CONCEPTUAL DESIGN ANALYSIS OF 4 K IRRADIATION FACILITY IN KOREAN HANARO RESEARCH REACTOR

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ABSTRACT

A conceptual design of a 4 K irradiation test facility has been conducted in support of the International Thermonuclear Experimental Reactor (ITER) magnet development program. A new research reactor designated as HANARO at the Korea Atomic Energy Research Institute has a Cold Neutron Source (CNS) port that is identified to be suitable for the fast neutron irradiation of metals and insulation materials for superconducting magnets at 4 K. A 40 hours of irradiation at full power will produce 2.5×10^{17} n/cm^2 of the ITER magnet design neutron fluence with energy above 0.1 MeV. A material testing laboratory of Irradiated Materials Evaluation Facility (IMEF) that is located next to HANARO has been equipped with 77 K test machines and fracture analysis microscopes for radioactive specimens which can be upgraded for 4 K test without any intermediate warming. CNS radiation spectrum determined by Monte Carlo method is found to be more favorable for metal irradiation than for insulation materials with absorbed gamma dose that is 7~10 times the fast neutron dose. A lead-shielded irradiation capsule design with a 1 cm diameter specimen in 3 cm cold-bore diameter and 18 cm height will require about 120 watt cooling capacity at 4.6 K.

INTRODUCTION

The ITER magnet system is designed based on superconducting magnet technology [1]. Fast neutron and gamma radiation from D-T fusion can degrade materials integrity and the magnet reliability during operation. Organic insulation materials that are extensively used in toroidal coils are known for its susceptibility to ionizing radiation. Over the ITER lifetime, fast neutron fluence for magnet design activities has been reduced from 10^{19} to 10^{18} and finally to 2.5×10^{17} n/cm^2 in order to limit the radiation damage in insulation materials[2-4]. Metallic structural materials and Nb_3Sn superconductors are more resistant. Nevertheless effects on their properties after 4 K irradiation have never been verified for advanced cryogenic structural alloys.

Most of available low temperature irradiation test data are from liquid hydrogen (20 K) or liquid nitrogen (77 K) environments[5]. Due to significant thermal annealing effect at these temperatures 4 K irradiation tests on the ITER magnet materials have been conducted. The shutdown of Low Temperature Neutron Irradiation Facility(LTNIF) at ORNL left FRM of Technical University of Munich as the only available facility for 4 K irradiation test with

Table 1. HANARO Parameters for the Monte Carlo Analysis Using MCNP

Parameter	Condition used in the analysis
Reactor thermal power	30 MWt (4 week at full power and one week refueling shutdown)
Burn-up	Fresh core with all control rods removed
Core height	70 cm
Warm-bore diameter	16 cm for the base case with 100 % graphite
Cold-bore diameter	8 cm for case a) of Fig. 2 3 cm for cases b) and c) of Fig. 2
Cold region volume share	100% Liquid He (LHe) for case a) 85% LHe and 15 % Stainless Steel for cases a) and b) 76% LHe, 11% Polymer, 13% S.S. for case c)
Number of neutrons in MCNP analysis	1 million for base case and case a) 2 million for cases b) and c)

adequate fast neutron flux. The German facility is overloaded and has limitation on allowable specimen size. Hence a new 4 K irradiation facility with the capacity for larger specimens is desired to better support the ITER magnet development programs.

A new research reactor at the Korea Atomic Energy Research Institute(KAERI), designated as HANARO, has reached its criticality since February, 1995 and is scheduled to operate at 50 %, and 100 % of 30 MWt design power by the end of year 1995 and 1996, respectively. A vertical hole with 16 cm bore diameter that is located in the moderator region just outside the reactor core is provided for the future development of Cold Neutron Source (CNS). The CNS port is chosen in this study as the 4 K irradiation position because of significant advantages; 1) large bore size, 2) high neutron flux, 3) less burden on reactor operation/safety for its ex-core location, and 4) low user activity for the next several years.

