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Capsule Irradiation Tests of Non-Fissile Materials in HANARO

K.N. Choo, J.M. Sohn, B.G. Kim, Y.T. Shin, J.M. Oh, I.C. Lim, Y.H. Kang

Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseong-ku, Daejeon 305-353, Korea 17 Haengdang, Sungdong

Abstract

The R&D programs on the nuclear reactor materials require numerous in-pile tests in HANARO. Extensive efforts have been made to establish design and manufacturing technology for the development of irradiation facilities. Material capsule and rabbit(small non-instrumented capsule) systems were developed for the irradiation test of non fissile materials in HANARO. Several irradiation capsules (8 instrumented and 2 non-instrumented capsules) and rabbits(17 rabbits) has been designed, fabricated and successfully irradiated in HANARO CT, IR, HTS or IP test holes since 1995. Capsules were designed for the irradiation of RPV (Reactor Pressure Vessel), reactor core materials, and Zr-based alloys. Most capsules were made for KAERI material research projects, but 3 capsules were made as a part of national projects for the promotion of HANARO utilization. Rabbits were used for the irradiation of semi-conductors(Si, Sapphire) and magnetic materials. 3,300 specimens from domestic 13 research institutes, 2 nuclear industry companies and 51 universities, were irradiated in HANARO for 26,000 hours using capsule and rabbit irradiation systems. Through this research, the nuclear characteristics of HANARO capsules and rabbits were also produced and piled up in our database.

1. Introduction

Various irradiation facilities such as the rabbit(small non-instrumented capsule) 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(High flux Advanced Neutron Application ReactOr) [1]. Among the irradiation facilities, a capsule is the most useful system to cope with various test requirements. Instrumented and non-instrumented capsules have been developed at HANARO for new alloy and fuel developments and life time estimation of nuclear power plants. Extensive efforts have been made to establish design and manufacturing technology for the capsule and temperature control system, which should be compatible with HANARO's characteristics [2-12]. 8 instrumented and 2 non-instrumented capsules were designed, fabricated and successfully irradiated since the first non-instrumented capsule (96M-01K). The capsule related systems including capsule temperature controlling system, supporting system and cutting system were also developed. The rabbit irradiation system in HTS(Hydraulic Transfer System) and IP(Irradiation Position) holes that was originally designed for RI Production can be used for the irradiation of small sized specimens in the lower neutron flux condition than capsule system.

The main activities of the capsule development and utilization programs are focused on in-reactor material test, new and advanced fuel research and development, safety-related research and development for nuclear reactor(commercial and next-generation) materials and components, and basic irradiation research of university. Most capsules were made for KAERI material research projects, but 3 capsules were made as a part of national projects for the promotion of HANARO utilization started in 2000. Rabbits were used for the irradiation of semi-conductors(Si, Sapphire) and magnetic materials requested by universities.

In this paper, current status of non-fissile material irradiation test and recent capsule development direction in HANARO are described.

2. Development of Irradiation Capsule

2.1. HANARO Reactor

The High-flux Advanced Neutron Application Reactor (HANARO) is a multi-purposed testing reactor located in KAERI, Korea. It was designed to provide a peak thermal flux of $5x10^{14}$ n/cm^2.sec. The core features a combination of light-water cooled/moderated inner core and light-water cooled/heavy-water moderated outer core. The inner core has 28 fuel sites and 3 test sites. 3 test sites are in hexagonal shapes and used for capsules. 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 core of HANARO, and LH(Large Hole), HTS(Hydraulic Transfer System) and IP(Irradiation Position) in reflector region of the reactor for nuclear fuels/materials irradiation testing, as shown in Fig. 1,2. Table 1,2 show characteristics of reactor and test holes for fuel/material irradiation in HANARO.

