coolant pump and steam generators are located inside the reactor vessel in the SMART system as shown in Fig. 5 [14].

Alloy 690 was selected as the candidate material for the heat exchanger tube of the steam generator of SMART [14]. SMART R&D was facing the stage of so-called “engineering verification and approval of standard design” toward application to the prototype DEMO reactor. Therefore, evaluation of material performance under the relevant environment is required. One of the most important material performance issues is fracture toughness for which an engineering database is necessary to design a steam generator. Because the SMART steam generators are located inside the reactor vessel, the degradation of the fracture toughness of the Alloy 690 heat exchanger tube should be clearly determined for a design lifetime. However, the neutron irradiation characteristics of the alloy are barely known. Therefore, irradiation tests of the Alloy 690 materials to obtain the neutron irradiation characteristics of the alloy were successfully performed at HANARO. To obtain the post-irradiation properties of the Alloy 690 specimens, various specimens including standard and sub-size plate tensile specimens, 0.4T compact tension (CT) specimens, hardness, microstructure (Optical and TEM), and thermal diffusivity (TD) specimens were prepared, as shown in Fig. 6.

The fast neutron fluence of Alloy 690 was required to be 1×10^{18} cm^{-2}, 1×10^{19} cm^{-2}, and 1×10^{20} cm^{-2} (E>1.0 MeV), considering the lifetime neutron fluence (1.1×10^{18} cm^{-2}) of the SMART steam generator [15]. To obtain these neutron fluences, three different irradiation capsules were successfully irradiated in the OR and CT test holes of HANARO, as shown in Fig. 7. The target of the irradiation temperature of the specimens was determined as 250 ± 10°C, considering the operating temperature of 247°C-282°C of the steam generator tube with the highest neutron fluence [16].

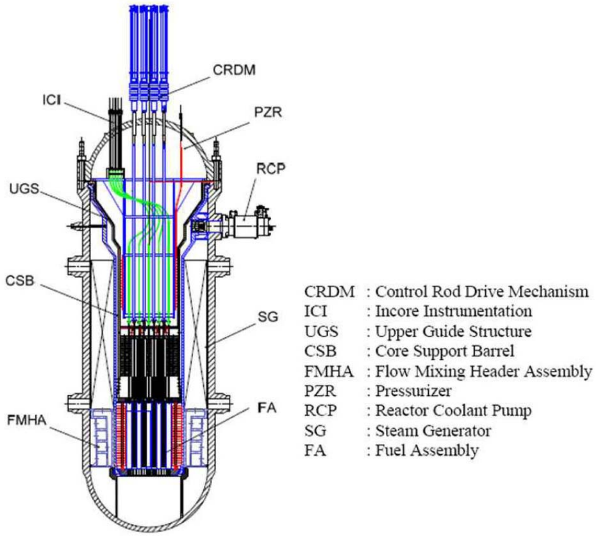

Fig. 5. SMART Reactor Assembly.

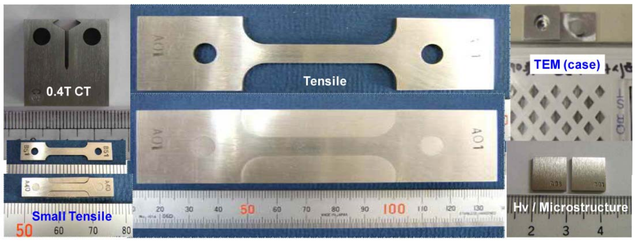

Fig. 6. The Specimens Stacked with Spacers in the SMART Irradiation Capsule.

Fig. 7. Irradiation Test of SMART Capsule at HANARO.

Fig. 8. The Irradiation Capsule of Reactor Materials

The irradiated specimens were tested to evaluate the neutron degradation of the tensile, fracture toughness, hardness, and thermal conductivity properties of the Alloy 690 heat exchanger tube material. The obtained test results were used as useful information to design and evaluate the operational safety of the SMART steam generator. This data was crucial for acquiring the standard design approval of SMART from the Korean licensing authority.