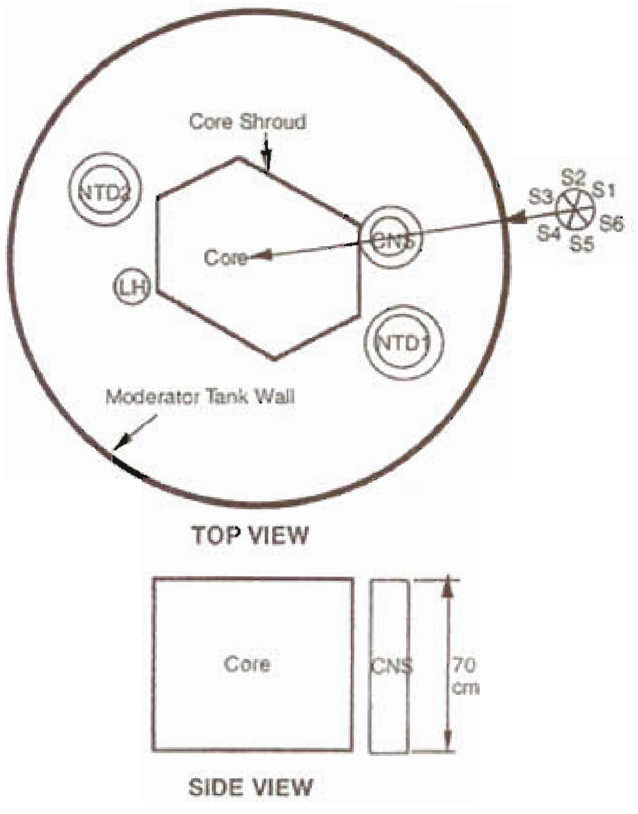

Figure 1. MCNP Analysis Geometry for HANARO Cold Neutron Source Port.

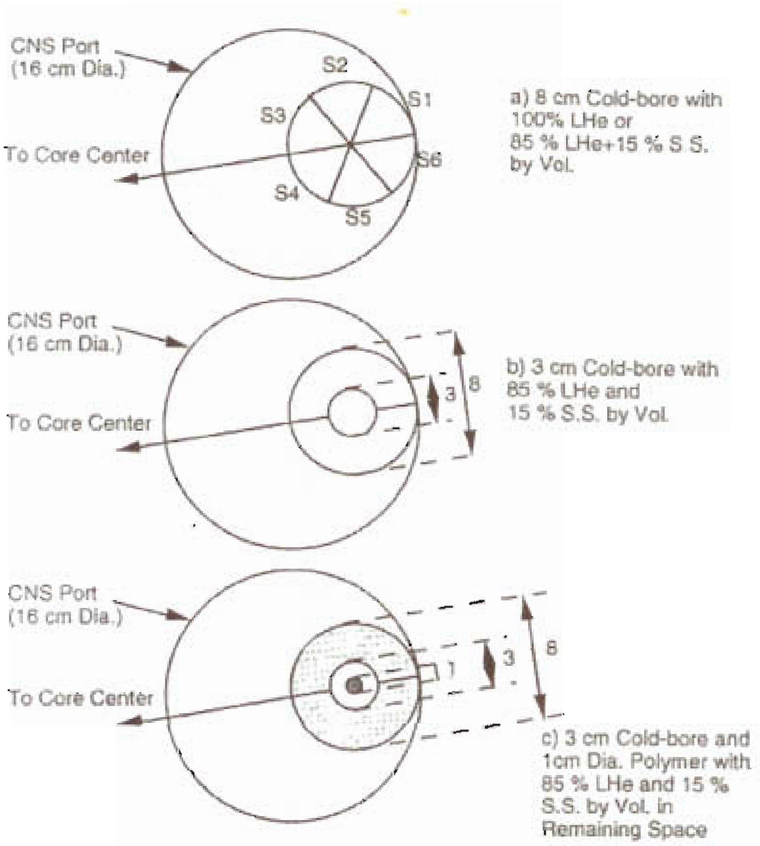

Figure 2. Cold Neutron Source Port Analysis Geometry. Cases a), b), and c).

