EPJ Web of Conferences **106**, 01004 (2016)
DOI: 10.1051/epjconf/201610601004

Neutron Flux Characterization of Irradiation Holes for Irradiation Test at HANARO

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Abstract. The High flux Advanced Neutron Application ReactOr (HANARO) is a unique research reactor in the Republic of Korea, and has been used for irradiation testing since 1998. To conduct irradiation tests for nuclear materials, the irradiation holes of CT and OR5 have been used due to a high fast-neutron flux. Because the neutron flux must be accurately calculated to evaluate the neutron fluence of irradiated material, it was conducted using MCNP. The neutron flux was measured using fluence monitor wires to verify the calculated result. Some evaluations have been conducted, however, more than 20% errors have frequently occurred at the OR irradiation hole, while a good agreement between the calculated and measured data was shown at the CT irradiation hole.

1. Introduction

The High flux Advanced Neutron Application Reactor (HANARO) is a unique research reactor in the Republic of Korea used for material and fuel irradiation tests, the utilization of a neutron beam, and the production of radioactive isotopes. Since 1998, irradiation tests for many materials such as a reactor pressure vessel, cladding, fuel assembly, and reactor structure material have been conducted at HANARO to evaluate their irradiation performance [1]. Recently, the need for irradiation testing is increasing for the following reasons:

(1) Demand for safety improvements for operating aging nuclear power plants after the Fukushima accident in Japan;
(2) Development and performance verification from in-pile tests for future nuclear systems and fusion materials;
(3) To produce the design data for a research reactor and a system-integrated modular advanced reactor (SMART).

Therefore, it is expected that many irradiation tests will be conducted at HANARO.

The fast neutron fluence is an important factor because it can lead to integrity degradation of the material due to the increase in inflexibility and hardness and the reduction of ductility and toughness. For this reason, at a commercial nuclear power plant, the fast neutron fluence for the reactor pressure vessel is periodically measured and regulated [2]. Therefore, the fast neutron fluence of irradiation-tested material must be accurately evaluated.

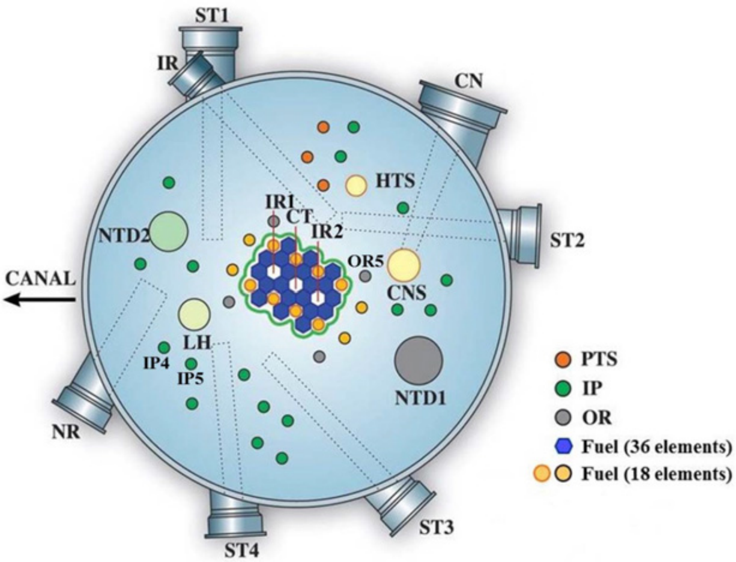


Figure 1. A cross-sectional schematic diagram of HANARO core and irradiation holes.

During the irradiation test, the specimen temperature can be controlled by the degree of vacuum and the micro-heater. However, the fast neutron fluence cannot be controlled directly. Generally, neutron fluxes were calculated using a computing code before the irradiation test to design a material irradiation capsule. At HANARO, some irradiation holes were used for the irradiation test, and thus the irradiation hole must be selected by designing the capsule before the irradiation test considering the appropriate neutron fluence. After the irradiation test, the neutron fluence must be verified by the experimental measurement. At HFR [3] and JMTR [4], the results of a comparison between the calculated and measured data of fast neutron flux were mostly showed within ±10%.