Table 1. Reactor specifications

Type	Open-tank-in-pool
Maximum thermal power	30 MW
Coolant	Light water
Reflector	Heavy water
Fuel material	U_3Si in aluminum matrix, 19.75 w/o enriched
Absorber material	Hafnium
Secondary cooling	Cooling tower
Reactor building	Confinement

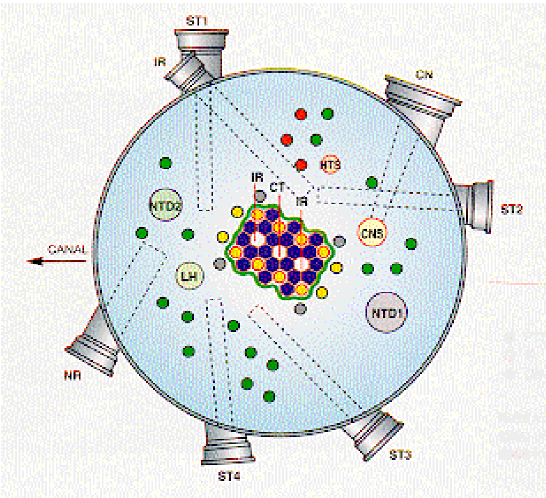

Fig. 1. Core configuration of HANARO

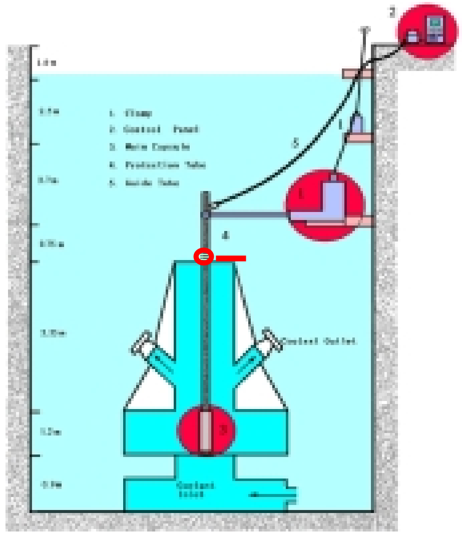

Fig. 2. Schematic view of HANARO capsule system

Table 2. Characteristics of test holes for fuel/material irradiation in 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 IR OR	1 2 4	7.44 7.44 6.00	2.10×10^{14} 1.95×10^{14} 2.23×10^{13}	4.39×10^{14} 3.93×10^{14} 3.36×10^{14}	Fuel/material test Fuel/material test Fuel/material test, isotope production
Reflector	LH HTS IP	1 1 17	15.0 10.0 6.0	6.62×10^{11} 9.44×10^{10} 1.45×10^{9} - 2.20×10^{12}	9.77×10^{13} 47.97×10^{13} 2.40×10^{13} - 1.95×10^{14}	Fuel/material test Isotope, fuel/semi-conductors tests ”

2.2. Rabbit and Non-Instrumented Capsule

The rabbit(small non-instrumented capsule) was originally designed for the isotope production, but it can be used for the irradiation test of fuel and material. Fig. 3 shows the typical rabbit(20mm in diameter and 30mm in length) inserted in the HTS(Hydraulic Transfer System) hole. It is very useful for the numerous irradiation tests of small specimens at low temperature(below 200^{o}C) and neutron flux condition.

The first non-instrumented capsule for material irradiation testing was designed, fabricated and successfully irradiated in the CT test hole of HANARO in 1995. The non-instrumented capsule is typically 1m in length and 60mm in diameter. Specimen temperatures are designed by the pressure and widths of He gas filled gaps between the specimens and specimen holders, and monitored with the temperature monitors consisted of different alloys having different melting points. In HANARO, 2 non-instrumented capsules were manufactured and irradiated in HANARO for the evaluation of irradiation properties of RPV and Zr-based materials. Fig. 3 shows the typical non-instrumented capsule (98M-01K) and parts.