MONTE CARLO ANALYSIS OF RADIATION SPECTRUM

A Monte Carlo Analysis Code, MCNP developed by Los Alamos National Laboratory, was used for the calculation of radiation flux, spectrum and heat generation rate [6]. The primary focus of the conceptual design analysis is the determination of 1) neutron and gamma flux, 2) neutron-to-gamma absorbed dose ratio, and 3) cryogenic cooling requirement for the irradiation test facility. Neutron flux and spectrum data available from HANARO Design Report were based on energy cut-off of 0.82 MeV whereas 0.1 MeV is used in ITER design. Gamma flux and spectrum were not available from the Report for the CNS port. Therefore a detailed MCNP analysis has been conducted specifically for the ITER magnet material irradiation test. HANARO parameters used in the study is summarized in Table 1.

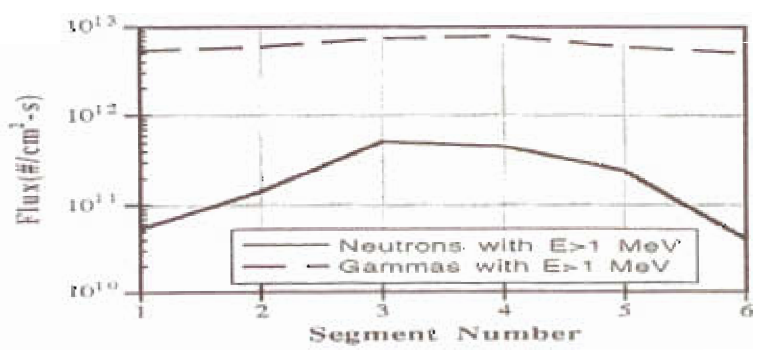

Figure 3. Angular Distribution of Neutron and Gamma Fluxes for Geometry in Case a).

Table 2. Calculated Radiation Flux and Heat Generation in Cryogenic Irradiation Capsule at CNS for Case b) with 3 cm Diameter Cold-bore

Energy(MeV)	Neutron Flux (#/cm2-s)	Neutron Heat (W)	Prompt Gamma Flux (#/cm2-s)	Prompt Gamma Heat (W)	Total Heat (W) Axial Length 70 cm	18 cm
>1.0000	6.76×10^{11}	1.93	8.25×10^{12}	97.3	197	51
0.1~1.0	1.04×10^{12}	0.51	5.08×10^{12}	6.89	14.3	3.7
0.01~0.1	1.30×10^{12}	0.04	2.91×10^{11}	1.82	3.7	0.9
0.001~0.01	1.56×10^{12}	0.004	3.86×10^{9}	0.19	0.4	0.1
0.0001~0.001	1.81×10^{12}	0.004	0.0000	0.0	0	0
10^{-4}~10^{-5}	1.91×10^{12}	0.004	0.0000	0.0	0	0
<10^{-5}	8.76×10^{12}	8.62	0.0000	0.0	8.6	2.2
All Energy	1.71×10^{13}	11.1	1.3×10^{13}	106	224	58

The geometry of CNS port is shown in Figure 1. A base case calculation assumed that the 16 cm warm-bore was filled with graphite in order to obtain reference neutron and gamma flux levels. Neutron flux for E>0.821 MeV was 1×10^{12} n/cm^2-sec and prompt gamma with E>0.1 MeV was about 5×10^{13} n/cm^2-sec. Since delayed gamma flux is about the same as the prompt gamma, total gamma flux is determined to be 10^{14} n/cm^2-sec.

Case a) 8 cm Diameter Cold-bore

To reduce gamma flux the 16 cm port was shielded with lead to leave a 8 cm diameter cold-bore. A strong angular dependence of radiation required that lead shielding be maximized toward the core center with a configuration shown in Figure 2a). The angular

