DEVELOPMENT STATUS OF IRRADIATION DEVICES AND INSTRUMENTATION FOR MATERIAL AND NUCLEAR FUEL IRRADIATION TESTS IN HANARO

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The High flux Advanced Neutron Application ReactOr (HANARO), an open-tank-in-pool type reactor, is one of the multi-purpose research reactors in the world. Since the commencement of HANARO's operations in 1995, a significant number of experimental facilities have been developed and installed at HANARO, and continued efforts to develop more facilities are in progress. Owing to the stable operation of the reactor and its frequent utilization, more experimental facilities are being continuously added to satisfy various fields of study and diverse applications. The irradiation testing equipment for nuclear fuels and materials at HANARO can be classified into capsules and the Fuel Test Loop (FTL). Capsules for irradiation tests of nuclear fuels in HANARO have been developed for use under the dry conditions of the coolant and materials at HANARO and are now successfully utilized to perform irradiation tests. The FTL can be used to conduct irradiation testing of a nuclear fuel under the operating conditions of commercial nuclear power plants. During irradiation tests conducted using these capsules in HANARO, instruments such as the thermocouple, Linear Variable Differential Transformer (LVDT), small heater, Fluence Monitor (F/M) and Self-Powered Neutron Detector (SPND) are used to measure various characteristics of the nuclear fuel and irradiated material. This paper describes not only the status of HANARO and the status and perspective of irradiation devices and instrumentation for carrying out nuclear fuel and material tests in HANARO but also some results from instrumentation during irradiation tests.

KEYWORDS : HANARO, Irradiation Devices, Instrumentation, Materials, Nuclear Fuels

1. INTRODUCTION

The High flux Advanced Neutron Application ReactOr (HANARO) is a multi-purpose research reactor of an open-tank-in-pool type with 30MW of thermal power. Its general design features are given in Table 1. Detailed information is available in the International Atomic Energy Agency (IAEA) Research Reactor Data Base (RRDB) or at the HANARO home page (http://hanaro.kaeri.re.kr).

Since the commencement of HANARO's operation in 1995, some parts of the reactor systems have been gradually improved for the continued stable operation of the reactor, while the operation mode has been flexibly adjusted to meet user demands [1]. The reactor is now being successfully utilized in such areas as neutron beam research, fuel and materials irradiation tests, radioisotopes production, neutron activation analysis, and neutron transmutation doping, etc. A significant number of experimental facilities have been developed and installed since the beginning of the reactor's operation, and continued efforts to develop more facilities are in progress. As new experimental facilities are added, HANARO has seen a

Table 1. General Design Features of HANARO

Reactor Type	Open-Tank-In-Pool
Thermal Power	30 MW
Thermal Neutron Flux (Max.)	5.4×10^{14} n/cm^2-s (E<0.625eV)
Fuel Element	19.75% enrichment, U_3Si-Al Matrix, Al Clad
Coolant	H_2O
Moderator	H_2O/D_2O
Reflector	D_2O
Core Cooling	Upward Forced Convection Flow
Absorber Material	Hafnium

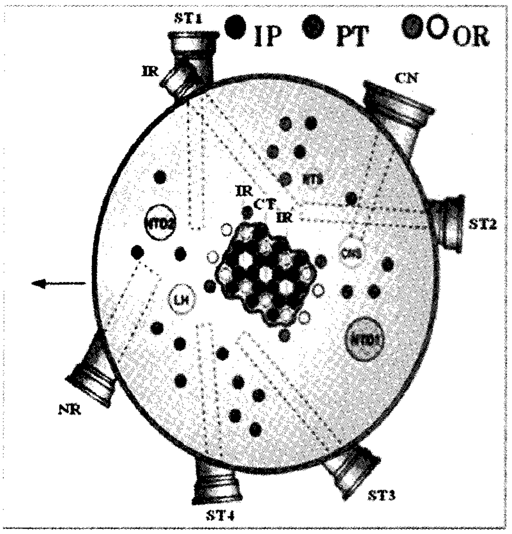
rapid growth in its utilization in terms of the number of users as well as the fields of application. In other words, HANARO has established its status as a national neutron research facility. The internationally competitive experimental facilities of the reactor and the support of the government for HANARO users have promoted new researches in a wide range of areas to include the use of neutrons in research activities, and the volume of this new research is reflected in the high annual growth record of HANARO's utilization. An international symposium on research reactors and neutron science was held in commemoration of the 10th anniversary of HANARO in 2005 [2,3]. Irradiation devices, such as capsules for irradiating nuclear fuel and material under various conditions and a fuel test loop (FTL) for irradiating nuclear fuel under the operating conditions of commercial nuclear power plants, have been continuously developed at HANARO since its start of operation.