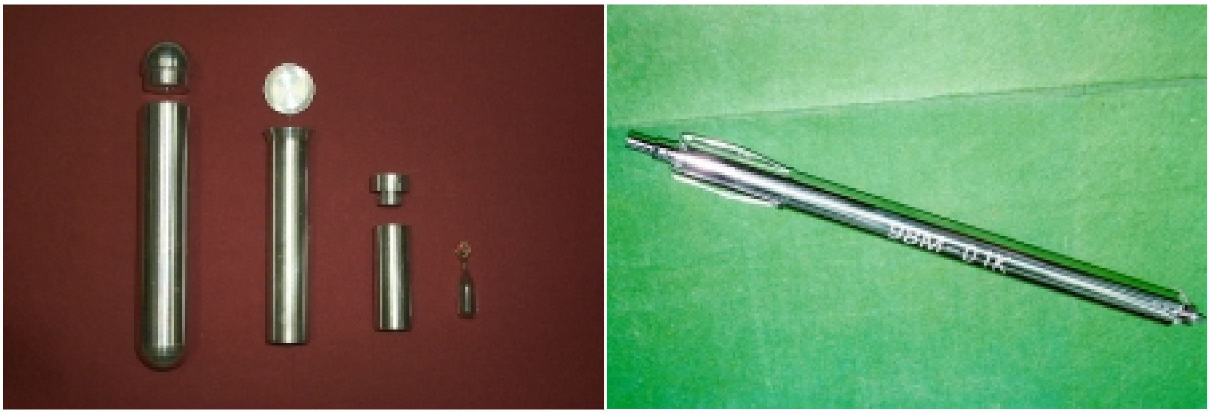

Fig. 3. Irradiation rabbit and non-instrumented capsule

2.3. Instrumented Capsule

The instrumented capsule technology for material irradiation in HANARO has been developed in the capsule team as a part of national nuclear R&D programs since 1994. The first instrumented capsule, 97M-01K, for the irradiation test of RPV materials was irradiated in 1998. These instrumented capsules are being actively utilized in the various irradiation tests for the development of nuclear fuel and materials. During last years, 8 instrumented capsules were designed, manufactured and irradiated in HANARO for the evaluation of irradiation properties of various nuclear materials as shown in Table 3. Most capsules were made for KAERI's material researches, but the 00M-01U, 01M-05U, and 02M-05U capsules were made as a part of national project for the promotion of HANARO utilization, especially for external researchers from universities.

The instrumented capsule consists of three main parts that are connected each other: protection tube (5m), guide tube (9.5m) and capsule mainbody. The mainbody including specimens and instruments is a cylindrical shape tube of 60mm in diameter and 829mm in length. The main body has 5 stages having independent micro-electric heaters and contains 14 thermocouples and 5 sets of Fe-Ni-Ti and Al_2O_3 Sapphire neutron fluence monitors to measure the temperatures of the specimens and fast neutron fluences, respectively. Heaters and thermocouples are connected to capsule temperature controlling system through guide tube and Junction Box system. The temperature of the specimens during irradiation is initially increased by the gamma heating and then roughly adjusted to the optimum condition by the gas control system and then finally adjusted to the desired value by micro-electric heater. Therefore, parametric irradiation tests of reactor power, He pressure, and heater capacity must be precisely performed at the beginning of irradiation test to obtain optimum irradiation condition of each capsules. The Fig. 2 shows the schematic diagram of HANARO instrumented capsule system and Fig. 4 shows the typical HANARO instrumented capsules, 99M-01K and 99M-02H.