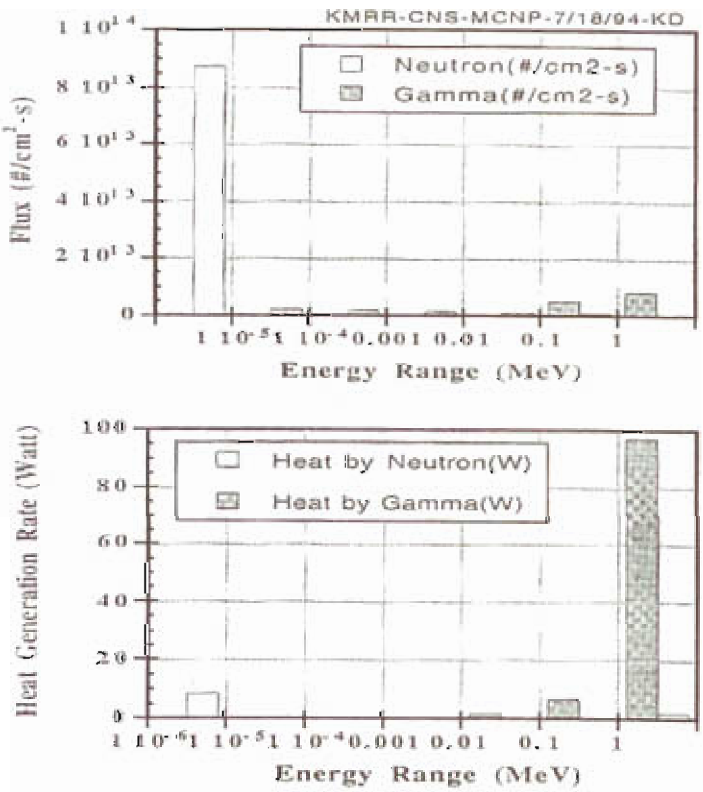

Figure 4. Energy-dependence of Neutron and Prompt Gamma Flux and Heat Generation Rate in Irradiation Capsule for CNS Geometry of Case b).

Table 3. Chemical Composition of BMI and S-2 Glass used for Insulation Materials Analyses (atomic %)

Material	Specific gravity	H	C	N	O	F	S	Mg	K	Al	Si
BMI	1.2	43	48	2	7	0	0	0	0	0	0
S-2 glass	2.49	0	0	0	63	0	0	3	0	15	19

Table 4. Heat Generation in 1 cm Diameter Insulation Specimen and Capsule Constituent Materials for 3 cm Cold-bore and 18 cm Axial Length

Material	Heat by Neutron (W)	Heat by All Gamma (W)	Total Heat (W)	Absorbed Heat Ratio (Neutron/Total)
BMI	1.7	9.2	11	0.16
S-2 glass	2.1	20	22	0.09
He&S.S.	2.2	40	42	0.05

distribution of the gamma and neutron for Figure 2a) is determined for surface segment (S1~S6), as shown in Figure 3. For both gamma and neutron flux, the maximum value occurred in the direction to the core center and the minimum in the opposite direction. For gamma flux, the maximum-to-minimum ratio was within a factor of two which is considered to be acceptable. For neutron flux the maximum/minimum ratio was about ten. Since the specimen diameter would be much smaller than fast neutron mean free path that is about a meter, the anisotropy presents no problem in obtaining uniform dose in the specimen.

Total heat generation(with a factor of two multiplied on the prompt gamma heat to account for the delayed gamma) is calculated to be 2.78 kW that is unacceptably high from the cryogenics cooling requirement standpoint. Since more than 99 % of the heat comes from high energy gamma, additional shielding was desired at the expense of cold-bore size.

Case b) 3 cm Diameter Cold-bore without Insulation Specimen

By using a concentric lead-shielding inside the 8 cm hole, the cold bore was reduced to 3 cm that is still considered to be large enough to accept a 1 cm diameter specimen, as shown in Figure 2b). With this configuration the heat generation rate is found to be significantly reduced due to 1) the reduction in the cold volume and 2) the reduction of gamma flux by additional shielding. Results for the case with Figure 2b) configuration are summarized in Table 2. Figure 4 shows the energy-dependence of neutron and gamma flux and associated heat generation based on Table 2. It is high energy (E>0.1 MeV) gamma that generates most of heat. Neutron flux with energy> 0.1 MeV was about 1.7×10^{12} n/cm^2-sec. To achieve an ITER magnet fluence of 2.5×10^{17} n/cm^2, it will take about 40 hours. This is sufficiently short compared with about one month of continuous operation period of HANARO. Low energy neutrons are the primary source of neutronic heat. These neutrons, however, can be removed by cadmium foils when necessary.