In this paper, an evaluation of a fast neutron flux was conducted for the irradiation test. The neutron flux and spectrum were calculated to evaluate the neutron fluence of the irradiated material. The neutron flux was measured using fluence monitor wires. The calculated and measured data were compared to evaluate the fast neutron flux and the reliability of the calculation method for the irradiation test. These results can be used as the basic neutron dosimetry data for the HANARO irradiation facility.

2. Irradiation Facility of HANARO

2.1 HANARO and its Irradiation Holes

HANARO is an open-tank-in-pool type research reactor with a rated power of 30 MWth. Heavy and light water are used as a moderator and coolant, and U_3Si-Al is used as a fuel material. Figure 1 shows a cross-sectional schematic diagram of the HANARO core and irradiation holes. There are 23 hexagonal and eight circular flow tubes in the core and some circular flow tubes are located outside the core reflector region such as OR, IP, PTS, LH and NTD. Generally, among them, three hexagonal and three circular flow tubes are used to conduct the material irradiation test, such as CT, IR1, IR2, OR5, IP4 and IP5. However, because a Fuel Test Loop (FTL) is installed in IR1 and the nuclear features are similar between some irradiation holes, CT, IR2, OR5 and IP5 were mainly used for the material irradiation test at HANARO. Table 1 shows the maximum fast neutron fluxes calculated by the HANARO core analysis system in the CT, IR2, OR5 and IP5 irradiation holes. Because of the difference in fast neutron flux, the

Table 1. The maximum fast neutron fluxes of irradiation holes for material irradiation test at the end of the cycle (the height of control absorber rod = 550 mm, neutron energy >0.821 MeV).

Irradiation hole	Fast neutron flux (n/cm^2-sec)
CT	1.95×10^{14}
IR2	1.76×10^{14}
OR5	1.92×10^{13}
IP5	5.82×10^{10}

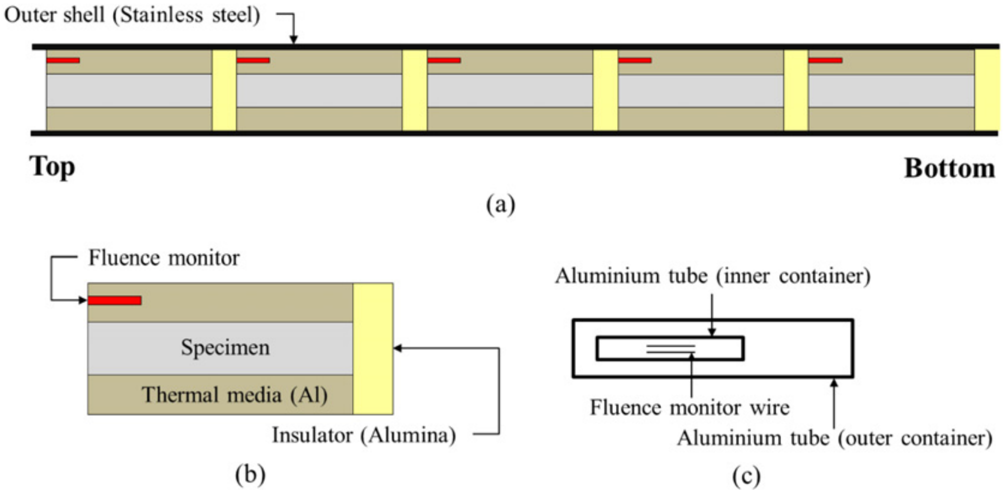


Figure 2. A schematic diagram of the irradiation capsule (a) Assembled capsule, (b) structure of each stage, (c) fluence monitor assembly.

irradiation hole was selected according to the target fast neutron fluence. CT and OR5 irradiation holes were used for the irradiation test of nuclear materials due to a high fast-neutron flux. The irradiation test for electromagnetic materials is conducted in IP and other irradiation holes with a high thermal-neutron flux.