2. HANARO AND TESTS HOLES

HANARO was designed to provide a peak thermal of 5.4×10^{14} n/cm^2·sec (E<0.625eV) and a fast flux 2.1×10^{14} n/cm^2·sec (E>1.0MeV) at 30MW of thermal power. Since the achievement of HANARO's initial criticality in February 1995, some parts of the reactor systems have been improved gradually for the stable operation of the reactor, while the operation mode has been flexibly adjusted to meet user demands. Currently, HANARO is at its full power capacity of 30 MW, up from a conditional operation at 24 MW, and follows an established operation mode of 24 days of operation followed by an 11-day shutdown. Up to now, a significant number of experimental facilities have been developed and installed for the use of the 32 vertical holes and the 7 horizontal beam ports, and are successfully being utilized. The arrangement of the vertical holes and the beam ports are shown in Fig. 1.

Three flux traps in the core (CT; Central Flux Trap, IR1 and IR2; Irradiation Hole in the Inner Core), providing a high fast neutron flux, can be used for material and fuel irradiation tests. They are also suitable for the production of high specific activity radioisotopes (RI). Four vertical holes (OR) in the outer core region, abundant in epithermal neutrons, are used for the fuel or material irradiation tests and radioisotope production. Several isotope production (IP) holes of the 25 vertical holes which have high quality neutrons are also used to irradiate materials and nuclear fuels in the heavy water reflector region. Thermal and fast neutron fluxes of these test holes are listed in Table 2.

There are 7 horizontal beam ports (NR; Neutron Radiography Beam Tube, ST1~ST4; Standard Beam Tube, CN; Cold Neutron Beam Tube, IR; Irradiation Beam Tube) of different types available for researches on neutron scattering, neutron radiography, prompt gamma neutron activation analysis (PGAA) and medical applications such as a boron neutron capture therapy (BNCT). A number of experimental facilities have been developed and installed



(CNS; Cold Neutron Housing Hole, NTD; Neutron Transmutation Doping Hole)

Fig. 1. Core Arrangement of HANARO

Table 2. Neutron Flux of Vertical Test Holes

Location	Hole		Inside Dia. (cm)	Neutron flux(n/cm^2•sec)		Remarks
	Name	No.		Fast (>0.82MeV)	Thermal (<0.625eV)	
Core	CT	1	7.44	2.10×10^{14}	4.39×10^{14}	Fuel/Mat. Irradiation and RI Production
	IR	2	7.44	1.95×10^{14}	3.93×10^{14}	
	OR	4	6.00	2.23×10^{13}	3.36×10^{14}	
Reflector	LH*	1	15.0	6.62×10^{11}	9.77×10^{13}	Fuel/Mat. Irradiation and RI Production
	HTS*	1	10.0	9.44×10^{10}	4.79×10^{13}	
	IP	17	6.0	1.45×10^{9} ~2.10×10^{12}	2.40×10^{13} ~1.95×10^{14}	

* LH; Large Hole in the Reflector, HTS; Hydraulic Transfer System

since the beginning of the reactor operation, and efforts for developing additional facilities continue. As new experimental facilities such as the FTL and the Cold Neutron Research Facility (CNRF) have been added, there has been a rapid growth of user facilities and in the nature of applications. In other words, as a nation-wide neutron research facility, HANARO facilities, bolstered by governmental support, have promoted and attracted international participation in a wide range of research activities, including in irradiation tests of nuclear materials.