Case c) 3 cm Cold-bore with Insulation Specimen

To further reduce the thermal load, the axial length of irradiation capsule is reduced to 18 cm such that it extends over the top quarter of the core. Hence the configuration of a 3 cm cold-bore with 18 cm axial length is used for the insulation material study. Two types of insulation materials with chemical composition in Table 3, were studied: BMI and S-2 glass. The insulation material was assumed to be a cylindrical specimen of 1 cm diameter located at the center of the 3 cm cold-bore, as shown in Figure 2c. The specimen size is adequate for the insulation property measurement and also for providing statistical sufficiency of MCNP calculation results. The result is given in Table 4.

The gamma-to-neutron absorbed dose ratio is improved to 7 ~ 10 by lead-shielding although gamma is still dominant. The ITER toroidal magnets are expected to have more energy absorption by neutron than by gamma. For insulation material irradiation, the excessive presence of gamma radiation can produce significant additional damage at the fixed fast fluence. For this reason it is desired to obtain at least 50% of absorbed dose from fast neutrons in 4 K testing of ITER insulation materials. The neutronic heat is about equally contributed by fast (E>0.1 MeV) and low energy neutron (E< 10 eV) for the insulation. Therefore the CNS irradiation test results for insulation materials would require appropriate interpretation on the spectrum effect with respect to the ITER design.

The spectrum can be improved by moving from the ex-core CNS to an in-core position as illustrated by the fact that the in-core position of FRM reactor gives gamma-to-neutron dose ratio of about 2. If the ITER blanket is cooled by liquid metal instead of water the neutron spectrum at the magnet is expected to be significantly hardened such that about 7 % of all neutron are at E> 5 MeV. In this event, all water-reactor irradiation data would require the interpretation of spectrum effect. For metallic materials where displacement cross section of gamma in MeV range is about two orders of magnitude smaller than that of neutrons, the CNS spectrum can be directly used for the ITER magnet material test[7].