2.2 Irradiation Capsule

Figure 2 shows a schematic diagram of the irradiation capsule for the irradiation test of nuclear materials. There are five vertical stages in the capsule for containing various specimens for compact tension, tensile, hardness, and microstructure observation tests. To measure the fast neutron flux, the method of dosimeter activation analysis has been used for the irradiation test capsule. Fluence monitors (F/M) were inserted in the top position of the thermal media at each stage. Pure metal foils and wires were used as the F/M. In this study, Fe and Ti wires were used as an F/M due to an active reaction with fast neutrons. Before installation in a capsule, the mass of the F/M wires was measured. After the irradiation test, these F/Ms were disassembled from the capsule and the absolute activities of the F/M were measured by a gamma-ray analysis using an HPGe detector.

SMART is small- and medium-sized reactor that is under development and licensing for use in desalinating seawater and providing electricity to a limited area [5]. SMART enhances safety via the removal of primary connecting pipes. A steam generator (S/G) is located inside the reactor pressure vessel, and thus the S/G tube is exposed under neutron irradiation during the operation. Therefore, the

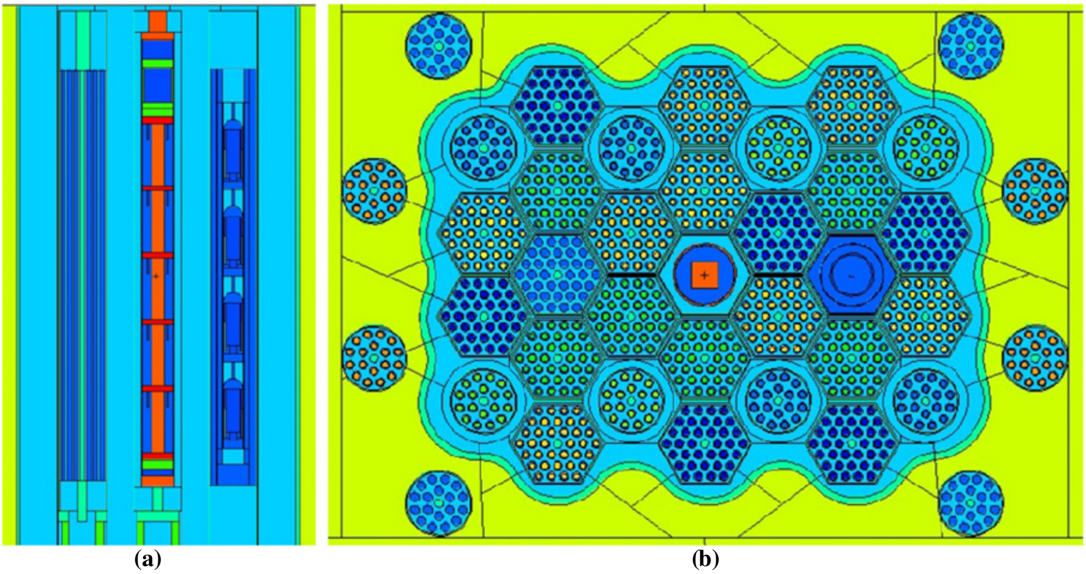


Figure 3. The MCNP calculation (a) vertical and (b) horizontal model of HANARO core (the irradiation test capsule was loaded in CT irradiation hole).

irradiation performance of the S/G tube material must be verified. 09M-02K, 10M-01K, and 11M-03K irradiation capsules were designed to conduct the irradiation test for Alloy 690, an S/G tube material for SMART. The irradiation capsules of 09M-02K and 11M-03K were irradiated in an OR5 irradiation hole, and 10M-01K was irradiated in a CT irradiation hole.