3. IRRADIATION DEVICES AND INSTRUMENTATION

According to function and application, irradiation equipment at HANARO may be classified as either capsules or the FTL. Capsules for irradiation tests of nuclear fuels and materials have been developed and then extensive efforts have been expended to establish irradiation and instrumentation technologies for irradiating nuclear fuels and materials by using capsules and associated systems which are compatible with HANARO's requirements. Devices for fixing capsules during an irradiation test, and for cutting and transporting a capsule's main body after irradiation were also developed, and so the developed capsules have been well utilized for various tests requested by users or customers. Based on accumulated experience and increasingly sophisticated user requirements, capsules for performing creep testing or fatigue testing of materials have also been developed during irradiation at HANARO. The irradiation plans related to Gen-IV reactor systems development, such as sodium-cooled fast reactors (SFRs) and very high-temperature reactors (VHTRs), will put even more emphasis on developing capsules and instrumentation focusing on irradiation tests of materials or fuels for Gen-IV reactor systems in Korea. The FTL is one such irradiation device, and can conduct an irradiation test for a nuclear fuel in HANARO under the operating conditions of commercial nuclear power plants. Three test fuel rods can be installed with instrumentation, such as thermocouples and LVDTs, and can be simultaneously irradiated in HANARO by using the FTL. The installation of the FTL was completed in March 2007, and the commissioning test was finished in September, 2009. Its first use will be for an irradiation test of an advanced nuclear fuel for a pressurized water reactor (PWR) in the near future.

3.1 Capsule [4-10]

One type of irradiation device which can be used in the evaluation of the irradiation performance of nuclear and high-technology materials at HANARO is the capsule. The main activities of the capsule development and utilization programs at HANARO are focused on in-reactor material tests, new and advanced nuclear fuel research and development, safety-related research and development for nuclear reactor materials and components, and basic research. There are three kinds of capsules for material and nuclear fuel irradiation testing: a non-instrumented capsule, an instrumented capsule and an advanced capsule to perform creep testing or fatigue testing, etc. At present, capsules have been developed and are being utilized for the irradiation tests of materials and nuclear fuels at HANARO, and have also been developed to study the creep or fatigue behavior of materials.

A non-instrumented capsule for material or nuclear fuel irradiation testing is typically about 1 m in length and 60 mm in diameter. A variety of specimens can be included in 5 stages to installing specimens in non-instrumented capsule, which is developed in 1998 for material irradiation testing. The temperature of the material specimens is controlled by varying the widths of gas-filled gaps between the specimens and the specimen holders, and the temperature of specimens and the fluence are evaluated by temperature monitors such as eutectic alloys and passive F/Ms, respectively. A non-instrumented capsule for a nuclear fuel irradiation test was developed in 1999 and has been utilized for irradiation characteristics testing at HANARO of the Direct Use of PWR spent fuel in CANDU (DUPIC) fuel and of advanced fuel pellets for a PWR.

The development of instrumented irradiation capsules and related technology started in 1995. The first instrumented capsule was installed to irradiate some materials at HANARO in 1998. Now, this capsule has an important role in the evaluation of the integrity of reactor core materials and in the development of new materials through the irradiation testing of specimens such as reactor pressure vessels (RPVs), reactor cores, pressure tubes, fuel cladding and high-technology materials. A typical instrumented capsule for a material irradiation test at HANARO is shown in Fig. 2. An instrumented capsule is cylindrical and its main body is 60mm in diameter and 870mm in length. The basic instruments of the capsule, provided to fulfill user requirements, are thermocouples, fluence monitors and heaters. The temperature of the specimens in 5 stages , to installing specimens in instrumented capsule, is independently controlled by a temperature control system. The main utilization fields of these capsules are 1) irradiation tests and damage evaluation of a pressure vessel, reactor core, and high-technology materials, etc., 2) safety/integrity evaluation and life-extension researches of a commercial reactor and the production of design data for new nuclear materials for next generation nuclear power reactors, and 3) basic researches on irradiation effects on materials.

Instrumented capsules are also suitable to study the irradiation characteristics of nuclear fuel pellets and to obtain in-core performance and design data for nuclear fuels. A typical instrumented capsule for a nuclear fuel irradiation test at HANARO is shown in Fig. 3. An instrumented capsule is installed in the OR4 or OR5 test hole of HANARO; its main-body is 56mm in diameter and about 1 m in length, and its total length is about 5m, including the protection tube. The capsule includes several