Table 3. List of the capsules irradiated in the HANARO

Capsule	Institute	Specimen (No)	Material	Condition	Remarks
96M-01K (non-instrment)	KAERI (Capsule)	Tensile / Charpy **(87)**	STS304, nconel Zr-Nb, SA508	15-22MW CT/IR2, 140days 210-285℃ 1.35x10^{21} n/cm^2	95.1 Fabrication 95.11.3-96.9.22
97M-01K	KAERI (Capsule)	SP / Tensile / Charpy MBE / TEM **(251)**	STS304, SA508-3	20MW CT/IR2, 0.54day 290±10℃ 2.8x10^{18} n/cm^2	97.6.30 Fab. 98.5.21/9.2
98M-01K (non-instrment)	KAERI (RPV/Cap.)	CT / Charpy / PCVN / ABI Tensile / MBE / SP **(258)**	SA508-3	20MW CT, 0.4day 290±10℃ 4.5x10^{18} n/cm^2	99.2 -
98M-02K	KAERI (RPV)	CT / Charpy / PCVN / MBE / SP **(329)**	SA508-3	20MW CT, 2.2days 290±10℃ 2.6x10^{19} n/cm^2	99.1.28 Fab. 99.7.9-7.11
99M-01K	KAERI(RPV) HANJUNG	CT / Charpy / PCVN / ABI/Tensile/MBE/SP**(134)**	SA508-3	22MW IR2, 3days 290±10℃ 3.0x10^{19} n/cm^2	00.3.31 Fab. 00.6.14-6.17
99M-02H	HANJUNG	Charpy / PCVN / ABI Tensile / MBE / SP **(131)**	SA508-3	22MW IR2, 3days 290±10℃ 2.9x10^{19} n/cm^2	00.3.31 Fab. 00.5.31-6.3
00M-01U	Universities	Charpy / Tensile / Growth Tube / TEM / EPMA **(606)**	**Zr alloys** SA508, STS304	24MW IR2, 10days 290-350℃ 1x10^{20} n/cm^2	00.10.17 Fab. 00.11.8-11.18
00M-02K	KAERI (RPV)	CT / Charpy / PCVN / MBE / SP **(488)**	SA508-3 (Y3-5,U4,K1,J)	24MW IR2, 3days 290±10℃ 2.6x10^{19} n/cm^2	01.3.23 Fab. 01.5.2-01.5.6
00M-03K	KAERI (Zr PT/RCM)	Growth / TEM / Tensile **(267)**	Zr alloys STS304, Cr-Mo	24MW IR2, 11days 300/330℃ 1x10^{20} n/cm^2	01.3.23 Fab. 01.8.30-01.9.10
01M-05U	KAERI Universities	Tensile/ Growth /Hardness Tube / Optical / TEM **(267)**	**Zr alloys** Al-Cu, Ti alloys	24MW CT, 20days 290-350℃ 3.2x10^{20} n/cm^2	02.03.30 Fab. 02.04.27-05.26
02M-02K	KAERI (RPV)	PCVN / Charpy / SP / Tensile Hv / ABI **(776)**	SA508-3 (Y4-5,U4,IHT)	24MW CT, 4days 290±10℃ 2.6x10^{19} n/cm^2	03.3.11 Fab. 2003 -
02M-05U	KAERI Universities	SP / Tensile / Growth / Charpy Hv / TEM **(502)**	**Zr alloy, SA508** Al alloy, Cu-Nb	24MW CT, 28days(2cycles) 290-330℃ 4.02x10^{20} n/cm^2	03.03.11 Fab. 2003 -

