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Design of an irradiation rig using screen method for silicon transmutation doping at the Dalat research reactor

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Abstract: The neutron transmutation doping of silicon (NTD-Si) at research reactors has been successfully implemented in many countries to produce high-quality semiconductors. In the late 1980s, NTD-Si has been tested at the Dalat Nuclear Research Reactor (DNRR) but the results have been limited. Therefore, the design and testing of an irradiation rig for NTD-Si at the DNRR are necessary to have a better understanding in order to apply the NTD-Si in a new research reactor of the Research Centre for Nuclear Science and Technology (RCNEST), which has planned to be built in Viet Nam. This paper presents the design and testing of a new irradiation rig using screen method for testing NTD-Si at the DNRR. The important parameters in the rig such as neutron spectrum and thermal neutron flux distribution were determined by both calculation using MCNP5 computer code and experiment. The aluminum ingots, which have similar neutronic characteristics with silicon ingots, were irradiated in the rig to verify the appropriate design. The uniformity of thermal neutron flux in the rig is less than 5% in axial and 2% in radial directions, respectively. However, the thermal/fast flux ratio of the irradiation rig is 4.38/1 would affect target resistivity of testing Silicon ingots after irradiation.

Keywords: *NTD-Si, MCNP5, Dalat Nuclear Research Reactor (DNRR), screen method, foil activation, irradiation rig.*

I. INTRODUCTION

One of the most important requirements of NTD-Si is to maintain the uniformity of radial and axial thermal neutron flux in irradiation channels. At present, the uniformity of irradiation from 5 ~ 6% would meet commercial request depend on ingot dimension [1]. In a research reactor, normally, the axial and radial distributions of thermal neutron in irradiation channels are not uniformed. In order to meet customer's requirements, a change in configuration of irradiation channels is needed to uniform thermal neutron flux distribution and maximize usage of the channel. Three major methods could be applied to axially uniform thermal neutron flux distribution are inversion, reciprocating motion and flux screen [1]. Depending on the design characteristics and core configuration of the reactors, the method applied for neutron flux uniformity should be chosen. In the late 1980s, the inversion method has been tested at the DNRR but the results have been limited [2]. Therefore, the design and testing of an irradiation rig using flux screen method for NTD-Si at the DNRR are necessary to have a better understanding and

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experience in NTD-Si application. The new irradiation rig using various screen materials (stainless steel, aluminum and light water) was designed, installed and tested in the core of DNRR. The results would provide good experiences in the application of NTD-Si on the new research reactor, which has planned to be built in Vietnam.

II. CALCULATION MODEL AND EXPERIMENTAL METHOD

A. Dalat research reactor and its parameters

The DNRR, 500-kW pool-typed, light water cooled and moderated, was reconstructed and upgraded from the USA 250 kW TRIGA MARK II reactor. The reactor has been officially put into operation for the purposes of radioisotope production, neutron activation analysis, fundamental and applied research, and manpower training. The summary description of the DNRR is shown in Table I and Figure 1 [3].

Table I. Summary description of the DNRR [3]

Parameter	Description
Nominal power	500 kW
Neutron flux (thermal, max)	2×10^{13} n/cm^2.s
Fuel	VVR-M2, mixed UO_2-Al, 19,75% enrichment
Moderator and coolant	Light water
Reflector	Graphite, beryllium and light water
Core cooling	Natural convection
Heat rejection	Two-loop cooling system
Control rods	2 safety, 4 shim (B_4C) and 1 regulating (stainless steel)