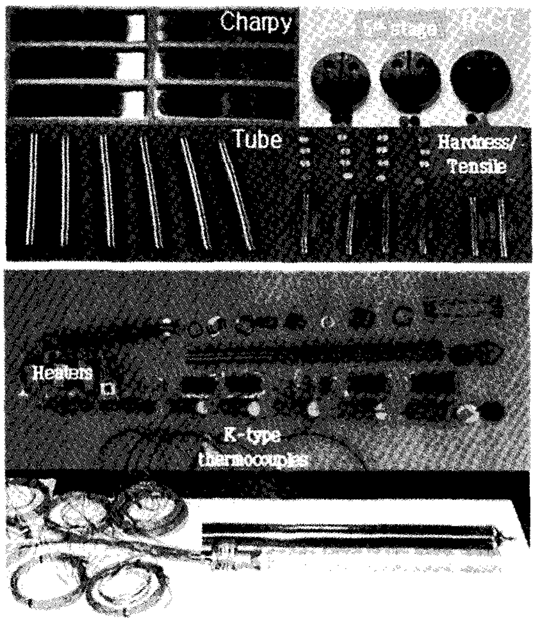


Fig. 2. Instrumented Capsule for Material Irradiation

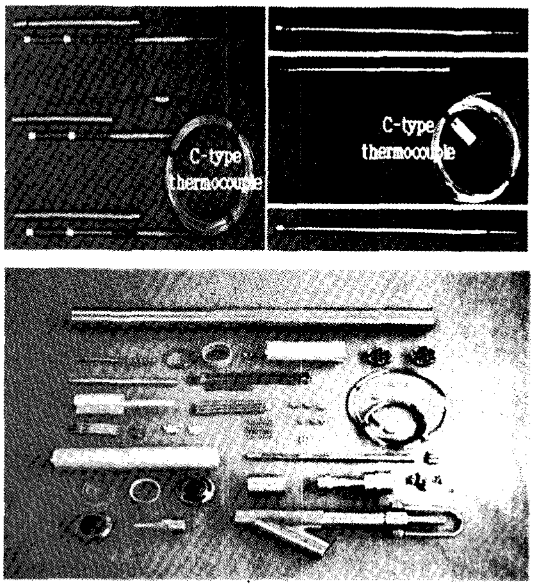


Fig. 3. Instrumented Capsule for Nuclear Fuel

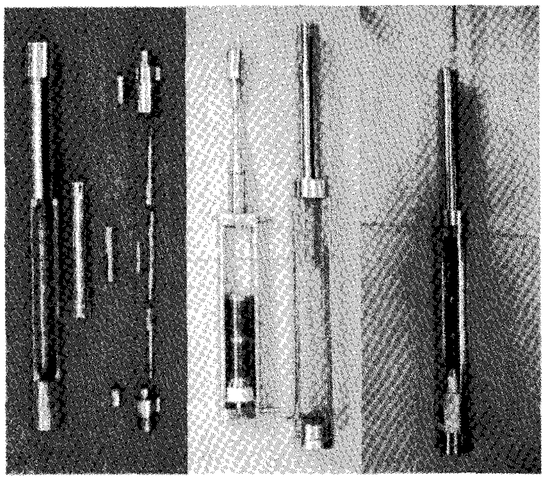


Fig. 4. Capsule for a Creep Test

test fuel rods instrumented with thermocouples, pressure transducers and elongation detectors to measure the fuel temperature, the internal pressure of a fuel rod, and the fuel deformation, respectively. The SPNDs are to detect the neutron flux during irradiation. The design verification test of an instrumented capsule was completed in one of HANARO's test holes in 2003. Now, the instrumented capsule is used to measure the fuel temperature, the internal pressures of fuel rods, the fuel deformation, and neutron flux during a fuel irradiation test. The utilization fields of this capsule are as follows: 1) irradiation of a nuclear fuel for DUPIC, advanced PWR and CANDU; 2) study on the in-core characteristics of a UO_2 pellet and a UO_2 pellet including additives, and basic study on fission gas release, etc.

In 2002, a creep capsule was developed to obtain the creep characteristics of a nuclear material during irradiation, and the capsule has since been improved to increase the number of testable specimens. A typical capsule for a creep test at HANARO is shown in Fig. 4. A fatigue capsule was also developed in 2005. In order to realize various requirements and obtain reliable data from creep testing or fatigue testing, the design and the instrumentation of these capsules are under modification. Additional advanced capsules will be continuously developed to support the development of nuclear materials and nuclear fuel for Gen-IV reactor systems.

3.2 Fuel Test Loop (FTL)

The FTL can simulate commercial NPPs' steady state operating conditions such as their pressure, temperature, flow, water chemistry conditions and neutron flux levels to conduct irradiation and thermo-hydraulic tests [11]. The conceptual design of the FTL was initiated at the end of 2001 and both the basic and detailed designs were finished in March 2004. The installation of the FTL was completed successfully in March 2007, and its commissioning test to obtain the licence for normal operation from the regulatory body was successfully performed.