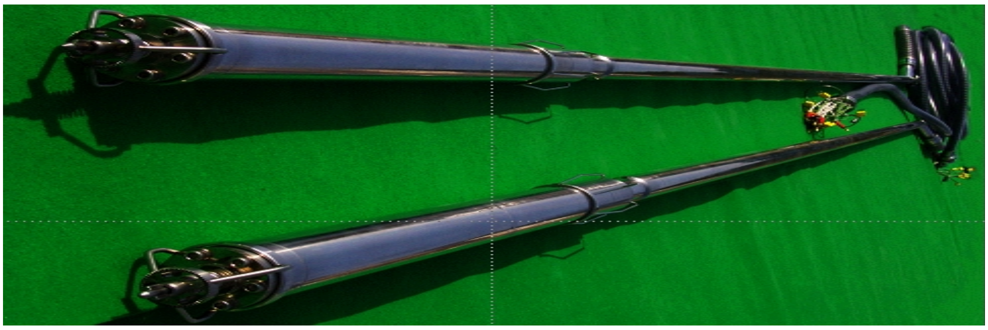

Fig. 4. Typical HANARO instrumented capsules, 99M-01K and 99M-02H

Various types of specimens such as (small) tensile, (1/3) Charpy, small punch, CT (compaction tension), TEM (transmission electron microscope), MBE (magnetic Backhausen effect), ABI (automated ball indentation), (1/3) PCVN (pre-cracked V-notch), Growth, Tube, Hardness, EPMA, and Optical specimens of SA508 steel, stainless steels, and Zr,Ti,Al-based alloys were inserted into the capsules.

Based on the dimensions of the major parts and specimens, the details of the capsule mainbody were designed. To meet the various irradiation test requirements of the users, several specimen configurations including 5- or 6-hole specimen structure were analyzed using computer code and applied to actual capsule design. The temperatures of the capsule parts were calculated using GENGTC and ANSYS codes. The ANSYS code analysis using the thermal design data proved that the capsules have enough strength during irradiation tests. The 6-hole irradiation capsule of 01M-05U that contained 50% increased specimens was successfully designed, fabricated, and irradiated in the HANARO CT hole for 20 days.

2.4. Capsule Related System

For the development of instrumented capsule system, the capsule related systems such as supporting, connecting, controlling, and cutting were also developed as shown in Fig. 2. After locking in the test hole, the instrumented capsule is fixed by the chimney bracket and robot arm supporting systems. Three sets of cantilever type robot arm system for CT, IR1 and IR2 test holes were installed at the location of the platform level of reactor that is 5.5 m in height from the bottom of the capsule, but the in-chimney bracket is temporarily installed on the top of reactor chimney for capsule irradiation test.

At the Junction Box system, heaters and thermocouples can be easily connected and separated to/from the capsule controlling system before/after 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 irradiation test, the main body of the instrumented capsule is cut off at the bottom of protection tube with the cutting system and is transported to IMEF(Irradiated Materials Examination Facility) by using HANARO fuel cask.

3. Irradiation Tests in HANARO

10 irradiation capsules(8 instrumented and 2 non-instrumented capsules) and 17 rabbits has been designed, fabricated and successfully irradiated in HANARO CT, IR, HTS or IP test holes since 1995. Capsules were designed for the irradiation of RPV (Reactor Pressure Vessel), reactor core materials, and Zr,Ti,Al-based alloys. Rabbits were used for the irradiation of semi-conductors(Si, Sapphire) and magnetic materials at low temperature(below 200^{o}C) and neutron flux condition. Totally, 3,300 specimens from domestic 13 research institutes, 2 nuclear industry companies and 51 universities, were irradiated in HANARO for 26,000 hours since 2000 using capsule and rabbit irradiation systems. Fig. 5 shows the increasing trends of irradiation specimen and time requested by users. Most capsules were made for KAERI material research projects, but 3 capsules were made as a part of national projects for the promotion of HANARO utilization since 2000. Table 4 shows the details of researches undertaken by the national projects for the promotion of HANARO utilization.

The rabbits were inserted in the HTS and IP holes of HANARO and the capsules were inserted in the CT or IR1,2 holes of HANARO and irradiated for about 0.38-20 days at 15-

24MW, respectively. At the beginnings of capsule irradiation tests, parametric tests of reactor power, He pressure and heater power were performed to obtain optimum irradiation condition and capsule design data. The temperature of the specimens was initially determined by gamma heating and roughly elevated by adjusting the internal He pressure, and then finally adjusted by micro-heater to the desired temperature. Because the gamma heating varies along the vertical position of the reactor core, gap adjustment between capsule parts is very important to maintain uniform temperature of the specimens over the region. The He pressure of the capsule was adjusted in the range of 0.01-1atm and the heater power was adjusted in the range of 0-263W/cm. The measured temperatures of the capsule parts are discussed and compared with the theoretical values obtained using computer programs of thermal calculation (GENGTC or ANSYS code).