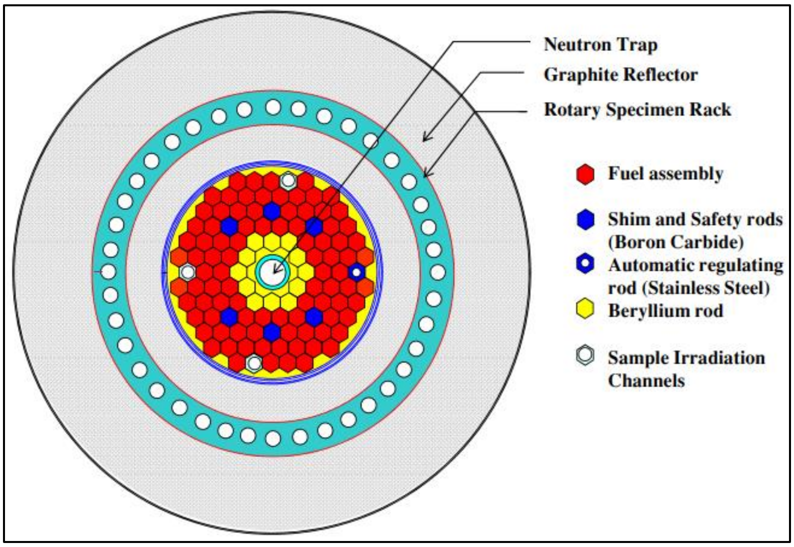

Fig. 1. Present working configuration of DNRR.

Since thermal neutrons are mainly used in NTD-Si, higher thermal neutron flux would result in a shorter irradiation time. The neutron trap, which has maximum thermal neutron flux in the core of DNRR, is dedicated for NTD-Si testing. Neutron trap is a water cylinder surrounded by Beryllium blocks located in center of the core. The neutron trap has 6.5 cm in diameter and about 2050 cm^3 in volume [3]. An aluminum tube installed in the neutron trap to load irradiation samples which have maximum of 4.2 cm in diameter as shown in Figure 1.

B. Determination of neutron spectrum and flux distribution

Determination of neutron spectrum and flux distribution at the neutron trap was obtained by using foil activation method. Bare gold foils and Cadmium covered gold foils were irradiated to obtain absolute neutron flux [4]. The following equation can be used to obtain thermal neutron flux:

$$\Phi_{th} = \frac{2.Ae^{-\lambda\tau}}{\sqrt{\pi}N_A\alpha\sigma_{0,act}G_{th}(1-e^{-\lambda T})}\sqrt{\frac{T_n}{T_0}}\left[\frac{A_b(T,\tau)}{m_b}-\frac{A_{Cd}(T,\tau)}{m_{Cd}}\right] \quad (1)$$

Where, m_b - mass of bare gold foil (g); m_{Cd} - mass of Cadmium covered gold foils (g); T - Irradiation duration (s); τ - cooling duration after irradiation (s); t_m - measurement in real time (s); $t_{m,eff}$ - effective time measurement (s); λ - decay constant of nuclide compound (s^{-1}); η - counting efficiency of detector; γ - gamma abundance factor; m - mass of foil (g); α - isotope enrichment; G_{th} - thermal neutron self-shielding factor; N_A - Avogadro constant; A - Atomic number of isotope; G – ratio of isotope in foil; T_n neutron temperature (K); T_0 room temperature (293 K).

To determine the thermal neutron flux distribution at the neutron trap, Lu-176 foils which have large thermal neutron absorption cross-section were used. Thermal neutron flux distribution was scaled relatively. The relative thermal neutron distribution was obtained by comparing of ratios of corresponding Lu-176 activities at various positions in the neutron trap.

The method used for neutron spectrum measurement is based on activation of a set of foils and determination of reaction rates. SANDBP program is used to obtain the neutron energy spectra after irradiation of the foils. The SANDBP program is designed to obtain a ’best fit’ neutron spectrum for a given input set of infinitely dilute foil activities [4].

MCNP5 computer code was also used for calculation of neutron flux distribution and neutron spectrum. This computer code is developed at the Los Alamos National Laboratory, USA [5]. The MCNP5 has been being officially used for core management of DNRR with ENDF/B7.0 library [6]. The calculation model for DNRR using MCNP5 computer code is shown in Figure 2.