The FTL provides high pressure and high temperature test conditions similar to the real conditions of commercial PWR and CANDU reactors. It is composed of an out-pile system (OPS) and an in-pile test section (IPS). The OPS includes a process system and an instrumentation and control (I&C) system. The IPS is loaded into the IR1 position in the HANARO core. The coolant is supplied to the IPS at the required temperature, pressure and flow conditions that are consistent with a test fuel. The nuclear heat generated

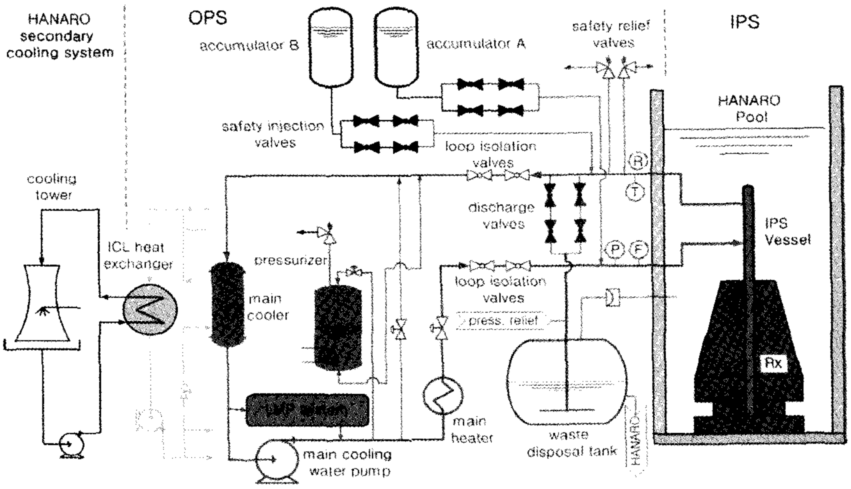


Fig. 5. Schematic Diagram of the FTL

within the IPS is removed by the main cooling water. Fig. 5 shows a schematic diagram of the FTL.

The process system contains several components, such as a pressurizer, a cooler, a heater, pumps, and a purification system, which are necessary to maintain the proper fluid conditions. The main circulating pump provides the necessary power to circulate the FTL coolant within the loop. After a pump discharge, an in-line heater provides the capability to increase the temperature for a start-up and for positive temperature control. A pressurizer is provided to establish and maintain the coolant pressure for a test fuel type. The process system includes the following systems [12]: the main cooling water system, the emergency cooling water system, the penetration cooling water system, the letdown, makeup, and purification system, the waste storage and transfer system, the intermediate cooling water system, the test loop sampling system, the IPS inter-space gas filling and monitoring system, and miscellaneous systems. The main test conditions for the FTL are given in Table 3. The I & C system has the following functions [13]: maintaining the irradiation test conditions by an automatic control, HANARO trip and FTL safe shutdown during transient or accident conditions, simultaneous operation of the FTL with HANARO, and data acquisition from the IPS.

In order to verify the performance of the FTL after its installation, the commissioning test of the FTL was initiated in April 2007. Its commissioning test was performed in three stages. An individual system performance test under room temperature was performed in the first stage, and the integral system performance test with mock-up fuels under a high temperature was performed in the second stage; finally, the integral system performance test with test fuels under a high temperature was performed in the third stage. The individual system performance test was successfully completed. The integral system performance test as a trial test with test fuels under a high temperature was completed at the end of September 2009. At that time, three SPNDs were installed in the upper, middle and lower parts of the irradiated section, three thermocouples were installed at the inlet, middle and outlet points of the test rig, an LVDT was installed to measure the fission product pressure, and thermocouples were installed to measure the centreline temperature of a test fuel. The irradiation tests for the PWR's fuels will be started in the near future.