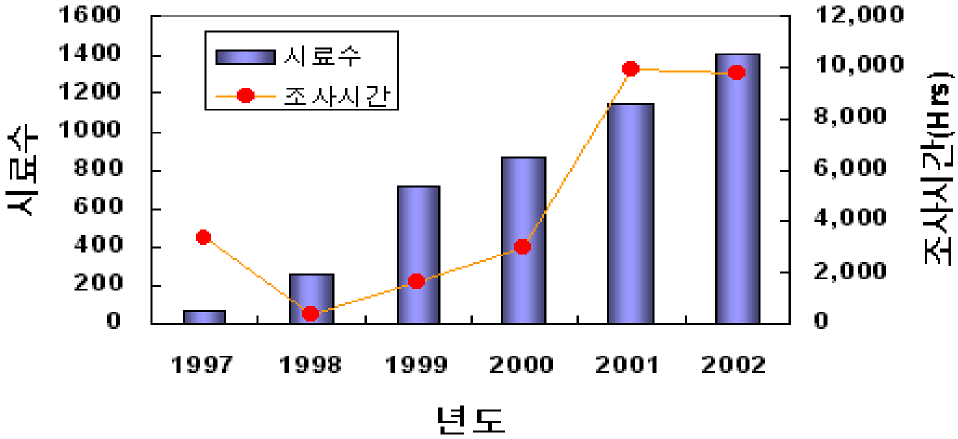

Fig. 5. The number of specimen and irradiation time requested by users

The specimens of the capsules were mainly irradiated in the irradiation temperature range of 280-360℃ and the fast neutron fluence (E>1.0 MeV) of the capsules were obtained in the range of 2.8×10^{18}-3.2×10^{20} (n/cm^2). The amount of neutron fluence of the specimens was calculated by computer code of VENTURE and compared with the measured values from neutron fluence monitors after irradiation test. Fig. 5 shows the figure of irradiation test and the variation of specimen mean temperatures of 01M-05U capsule irradiated in CT hole of HANARO at 24 MW.

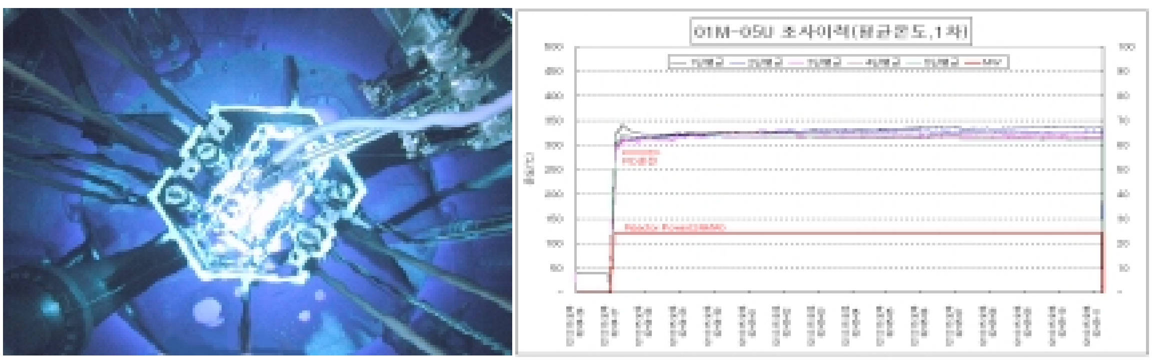

Fig. 5. Irradiation test and temperature variation of 01M-05U capsule in HANARO

Table 4. Researches undertaken by national projects for promotion of HANARO utilization