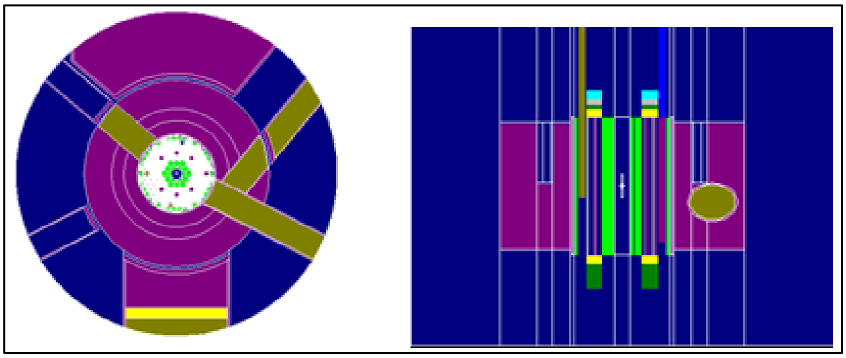

Fig. 2. Calculation model of DNRR using MCNP5 computer code.

Neutron spectrum divided into 3 energy groups calculated using MCNP5 computer code and neutron spectrum obtained from experiments at the neutron trap are shown in Table II. The reliability of simulation by MCNP5 computer code was confirmed through the good agreement of experimental and computational result. The discrepancies are about 2% in thermal neutron flux and more than 4% in epithermal neutron flux in comparison between the experimental and computational results.

Table II. Comparison of neutron flux of the neutron trap between calculation and experiment.

Flux (n/cm^2.s)	**Calculation**	**Experiment (error ±5-6%)**
Thermal	2.24×10^{13}	2.29×10^{13}
epithermal	6.52×10^{12}	6.22×10^{12}
Fast	2.56×10^{12}	2.64×10^{12}

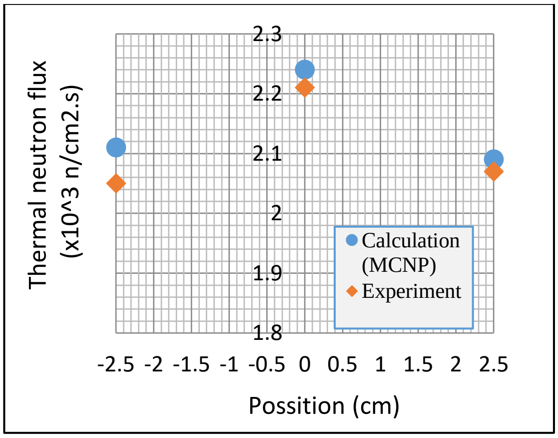

Fig. 3. Thermal neutron distributions in radial direction at the neutron trap (zero position is the neutron trap center)

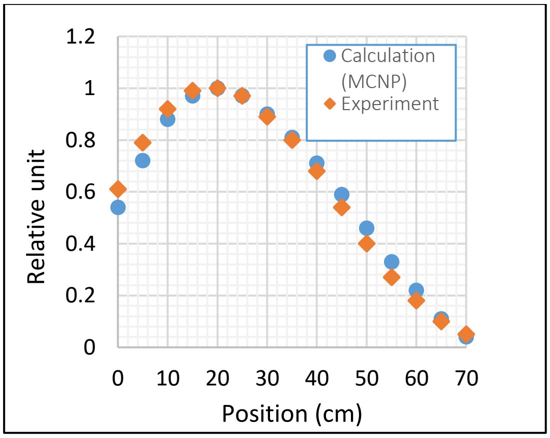

Fig. 4. Thermal neutron distributions in axial direction at the neutron trap

The experimental and computational results in Figure 3 show that the deviation of thermal neutron flux distribution in the radial direction at the neutron trap ranges within 5-7%. The experimental result is consistent with the computational result for thermal neutron flux distribution in the axial direction as shown in Figure 4. The maximum thermal neutron flux value is located at 20 cm away from the core bottom. The shift of maximum flux to the bottom of the neutron trap is mainly affected by control rod positions. With a large discrepancy of the thermal neutron distribution in both radial and axial directions, the current neutron trap needs to be redesigned to meet the requirements of NTD-Si test.