10M-15K was designed, fabricated and irradiated to evaluate the neutron irradiation properties of materials that will be used for the pressure vessel of the VHTR (Very High Temperature Reactor). It was irradiated in an OR5 irradiation hole.

To evaluate the fast neutron fluence, four irradiation capsules such as 09M-02K, 10M-01K, 10M-15K, and 11M-03K were used for the comparison between the calculated and measured values.

3. Calculation of Neutron Flux

The MCNP (Monte Carlo N-Particle) code version 5, which was a design verification code of the HANARO core, was used for this calculation. ENDF/B-VII was used as the main cross section library. Figure 3 shows the model of the irradiation test capsule and the HANARO core in this calculation. The equilibrium HANARO core was assumed. Because the position of control absorber rod (CAR) is changed with the operation, the neutron flux and spectrum were calculated at the CAR positions of 350, 450, and 550 mm to observe the influence of the CAR position. The irradiation test capsule for the irradiation test of the SMART S/G tube was assumed to use a center-concentrating specimen concept.

Fast neutron fluxes were calculated at 20 axial sections of the specimen. Each stage was divided into four sections. The height of one section was 2.85 cm. Generally, a control absorber rod (CAR) is operated from about a height of 250 mm at the beginning of the irradiation cycle. During the irradiation cycle, the CAR is increasingly withdrawn from the core to compensate for reactivity. At the end of the irradiation cycle, the height of CAR reached about 600 mm. Because the operation of the CAR was different for every cycle, it must be analyzed after the irradiation test to calculate the exact fast neutron flux. The axial flux distribution calculated by MCNP according to the height of CAR for the CT and OR5 irradiation hole is shown in Fig. 4. The maximum fast neutron flux was similar regardless of the

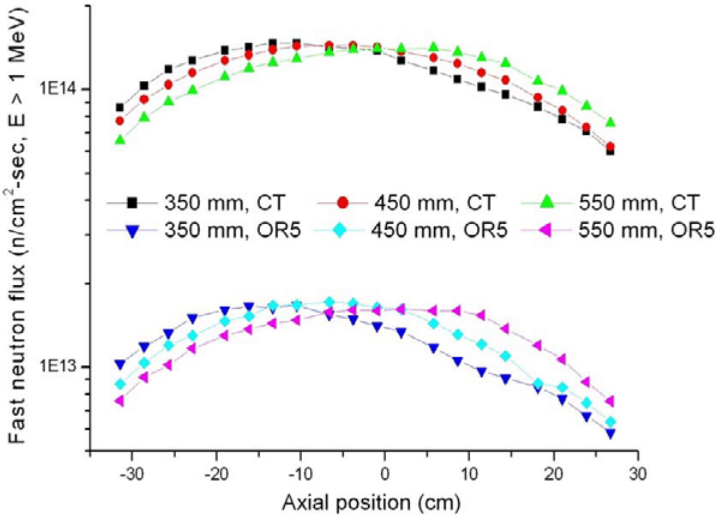


Figure 4. Axial fast neutron (> 1 MeV) flux distribution of the specimen calculated by MCNP according to the control absorber rod position.

height of the CAR. The peak height of the fast neutron flux was increased with an increase in the height of CAR. In addition, the neutron spectrum at each stage was calculated by MCNP. The CT irradiation hole is located at the center of the core; however, OR5 is located in the flow tube outside the core in the reflector region. Therefore, it is expected that the difference between the specimen and F/M may be observed according to the position of F/M in the OR5 irradiation hole. To evaluate its influence, the differences with 12 positions were calculated in the CT and OR5 irradiation hole. Figure 5 shows the neutron flux differences with 12 positions of the irradiation test capsule. The average neutron flux corresponded approximately with the neutron flux of the specimen. Although a maximum difference of 7.31% was observed, most of the results showed good agreement in the CT irradiation hole. Large differences were observed in the OR5 irradiation hole.