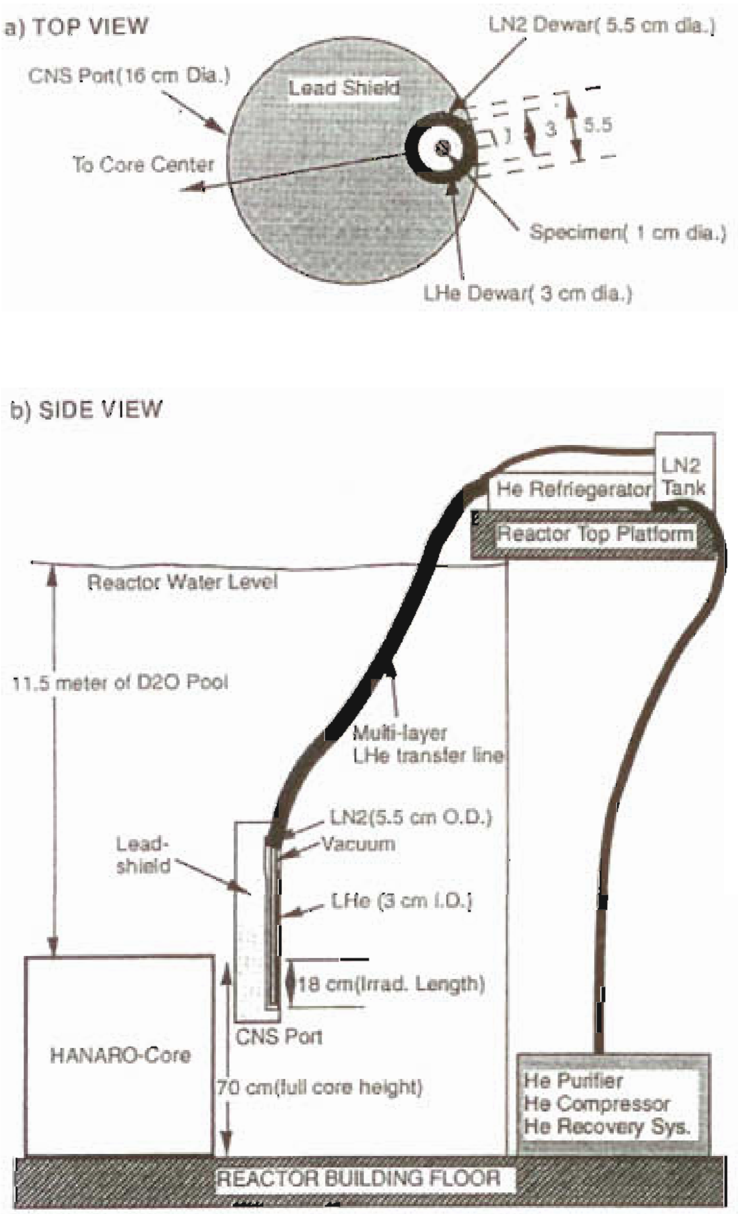

Figure 5. Conceptual Design Layout of 4K Irradiation Test Facility of HANARO.

CRYOGENIC COOLING REQUIREMENT

Considering limited space available for the cooler installation on the reactor top platform it was decided to minimize cooling requirements. To this end the length of irradiation capsule is reduced to 18 cm and the nuclear heat generation rate is cut to about 60 W. The core-average neutron and gamma flux values determined for the full-height case are still representative for the present case since the specimen location will be at one-quarter of core-height from the reactor top where radiation flux is about equal to core average values. Thermal radiation heat load in the capsule and liquid helium transfer tube penetrating about 11.5 meter deep water pool is estimated to be about 60 W which results in a total cryogenic load of 120 W at 4.6 K with auxiliary liquid nitrogen cooling. This is equivalent to liquid helium feed rate of 170 l/hr in an open system. Closed loop helium refrigerators with the required capacity are commercially available and can be accommodated in the given space of HANARO reactor building with a preliminary system layout, as shown in Figure 5.

Specimen size can be limited due to excessive hot spot temperature for insulation materials where thermal conductivity is low. About 1.6 watt/cm^3 of heat generation rate is expected for S-2 glass from Table 4. The radial temperature rise for a 1 cm diameter cylindrical insulation specimen is found to be about 1 K using a 4 K thermal conductivity of 0.1 W/m-K[8]. In the irradiation capsule, 15 % of cold space is assumed to be metals. For the 18 cm axial length, this amounts to 19 cm^3. Since the volume of dewar cold wall, if a thickness of 0.079 cm is assumed, is about 13 cm^3, about 6 cm^3 is available for the metallic specimen. This is more than sufficient for a tension test specimen and is acceptable for a subsize fracture test specimen of metallic materials.

The irradiation capsule with specimen will be raised into a shielded cask at the reactor top and transferred to the Irradiated Materials Evaluation Facility (IMEF) that is located next to HANARO. The IMEF has been equipped with a 5 ton dynamic 77 K test systems, a 20 ton dynamic tester that permit tensile, compression, and fracture test, related metallographic tools and hot-cell manipulators. Completed specimens can be transferred to existing radwaste handling systems at KAERI.

CONCLUSIONS

A conceptual design analysis of 4 K irradiation capsule showed that an ex-core Cold Neutron Source(CNS) port in HANARO reactor has spectrum characteristics that is favorable for irradiation test of the ITER magnet structural materials. After lead-shielding to reduce gamma heat, the irradiation capsule has a cold-bore diameter of 3 cm and an axial length of 18 cm extending over a top quarter of HANARO core. Fast neutron with energy greater than 0.1 MeV has a flux of about 1.7×10^{12} n/cm2-sec. To achieve an ITER magnet fast fluence of 2.5×10^{17} n/cm^2, it will take about 40 hours at 30 MWt full power. The CNS port has neutron absorbed dose that is about seven to ten times smaller than that of gamma which makes it more favorable for irradiation of metallic materials. For insulation materials, such as BMI and S-2 glass where gamma damage can be significant, irradiation test results need interpretation on the spectrum effect . A cryogenic cooling load of 60 W at 4.6 K for nuclear heat and 60 W for thermal radiative loss in helium transfer line can be covered by commercially available closed loop helium refrigerator system. Post-irradiation property measurement and microscopic examination can be made without warming at Irradiation Material Evaluation Facility that is located next to HANARO.

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