3.3 Contribution to the Research Reactor Project

As a part of the research reactor development's project, irradiation testing of materials used as reflector materials in a research reactor, such as graphite, beryllium and zircaloy-4, was required for up to eight reactor operation cycles at low temperatures (<100°C) of the specimens. Therefore, a new capsule design was prepared for irradiating the reflector materials of research reactors [17]. As the irradiation of the reactor materials was required to be irradiated at low temperature of less than 100°C, the irradiation capsule was designed to be directly cooled by a reactor coolant of 30°C. The capsule was first designed at HANARO to have the coolant flow through the capsule to cool down the irradiation temperature of the specimens as shown in Fig. 8. The capsule has the same outward shape of a typical capsule used for a closed He gas atmosphere.

Based on a preliminary geometrical shape of specimens with different shapes as shown in Fig. 9, a neutron flux and heat generation rates of capsule parts at 30MW thermal power of HANARO were evaluated using MCNP5 code. The specimens with different shapes are basically canned by a tube of 1 mm in thickness made of stainless steel. The surfaces of the canning tubes and the external tube come in contact with cooling water during the irradiation tests. The temperature of the specimens was evaluated using the ANSYS code, and the specimen size and allocation in the capsule were controlled to have low temperatures of less than 100°C regardless of the shape of the specimen and the location in the axial direction of the reactor core.

The safety of a new designed capsule should be fully checked before irradiation testing in the reactor. Based on the basic design of the capsule and nuclear and thermal analysis, an out-pile test capsule was designed and fabricated. To evaluate the soundness of the new capsule design, the capsule was out-pile tested in the single channel out-pile test loop. The capsule was tested and analyzed to satisfy several reactor requirements concerning the coolant flow and the vibration properties.

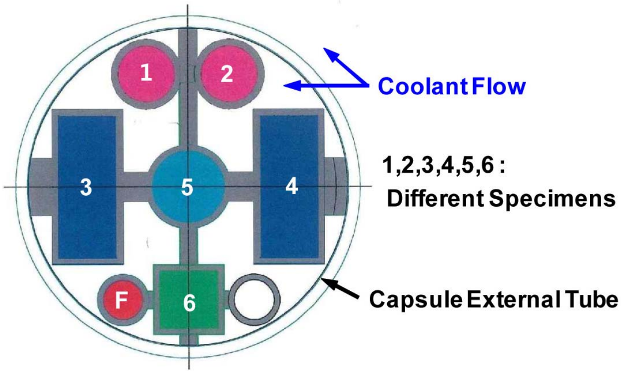

Fig. 9. Schematic Cross Section of the Capsule Main Body

Based on the out-pile test results, two irradiation capsules were designed and fabricated. The irradiation capsules were successfully irradiated for 4 and 8 cycles in the CT and IR2 test holes of HANARO, respectively. Fig. 10 shows the variation of the temperatures of the specimens of a capsule irradiated in the CT Hole of HANARO. The temperatures of the specimens were controlled in the range of 36~56°C during the irradiation. After the irradiation testing of the capsules, PIE (Post Irradiation Examination) on irradiated specimens will be carried out in IMEF (Irradiated Material Examination Facility) to obtain the characteristic data induced neutron irradiation on graphite, beryllium, and zircaloy-4. Then, it is known that this data from irradiated materials will be a contribution in obtaining the license for JRTR (Jordan Research and Training Reactor), a new research reactor in Korea, and exporting research reactors.