Table 3. Main Test Conditions in the FTL

Test conditions	Value
Operation cycles a year	9
Operation cycle length (EFPD/cycle)	24
Number of test rods	3
LHGR (W/cm)	≤ 320
Peak to average heat generation rate	≤ 1.16
Fast neutron flux in cladding surface (n/cm^2·sec)	1.2×10^{14}
Coolant temperature (°C)	300 ~ 308
Coolant pressure (kg/cm^2)	150 ~ 159
Coolant flow (kg/s)	1.52 ~ 1.8
B concentration (ppm)	≤ 1500
Dissolved oxygen concentration (ppm)	≤ 0.1
pH at 300°C	5.5 ~ 8.0
Electric conductivity (μS/cm)	≤ 50
Cl and F concentration (ppm)	≤ 0.2

3.3 Instrumentation

Figs. 2 & 3 show the typical instrumented capsules for the irradiating materials and nuclear fuels before assembling. As shown in Fig. 2, K-type thermocouples and small heaters are used to control and measure the temperature of the specimens during the irradiation of materials, and F/Ms are used to estimate the fast neutron fluence (E > 1.0 MeV) after an irradiation test. Typical cross-sections of the instrumented capsules for the materials irradiation tests are shown in Fig. 6. In addition, two kinds of thermocouples (K- and C-type), LVDTs and SPNDs are installed in an instrumented capsule to measure certain characteristics during the irradiation of the nuclear fuels, such as surface and centerline temperatures of UO_2 pellets, internal pressures of fuel rods, deformation of UO_2 pellets and thermal neutron flux, as shown in Fig. 3. A schematic cross-section of an instrumented capsule for a nuclear fuel irradiation test is shown in Fig. 7.

In-pile tests of materials and nuclear fuels by using these capsules and instrumentation have been performed at HANARO. K-type thermocouples and small heaters are used in the instrumented capsules to control and measure the temperature of these specimens, and they have been found to be stable from a test series of up to 4 months duration at about 300°C ~ 400°C and 24 MW ~ 30 MW thermal power at HANARO. Fig. 8 shows the typical temperature of specimens measured by 14 thermocouples during an irradiation test of one operating cycle (24.6 operating days) at 30MW thermal power at HANARO. As shown in Fig. 8, the measured temperatures are very stable because the temperatures were monitored and controlled via 5 small heaters and the He gas pressure, and because the irradiation duration was short. However, the degradation of the thermocouples and small heaters induced by neutron irradiation was not detectable during this irradiation. In addition, several measured results using C-type thermocouples, LVDTs and SPNDs for UO_2 pellets during an irradiation at 24 MW and 28 MW of thermal power were also stable, as shown in Figs. 9 to 11. During an irradiation test, some degradation and drift of the instrumentation were found between operating cycles (a) and (b) at HANARO, as shown in these figures. According to the Idaho National Laboratory (INL) results [14,15], commercial K- and N-type thermocouples could have drifted by > 100 °C or 8% after a heat treatment at

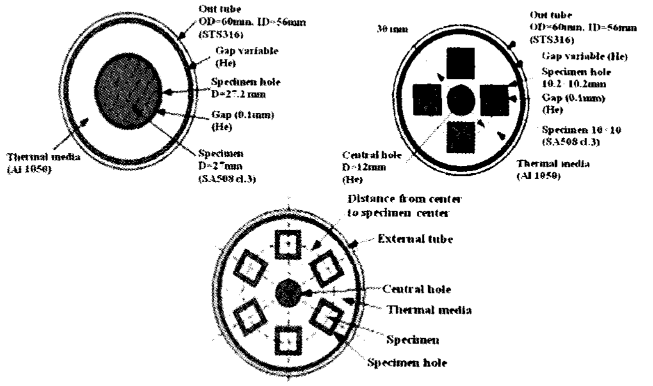


Fig. 6. Typical Cross-sections of Instrumented Capsules for Material Irradiation Test

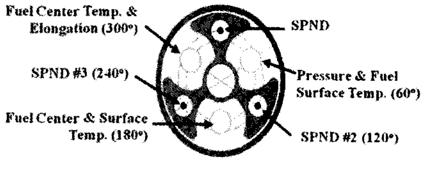


Fig. 7. Schematic Cross-section of Instrumented Capsule for Nuclear Fuel Irradiation Test