	Content of Research	Site	Remarks
Fuel	**Mono-crystal NFG products** Thermal Diffusion Coefficient	Kyoung -hee	Rabbit(UO_2/UO_2+Addition Mono-crystal) **Fission gas release** research
	NFG/Grain Boundary Effect	"	**FGR / GB** effect research
Mate -rial	**Reactor Structural mat. Irrad. Damage/Recovery**	KAIST	Instrumented Capsule (RPV materials) Irradiation Damage / Recovery
	Fuel **Carrier Stack cask Fracture Characteristics**	Chung -nam	Cap.(Cask mater.SA240SS, 350LF3, 508 4N) Fracture Analysis, Database
	Zr-base Reactor Core mat. Micro-structure / Corrosion	Inha	Capsule(Zr new alloy, Zr-Nb-Sn-Mo-Fe) **Korean Nuclear Fuel Cladding**
	Pro-Environmental RPV Microstructure of **Nano-mat.**	Sun -mun	Capsule(Ferritic low alloy steel/**HT9M**) Al alloys, Alumina, **Cu-Nb Nano-Comp.**
	Zr-based Alloys Neutron Irrad. Damage	Han -yang	Capsule (Zircaloy-4, Zr (Tube, Plate)) Cold Working, HT, grain size, ppt, Disl.
	Zr Alloy Embrittlement Alloying Element Effect	Chung -buk	Zr-Cu, Zr-Mn **Fuel Cladding Mat.**
	RPV Welds Irrad. Damage	KTT	**Welding Technology** of SA 508 cl.3
Semi Con duct or	**Broad Banded Semi-Cond. Irradiation Defect**	KBSI	Rabbit(**WBG Semi-Cond.**(ZnO,GaN)) Lighting Semi-Conductor
	Pure Silicon Crystal(Wafer) Irradiation Point Defects	Sunchu -nhang	**Mass Production of Uniform** Semi-cond. **P Distribution/Uniformity**
Mag netic	**Amorphous Ribbon/Wire Magnetic Properties**	Chung -buk	**Fe-Zr amorphous ribbon** Fe-based wire
	Magnetic Semi-Cond.	Chung -nam	GaMnAs, GaMnN, ZnO Magnetic Semi-Con.

Through this research, the design parameters and nuclear characteristics of HANARO capsule and rabbit were also produced and piled up in our database.

4. Future Plan

For the next research stage for a period of 2003-2006, we are planning to improve our instrumented capsule technology for more precise control of irradiation temperature and neutron fluence irrespective of reactor operation. Our proved 6-hole capsule structure will be valuably applied as a basic structure for new capsule technology. And we are also planning to develop the re-irradiation test technology of pre-irradiated materials. We will continue to produce material irradiation data and support the user's irradiation related R&D programs based on our established capsule technology.

5. Summary

Technologies and systems for HANARO irradiation tests have been developed in KAERI and 10 material irradiation capsules and 17 rabbits were designed and successfully irradiated in the CT, IR1,2, HTS, IP test holes of HANARO to evaluate the irradiation properties of non-fissile materials since 1995. Various instrumentation techniques such as temperature measuring and monitoring, gas controlling, micro-heating and neutron fluence monitoring and capsule related systems such as supporting, connecting, controlling, and cutting were also developed for the capsule irradiation system. The irradiation capsules were used for the irradiation of the RPV (reactor pressure vessel) and stainless steel reactor core materials, and Zr,Ti,Al-based alloys. Rabbits were used for the irradiation of semi-conductors(Si, Sapphire) and magnetic materials at low temperature(below 200^{o}C) and neutron flux condition. Totally, 3,300 specimens from 13 research institutes including 2 nuclear industry companies and 51 universities, were irradiated in HANARO for 26,000 hours using capsule and rabbit irradiation systems. The obtained irradiation data and experience will be effectively applied on the improved irradiation capsule design for various R&D programs of nuclear materials in KAERI and for basic researches of universities.

Acknowledgement

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