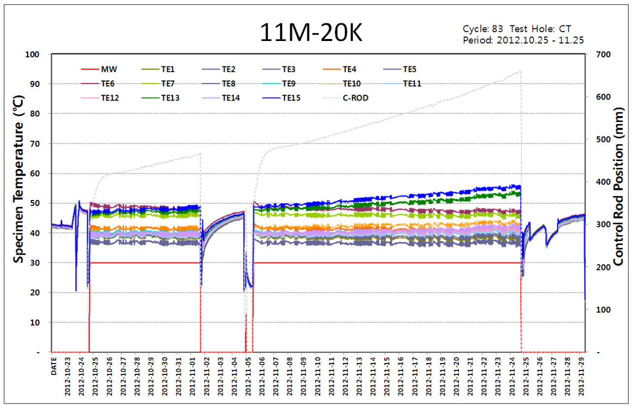

Fig. 10. Variation of the Temperatures of Research Reactor Materials Irradiated in the CT Hole of HANARO.

3.4 Contribution to the R&D of Future Nuclear Reactors

The Generation IV (GEN-IV) International Forum, or GIF, was chartered in July 2001 to lead the collaborative efforts of the world's leading nuclear technology nations to develop next generation nuclear energy systems to meet the world's future energy needs. Among the six GEN-IV systems, Korea has participated in the VHTR and SFR R&D programs. These new advanced nuclear reactor systems inevitably require higher irradiation test parameters than the conventional irradiation tests. Therefore, a strategic irradiation program at HANARO has placed more emphasis on a special purpose capsule system by focusing on the specific material or fuels for a next generation power reactor.

The VHTR is one of the leading reactor designs, developed with participation between Korea and the US. VHTR technology addresses the advanced concepts for a helium gas cooled, graphite moderated, thermal neutron spectrum reactor with a core outlet temperature greater than 900 °C. The VHTR environment is unique, and little data exists on the behavior of materials under irradiation and in the temperature and pressure ranges of interest. At present, no candidate alloy has been confirmed for use as either the cladding, or structural material in VHTRs. To meet these challenges, a GEN-IV R&D plan for the structural materials in VHTRs was initiated as an I-NERI Project, which is a bilateral research agreement between the Ministry of Science and Technology (MOST) of Korea and the Department of Energy of the US [18].

To obtain the proposed test conditions by the joint US/Korea I-NERI Project of 'VHTR Environmental and Irradiation Effects on High-Temperature Materials,' the development of new instrumented capsule technologies for an IP/OR irradiation test and a high-temperature irradiation test was successfully performed at HANARO [2].

9Cr-1Mo and 9Cr-1Mo-1W steels were selected as candidate materials of a reactor pressure vessel of the VHTR, and the OR5 test hole at HANARO was selected as the irradiation test hole. Two HANARO irradiation capsules of the high-temperature materials were successfully designed and irradiated in the OR5 test hole of HANARO. As a reactor pressure vessel material of the VHTR, modified 9Cr-1Mo steel manufactured by USINOR INDUSTEEL (Belgium) and forged 9Cr-1Mo-1W steel manufactured by DHI were procured. Various specimens, such as standard and 1/2-size Charpy and plate tensile specimens of the matrix, welded, and heat affected zone parts made of the steels, were prepared, as shown in Fig. 11.

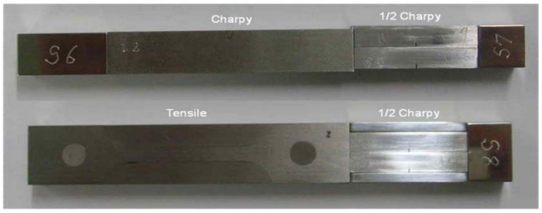

Fig. 11. The VHTR Specimens Stacked with Spacers in the Irradiation Capsules.

HANARO irradiation capsules were irradiated for 1 cycle (about 24 days) in the OR5 test hole of HANARO with a 30 MW thermal output. During the entire irradiation, the measured temperatures of the specimens were consistently maintained in the range of 390±10 °C. A fast neutron fluence of the specimens was obtained in the range of $1.1\text{-}4.4 \times 10^{19}$ cm^{-2} (E>1.0 MeV) depending on the irradiation time and specimen loading orientation in the reactor core. The DPA of the irradiated specimens was evaluated to be 0.03-0.07 using the SPECTOR code. After the irradiation test, the capsules were transported to the IMEF, and the irradiated specimens were mechanically tested for an evaluation of the neutron irradiation properties of the high-temperature materials for the VHTR.