2.3. Design and testing of irradiation rig using flux screen.

The flux screen method has been selected for the purpose of NDT-Si testing in DNRR because of its consistent with characteristics design of DNRR core configuration. The principle of flux screen method to flatten the neutron flux distribution is shown in Figure 5. A uniformity of the irradiation flux is achieved by using screens from different materials to absorb neutron or change the appropriate thickness of neutron absorbers. The screens are made of strong neutron absorbers in high neutron flux region (stainless steel) and weak absorbers in low flux region (aluminum).

Dimensions of the irradiation rig and screen materials used to flatten flux distribution has been calculated and modified repeatedly by comparing calculation results using MCNP computer code and experiment results. Figure 6 shows details of the design and materials of irradiation rig.

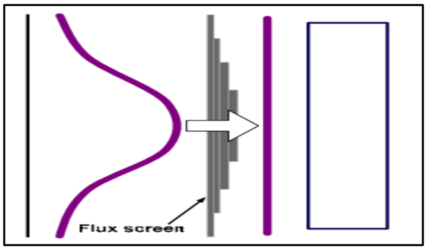

Fig. 5. Flux screen method [1].

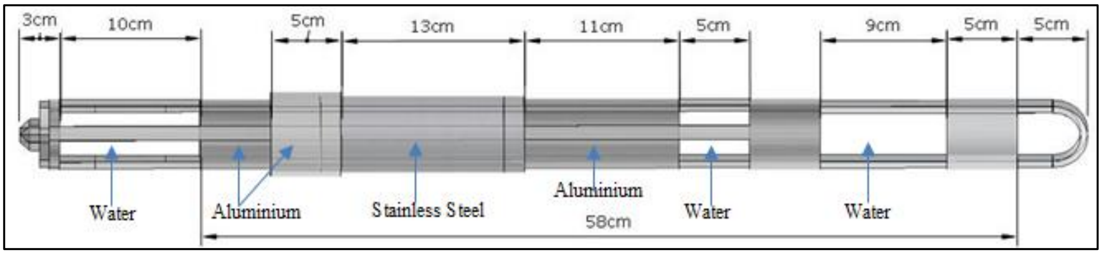

Fig. 6. The design of the irradiation rig for NTD-Si testing using flux screen method

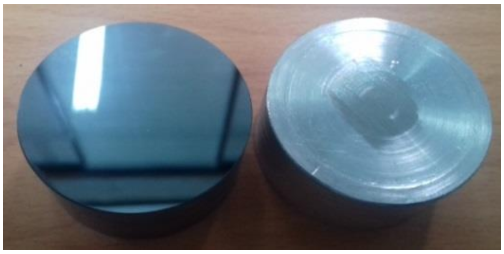

Fig. 7. Silicon ingot (left hand side) and aluminum ingot (right hand side)

Fig. 8. Aluminum ingots with Lu foils

The important parameters related to nuclear safety and radiation safety issues such as reactivity and radiation dose rate have been calculated before installing the irradiation rig in the neutron trap [7], [8]. Then, the experiment using aluminum ingots were performed. The aluminum ingots have similar neutronic characteristics and dimension of testing silicon ingots were inserted in the rig. Each ingot has a diameter of 4 cm and 2 cm in length. Lu-176 foils were attached on aluminum ingots and irradiated for the determination of thermal neutron flux distribution in the rig as shown in Figures 7 and 8.

III. RESULTS AND DISCUSSIONS

Figure 9 shows calculation results of neutron spectra when using water, aluminum or silicon in the irradiation rig. The fast neutron flux is higher than that in case of replacing of water volume in the rig by aluminum or silicon ingots.

Experimental results and calculations presented in Table III show that the deviation of thermal flux in axial direction at the irradiation region is within 5%. The distribution of thermal neutron flux in experiment is consistent with the calculation results. The thermal neutron flux peaks at 10 cm away from the bottom of the irradiation rig in the experiment and about 12 cm in the calculation. The flux distribution in the top half from the 30-34 cm of the irradiation rig tends to increase but still below the desired value of 5% in both calculation and experiment. These results show that the irradiation region of 10 cm to 36 cm in axial direction of the irradiation rig is suitable for NTD-Si test.