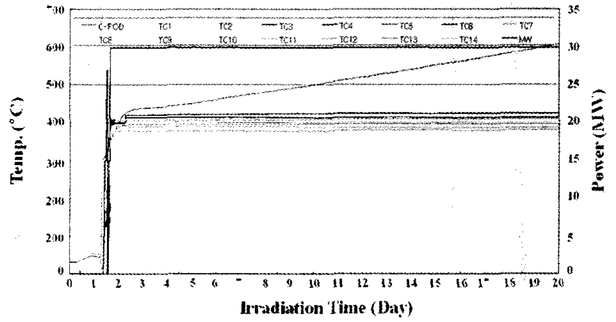
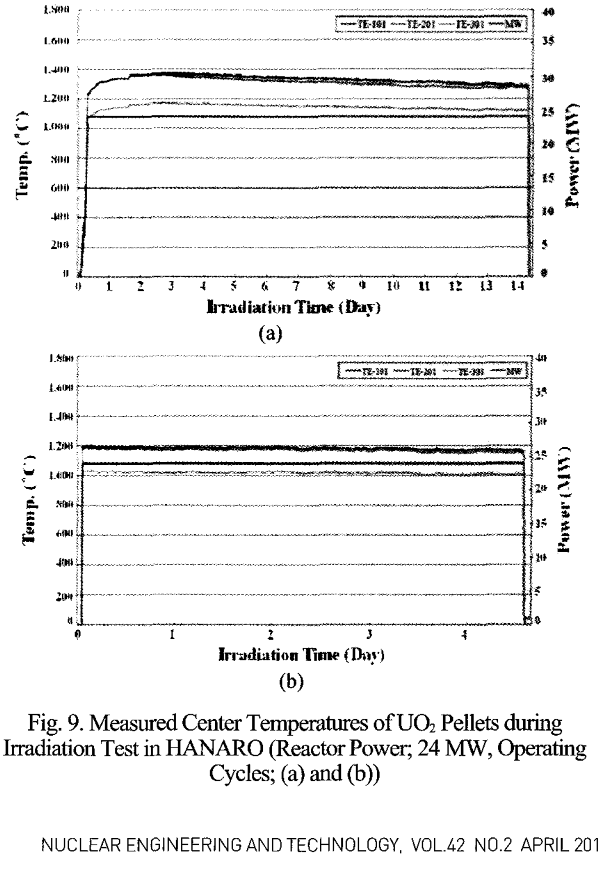


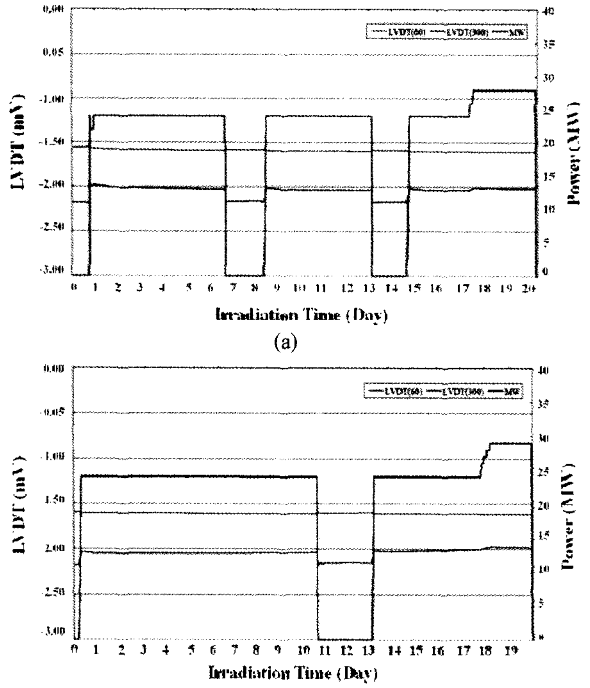
Fig. 8. A Typical Temperature of Specimens Measured during Irradiation Test of one Operating Cycle of HANARO. (Reactor Power; 30 MW)



(a)

(b)