KAERI seeks to develop and demonstrate the technologies needed to transmute the long-lived transuranic actinide isotopes in spent nuclear fuel into shorter-lived fission products, thereby dramatically decreasing the volume material requiring disposal and the long-term radio-toxicity and heat load of high level waste sent to a geological repository [19]. Metallic fuel has its advantages such as simple fabrication procedures, good neutron economy, high thermal conductivity, excellent compatibility with a Na coolant and inherent passive safety. U-Zr-Pu alloy fuels have been used for SFR related to the closed fuel cycle for managing minor actinides and reducing high radioactivity levels since the 1980s. Fabrication technology of metallic fuel for an SFR has been under development in Korea as a national nuclear R&D program since 2007 [19]. An irradiation test of U-Zr and U-Zr-Ce fuels at HANARO had been planned to validate the in-reactor performance. The reduced fuel elements of U-Zr and U-Zr-Ce fuels have been fabricated and irradiated at HANARO since November, 2010.

3.5 Contribution to Basic Research

As a national platform for basic and nuclear research, HANARO irradiation facilities have been actively used for irradiation tests of basic research requested by users from research institutes and universities. The irradiation tests requested from users, as shown in Table 3, have been sponsored by the National Project for Active Utilization of HANARO since 2000. The project has a call for research proposals every year. Proposals submitted through the homepage (http://www.nrf.re.kr) of the National Research Foundation of Korea (NRF) are competitively selected on the basis of an independent peer review that utilizes expert reviews from universities, national laboratories, and industry.

Table 3. Contribution of HANARO Irradiation Facilities on Basic Research

	Research Field	Materials & Topics
Fuel	Mono-crystal NFG products Thermal Diffusion Coefficient	UO_2 / UO_2+Addition Mono-crystal Fission gas release research
	NFG / Grain Boundary Effect	FGR / GB effect research
	Xenon Gas Diffusivity in U-N Fuel	U-Nitride Fuel / Xe Diffusivity
Material	Reactor Structural Materials Irradiation Damage / Recovery	RPV / nano ODS materials Irradiation Damage / Recovery
	Nuclear Fuel Carrier Stack cask Fracture Characteristics	Cask mater. SA240 SS, 350LF3, 508 4N Fracture Analysis, Database
	Zr-based Reactor Core material Micro-structure / Corrosion	Zr-base new alloys, Zr-Nb-Ni-Cr Korean Nuclear Fuel Cladding
	Pro-Environmental RPV material Microstructure of Nano-Materials	Ferritic low alloy steel/HT9M Al alloys, Alumina, Cu-Nb Nano-Composite
	Zr-based Alloys Neutron Irradiation Damage	Zircaloy-4, Zr (Tube, Plate) Cold Working, HT, grain size, ppt, Dislocation
	Zr-based Alloy Embrittlement	Zr-Cu, Zr-Mn Fuel Cladding Materials
	RPV Welds Irradiation Damage	Welding Technology of SA 508 cl.3
	STS deformation Property	STS304, STS430, HLSA
Semi-Conductor	Broad Banded Semi-Conductor Irradiation Defect	WBG Semi-Conductor(ZnO, GaN) Lighting Semi-Conductor
	Pure Silicon Crystal (Wafer) Irradiation Point Defects	Mass Production of Uniform Semi-conductor Phosphorus Distribution / Uniformity
	Degradation of Dielectric Devices	Si Semiconductor, Performance & Credibility
	Irradiation of Oxide Transistor	Oxide TFT, Degradation mechanism
Super-Conductor	Improvement of Superconductivity	YBCO, MgB_2 / Electromagnetic properties
	Superconductivity of MgB_2 by thermal neutron irradiation	MgB_2 / Surface Resistivity & Conductivity
	Optical / Electro-magnetic material Irradiation	$SrTiO_3$, MgO, ZnO Nano lattice defect measurement
Electro-Magnet	Amorphous Ribbon/Wire Magnetic	Fe-Zr amorphous ribbon / Fe-based wire
	Magnetic Semi-Cond. Irradiation	GaMnAs, GaMnN, ZnO Magnetic Semi-Con.
	Multiferroics	$LiFePO_4$, $Li(Ni\text{-}Mn)O_4$, $Cu(Fe\text{-}Ga)O_2$
Others	Neutrino Production	Cr, W, Pd wire
	Stress Evaluation of Irradiated Graphite	Graphite, Physical Properties
	Development of Neutron Detectors	Si/SiC Semiconductor, Severe Environments