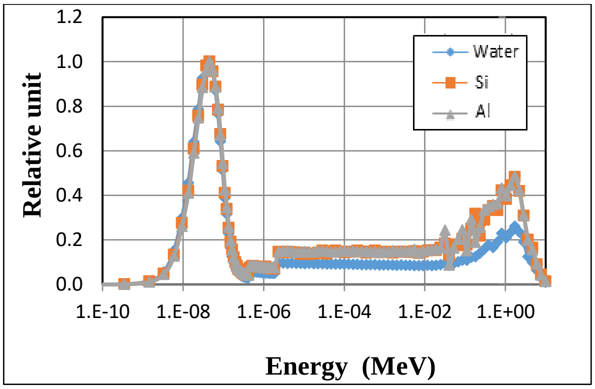

Fig. 9. Calculation of neutron spectra with water, aluminum or silicon in the irradiation rig

Table III. The relative distribution of thermal neutron flux in axial direction at the irradiation rig using flux screen method

Position (cm)	**Experiment** (error ±5-6%)	**Calculation**
10	1.000	0.991
12	0.992	1.000
14	0.999	0.995
16	0.991	0.987
18	0.960	0.972
20	0.980	0.974
22	0.967	0.969
24	0.968	0.955
26	0.979	0.962
28	0.961	0.951
30	0.958	0.953
32	0.955	0.968
34	0.960	0.971
36	0.948	0.954

Table IV and Table V present the deviation of thermal neutron flux in radial direction at the irradiation rig in calculation and experiment. The deviation is about 2% in experiment and 1% in the calculation for each position in the rig. The distribution of thermal neutron flux in radial direction in experiment is consistent with calculation result. The maximum thermal neutron flux value drops to 1.31×10^{13} n/cm^2.s in the irradiation rig due to combination of the absorption effects from the screen layers and the replacement of moderator by aluminum ingots in the irradiation rig. These results confirm that the irradiation rig using flux screen is capable of NTD-Si testing with the neutron flux uniformity in both radial and axial direction are less than 5%.

Table IV. Calculation result of thermal neutron flux distribution in radial direction at the irradiation rig using flux screen

Flux $\times10^{13}$ n/cm^2.s			
Position (cm)	Left side (-1.9 cm)	Center (0 cm)	Right side (+1.9 cm)
10	1.30	1.30	1.31
20	1.26	1.28	1.27
30	1.25	1.26	1.25

Table V. Experiment result of thermal neutron flux distribution in radial direction at the irradiation rig using flux screen

Relative unit			
Position (cm)	Left side (-1.9 cm)	Center (0 cm)	Right side (+1.9 cm)
10	0.98	1.00	0.99
20	0.96	0.98	0.97
30	0.95	0.96	0.96

Since fast neutron could cause defects in the Silicon crystal, the thermal/fast flux ratio of the irradiation channels using for NTD-Si should be at least 7/1 [9]. The calculation of the thermal/fast flux ratio of the irradiation rig using flux screen, however, is 4.38/1. The target resistivity of testing Silicon ingots would be affected by this low thermal/fast flux ratio after irradiation. In order to archive an acceptable uniformity, the silicon ingots in the irradiation area of low thermal/fast flux ratio of the rig should be replaced by dummy ingots (aluminum).

During the irradiation time, the change of power level and control rod positions of the reactor would affect the silicon irradiation condition. According to the operational workbook and lookup table of excess reactivity of the reactor, the power level and changing in control rod positions would cause an error less than 3% of the irradiation condition [7], [10].

IV. CONCLUSIONS

The irradiation rig using various screen materials has been designed and installed for NTD-Si testing at DNRR. The test with aluminum ingots, which have similar neutronic characteristics with silicon ingots, was carried out to confirm the appropriate design of the irradiation rig. The calculated and experimental results show that the uniformity of thermal neutron flux in the irradiation rig is less than 5% in height and 2% in radius, respectively.

However, the low thermal/fast flux ratio of the irradiation rig would affect target resistivity of testing Silicon ingots after irradiation. The processes of designing, installing and testing of the irradiation rig would provide good experiences in the application of NTD-Si on the new research reactor, which has planned to be built in Vietnam.

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