4. Comparison Results Between Calculated and Measured Flux

4.1 Consideration of the Operation History of Control Absorber Rod (CAR)

The CAR position is important for evaluating a fast neutron flux because the axial flux distribution changes according to the positional change of the CAR as shown in Fig. 6. Therefore, the operational history of the CAR must be analyzed to evaluate the exact neutron flux after the irradiation test. In this study, fast neutron fluxes were calculated by assuming a steady-state condition, i.e., a fixed CAR position. However, the fast neutron flux and the CAR position were actually changed during the irradiation test. To simulate this condition, a linear change of fast neutron fluxes was assumed according to the change of the axial CAR position from 350 mm, through 450 mm, to 550 mm. From the CAR operational history, the average CAR height was calculated and used for the detailed calculation. When the reactor power is only 30 MWth, the height of CAR was used to calculate the average height.

4.2 Comparison Between Calculation and Measurement of Fast Neutron Flux

To measure the fast neutron flux, $Fe^{54}(n,p)Mn^{54}$ and $Ti^{46}(n,p)Sc^{46}$ reactions were used in this study. The absolute activities of the reaction products were measured using a HPGe detector. The reaction rate can

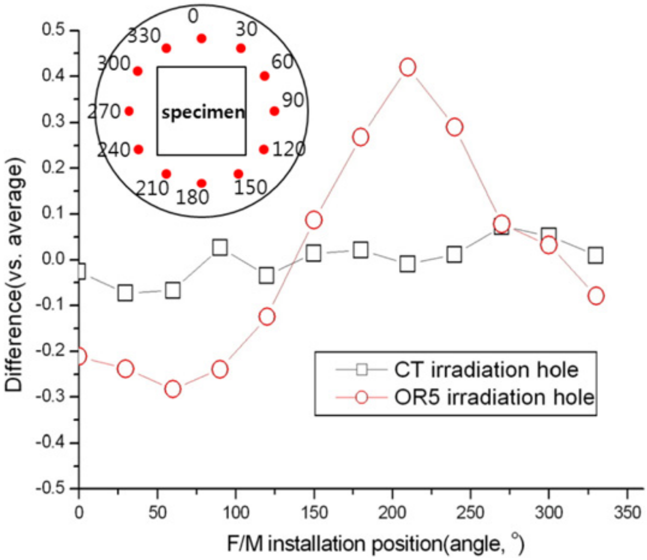


Figure 5. The neutron flux (E >1 MeV) differences with the F/M irradiated position (CAR = 450 mm, in the middle section of the irradiation test capsule).

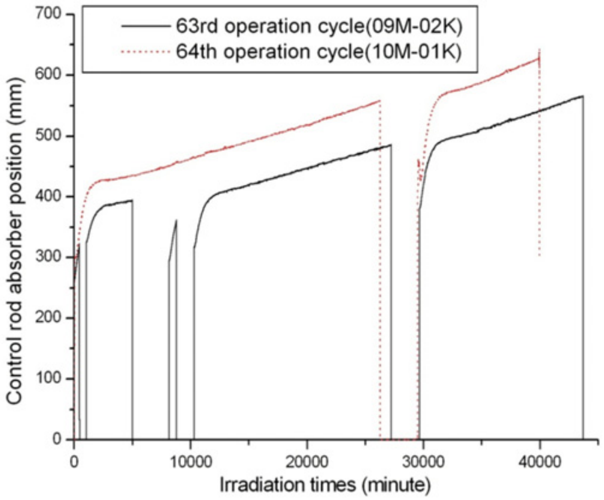
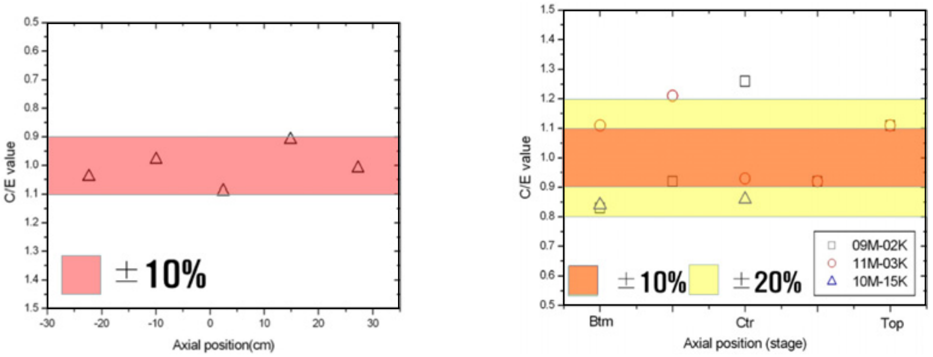