Various specimens such as nuclear fuels and materials, and new functional materials including conductors and optical/electrical materials have been irradiated using capsule and rabbit systems. The electro-magnetic and optical properties of the materials are closely dependent on the size and density of their internal defects, and neutron irradiation is a very effective method to produce micro-defects in these materials. Therefore, neutron technology can be applied effectively toward the development of new materials. Recently, several efforts have been made at HANARO to evaluate the effect of neutron irradiation on the physical properties of various functional materials [20].

4. DEVELOPMENT OF ADVANCED IRRADIATION TECHNOLOGIES

Based on the accumulated experience and sophisticated user requirements, several advances in material capsule technologies were made recently for more precise control and analysis of neutron irradiation effects at HANARO. New instrumented capsule technologies, for more precise control of the irradiation temperature and fluence of a specimen, irrespective of the reactor operation, have been developed. OR/IP capsule technologies for an irradiation test in the HANARO reactor, as well as the OR and IP test holes with a relatively lower neutron flux than the CT and IR test holes, have also been developed and successfully utilized [3].

HANARO has been operated as a platform for nuclear researches in Korea, and the functions of its irradiation systems should be improved continuously for future nuclear researches. After the Fukushima nuclear accident in Japan, precise ageing management and safety evaluation of the operating nuclear power reactors, especially of old life-expanded reactors, has become one of most crucial issues in the nuclear industry. Through the construction of a 5MW multipurpose research reactor, called the Jordan Research and Training Reactor (JRTR) and another domestic research reactor in Gijang, the Korean government hopes to be a crucial reactor vendor in the global nuclear market. The new research reactor in Gijang is under construction, and is due to start up in 2017. The new research reactor will become the most up-to-date research reactor available in the world and will specialize in radioisotope and NTD production and demonstrations of reactor designs. Therefore, HANARO will specialize more on irradiation research of nuclear fuels and materials. 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 present day reactor technology, especially regarding the combinations of operating temperatures, reactor coolant characteristics, and neutron flux and spectra.

To effectively support the national R&Ds relevant to the present NPP, research/SMR reactors, and future nuclear systems, the development of advanced irradiation technologies concerning irradiation temperature and instrumentation is being preferentially developed at HANARO. After operation of the new research reactor in Gijang, HANARO is supposed to be specialized more in irradiation research. For an activation of irradiation researches, a new 5-year research and development project was started at HANARO from June of this year. The R&D can be classified into three main groups, i.e., an improvement of both irradiation and analysis technologies, and the development of new technology for future reactor systems. The available irradiation temperature will be extended up to 100-1,000°C, and several key instruments such as thermocouple, LVDT, and SPND will be localized at HANARO. The precision of analyzing technology of neutron flux and fluence will be improved, and new irradiation technology needed to test advanced nuclear fuels and materials for the VHTR, SFR, and Fusion systems will be developed in the next five years. In addition, the research status and possibility of new electro-magnetic materials using neutron irradiation will be surveyed to ascertain a utilization of neutron irradiation technology in high-tech material industries. The study of irradiation influence on the materials is generally known to allow unique information about the electron states, electro-magnetic interaction, etc. Therefore, the foundation for the research of materials using neutron irradiation has a great possibility in the field of original information of electro-magnetic materials, promising a creation of future industry. It is necessary to strengthen international cooperation for enhancing the status of HANARO in the field of advanced material researches by neutron irradiation. Fig. 12 shows the R&D schedule of irradiation technology at HANARO.