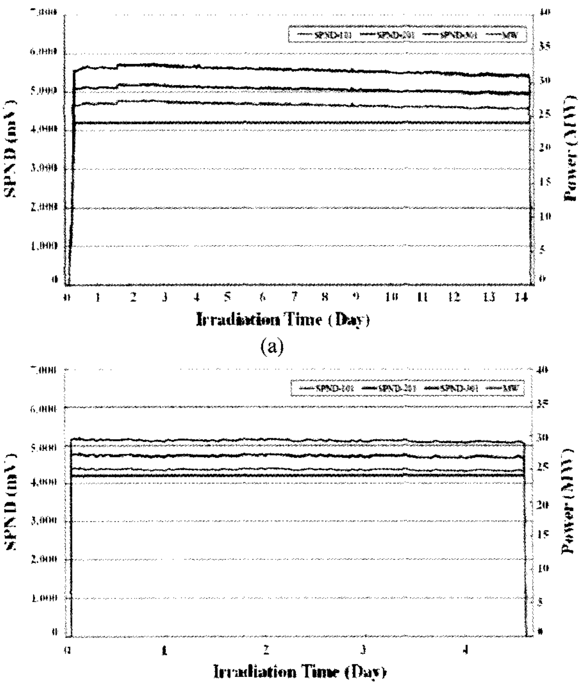
Fig. 9. Measured Center Temperatures of UO_2 Pellets during Irradiation Test in HANARO (Reactor Power; 24 MW, Operating Cycles; (a) and (b))



(a)

(b)

Fig. 10. Measured Data from LVDTs during Irradiation in HANARO (Reactor Power; 24 to 28 MW, Operating Cycles; (a) and (b))



(a)

(b)

Fig. 11. Measured Data from SPNDs during Irradiation in HANARO (Reactor Power; 24 MW, Operating Cycles; (a) and (b))

1200°C in a furnace. In the case of the commercial C-type thermocouple, it drifted nearly 100 °C in fluences exceeding 10^{21} c/cm^2; that is, it degraded at temperatures above 1100 °C or transmuted during irradiation [16]. However, the linear degradation of the Type C response is not always the case because the drift is very dependent upon the flux and temperature gradient to which the thermocouple is exposed. The temperature of the LVDT should not exceed the Curie temperature during irradiation. Then, the property of the magnetic material can be preserved during irradiation. The output from the SPND is also very dependent upon the flux and temperature gradient to which the SPND is exposed.

In order to yield more reliable data on the materials and nuclear fuels subjected to irradiation testing at HANARO, it is necessary to establish a re-calibration method for the testing instrumentation between the operating cycles of HANARO [17] and to understand the characteristics of the thermocouples, LVDT and SPND, etc., under neutron irradiation. Therefore, a relevant study was initiated which will incorporate international cooperative study if necessary.

Moreover, the irradiation plans related to Gen-IV reactor systems development, such as SFRs and VHTRs will require more emphasis on developing capsules and instrumentation focusing on irradiation tests of materials or fuels for Gen-IV reactor systems in Korea. In order to support the development of materials and nuclear fuels for Gen-IV reactors, an internal design of capsules has to be prepared and sensors suitable for irradiating in aggressive conditions are also needed. Related international efforts, e.g. at Commissariat à l'Énergy Atomique (CEA) in France, at the Advanced Test Reactor (ATR) in the US, and at the Halden Reactor Project (HRP) in Norway, are described in the references [18-20].

3.4 PIE Facilities

There are two facilities to perform a post-irradiation examination (PIE) at the Korea Atomic Energy Research Institute (KAERI). These are the Irradiated Material Examination Facility (IMEF) and the Post-Irradiation Examination Facility (PIEF). Detailed information about these facilities is available at the KAERI home page (http://www.kaeri.re.kr).

4. CONCLUSIONS

Since the commencement of HANARO operations in 1995, a significant number of experimental facilities have been developed and installed to make efficient use of the 3 vertical holes in the inner core region, the 4 vertical holes in the outer core region, the 25 vertical holes in the heavy water reflector region, and the 7 horizontal beam ports. As a platform for basic nuclear research in Korea, HANARO is now being successfully utilized in various fields such as neutron beam research, nuclear fuels and materials irradiation testing, radioisotope production, neutron activation analysis, and neutron transmutation doping, etc.

Capsules for the irradiation testing of materials and nuclear fuels have been developed and successfully used, and the development of capsules, irradiation and instrumentation technology will be continuously carried out to support the development of the Gen-IV reactor systems in HANARO. The commissioning test of the FTL was finished in September 2009. Therefore, both the capsules and the FTL will be used for materials and nuclear fuel irradiation tests in HANARO and will contribute to maximizing the utilization of HANARO. In order to obtain more reliable data from test instrumentation during the irradiation of materials and nuclear fuels in HANARO, a method for re-calibration of the instrumentation is being developed. Efforts are also being extended to support the development of materials and nuclear fuels for Gen-IV reactor systems by designing advanced capsules and instrumentation technology suitable for irradiating in aggressive conditions in HANARO.

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