Figure 6. The control absorber rod operational histories for the 63^{rd} (09M-02K) and 64^{th} (10M-01K) operation cycle of HANARO.

be expressed as follows.

$$\frac{A(t)e^{-\lambda t_e}}{N(1 - e^{-\lambda t_i})} = \int_{-\infty}^{\infty} \sigma(E)\phi(E)dE, \tag{1}$$

where, A(t) is the measured activity (absolute value), t_e is the elapsed time (from the end of the irradiation test to the activity measurement), t_i is the irradiation-tested time, λ is the decay constant, N is the atom density, σ is the reaction cross section, and ϕ is the neutron flux. The left side of the



(a) (b)

Figure 7. The comparison results of Fe^{54}(n,p)Mn^{54} reaction rate between calculated and measured value (C/E value) of irradiation test capsules irradiated in (a) CT and (b) OR5 irradiation hole.

(a) (b)

Figure 8. The rod tip of irradiation capsule loaded in (a) CT and (b) OR5 irradiation hole.

equation can be calculated by measured value from the activity of F/M. The right side of the equation, the reaction rate, can be calculated by MCNP.

Figure 7 shows the comparison results of the Fe^{54}(n,p)Mn^{54} reaction rate between the calculated and evaluated value (C/E value) of each F/M. All results of the F/Ms in a 10M-01K capsule irradiated in a CT irradiation hole showed good agreement within ±10% as shown in Fig. 7(a). The maximum difference between the calculated and measured values was 9.47%. In the case of the F/Ms in 09M-02K, 10M-15K and 11M-03K capsules irradiated in an OR5 irradiation hole, the difference was larger than the irradiated result in the CT irradiation hole. Most of the comparison results were outside ±10% and some evaluations were more than ±20%.

This large difference might be caused by the location of the irradiation hole. The OR5 irradiation hole is located outside the core near the boundary between the core and reflector, and thus the fast neutron gradient is large enough to cause a neutron flux fluctuation. Therefore, the difference in the fast neutron flux was large between the F/M installation position and specimen as shown in Fig. 5. In addition, the F/M irradiated position was inaccurate in the OR5 irradiation hole. Figure 8 shows the rod tips of the irradiation capsule that is fixed in the lower structure of the irradiation hole. In the CT irradiation hole, the position and direction of the irradiation capsule was fixed by the wings on the rod tip, as shown in Fig. 8(a). If the lower structure is damaged, the flow tube of the CT irradiation hole can be changed with a substitute. However, if the lower structure is damaged in the OR5 irradiation hole, it cannot be replaced because the OR irradiation hole is located in the D_2O tank, which is welded with a lower structure. For this reason, the exact F/M installation position is inaccurate. This might cause a large difference between the calculated and measure values.

5. Conclusions

The evaluation of the fast neutron flux was conducted for the irradiation test at HANARO. The neutron flux was calculated using the MCNP code and measured by F/Ms installed in the irradiation capsules, 09M-02K, 10M-01K, 10M-15K, and 11M-03K. The evaluation of a fast neutron flux was conducted by comparing the reaction rates between the calculated and measured values. At a capsule irradiated in a CT irradiation hole, the comparison results showed good agreement. A large difference in the comparison results was observed at the capsule irradiated in the OR5 irradiation hole, which might be caused by the location of the irradiation hole and the inaccurate F/M position in the capsule.

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