5. CONCLUSIONS

HANARO irradiation facilities such as capsule and rabbit systems have been developed and are actively being utilized for the irradiation testing of fuels and materials of commercially operating nuclear reactors in Korea. Although HANARO has been applied in several commercial-based irradiation tests, most irradiation tests have been related to national R&D projects relevant to present nuclear power reactors. HANARO has recently supported R&D projects relevant to SMART, research reactors, and future nuclear systems. Based on the accumulated experience and sophisticated requirements of users, HANARO has started a new R&D of irradiation technology such as an improvement of the irradiation and analysis technology, and the development of new technology for future reactor systems. It includes the extension of the available irradiation temperature, the localization of several key instruments, improvement of analyzing technology of neutron flux and fluence, development of new irradiation technology for future nuclear systems, and foundation for research of advanced materials using neutron irradiation.

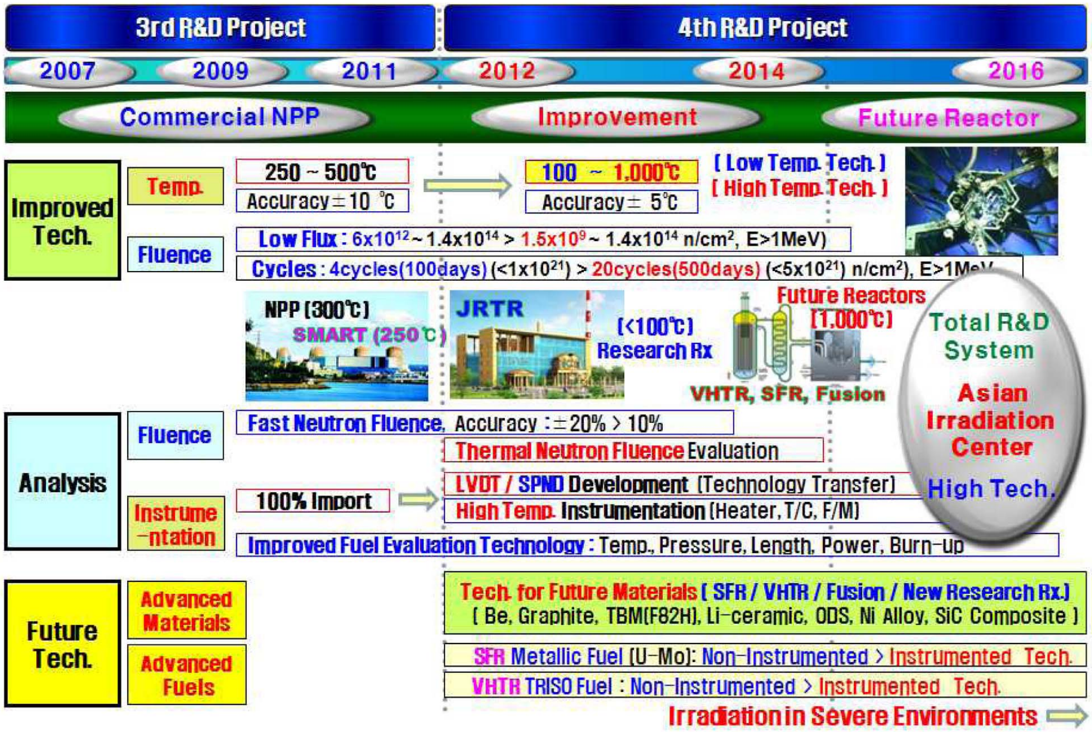

Fig. 12. Schedule of Irradiation Technology Development at HANARO.

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