THE PROPOSAL FOR A NEW NEUTRON IMAGING FACILITY AT DALAT RESEARCH REACTOR

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Abstract: In this paper, we present the results of computation for design of a new neutron imaging facility located at channel No. 3 of the Dalat Reactor. The design has two main parts: the neutron beam collimator and the radiation safety system. For the neutron beam collimator, the computational parameters such as neutron flux, cadmium ratio as well as ratio of neutron dose/gamma dose are reported. The geometry sizes and the used materials to make of the neutron beam collimator, the L/D ratio, in which L is the length of the collimator, and D is the inlet aperture diameter of the collimator, are also reported. For the radiation safety system of the facility, the sizes and the chosen materials were simulated, based on radiation safety criteria. The code MCNP - 4C2 was used to simulate. Using ASTM standards, the computed results show that the imaging facility achieves the beam quality classification of IA.

Introduction

Neutron imaging is a non-destructive testing method which produces an image when neutron penetrating through object, the same as is done with X-rays to image. However, while X-rays are attenuated by high density, high atomic number materials, neutron are attenuated by low density, low atomic number materials. These make neutron radiography supplementary tool to X-rays radiography. Neutron imaging technique has had many applications in technology, science and industrial. The first neutron radiographs taken by Kallmann and Kuhn in 1935 in Germany, using the neutrons from accelerator [1]. Thewlis et al. used the neutron radiograph technique for non-destructive testing applications in the quality control of Boral sheet and the discrimination of voids in uranium using the neutron source from research reactor in 1956 [2]. Barton et al. set up the neutron radiography facility at the 200 KW Juggernaut and applied this facility to study radioactive nuclear fuel [3]. Takenaka et al. applied the neutron radiography technique to study two-phase flow for watercooled reactors, molten lead-bismuth and water for steam generator for fast-breader reactors, two-phase flows in various components of a refrigerator, visualization of a cryogenic fluid heat exchanger using liquid nitrogen as the boiling fluid [4]. Domanus used the neutron radiography technique to determine cracks, migration effects, central voids, fabrication errors and deformations in nuclear fuels [5]. Neutron imaging technique has been applied in studying plant physiology, soil [6,7], and wood [8-11], and in fuel cell and hydrogen storage materials [12-15].

At Dalat research reactor, the neutron radiography facility was designed and constructed at the channel No.3 in 1984 [22,23]. After studying on this facility for short duration, we couldn’t find the customers, who were applying for our service, then we couldn’t continue to study on this field. Today, we have found some applications using neutron imaging technique then now we open a new project to setup a new neutron imaging.

The facility consists of the neutron beam, collimation system, sample area, and laboratory facilities. The collimation system consists of an aluminium pipe assembly and a set of diverging collimators which are made from cylindrical polyethylene and lead and are lined with cadmium slabs of 1 mm thickness. The aperture of the collimation system is 30 mm and the beam diameter on sample is 320 mm. This provides an L/D ratio of 120 and thermal neutron flux of 5×10^{6}n.cm^{-2}.s^{-1} at sample position. A single crystal of bismuth filter of 50 mm length is installed at the inlet of collimator system to reduce gamma-rays and fast neutron. The wall of the sample area is constructed from high density concrete block and the beam stopper is constructed of lead and borated paraffin to effectively reduces the radiation to the background level outside the sample area. The laboratory facility includes a dark room for image processing and a room for sample preparation which is constructed near reactor hall.

2. Material and methods

2.1 Dalat Reactor

Dalat reactor was rebuilt from an USA- made 250 kW TRIGA-MARK II reactor. The core, designed in the USSR, was installed in the 6.26 m height, 1.98 m aluminum tank of the original TRIGA-MARK II reactor. Fuel elements are of the Soviet VVR-M2 type fuel assembly of 19.75% enrichment of U-235. Water is used as moderator, coolant, reflector and biological protection. The maximum neutron flux is 2.21 $\times10^{13}$n.cm-2.s-1 at neutron trap. The reactor has 4 horizontal experimental channels, among which there are one tangential and 3 radial channels. Fig. 1 shows a horizontal cross section of the Dalat reactor. The neutron spectrum in the channel No. 3 was calculated at the position far from centre of reactor core 93.74 cm with the core configuration of 92 LEU fuel assemblies and 12 berrylium rods around neutron trap, tally volume 185.7815 cm3. Fig. 2 shows the neutron calculated spectrum.

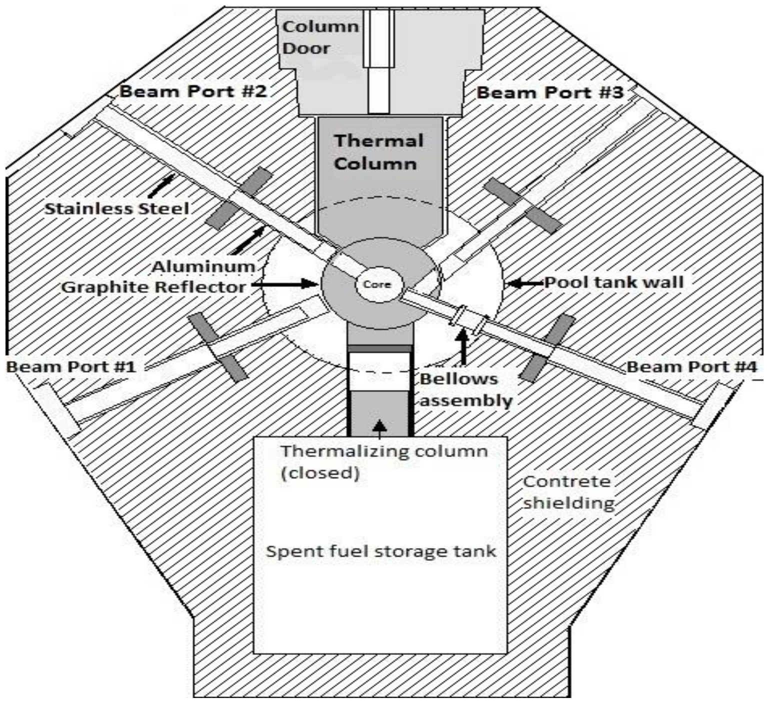

Fig. 1: Horizontal cross section of the Dalat reactor

2.2 Design criteria

The goal of design is from the neutron beam from the horizontal channel No. 3 of the Dalat reactor, using MCNP code to simulate to find out the optimum values of neutron flux and cadmium ratio at sample position and L/D ratio and neutron to gamma (N/G), so that the neutron imaging facility can perform conventional radiography and tomography. The key component of the neutron imaging facility is its neutron beam collimator, which is commonly divergent beam approach. Basing on the American Society of Testing and Material (ASTM) standards [3], the study design has been performed to meet L/D ratio about 120-150, the thermal neutron content and the neutron to gamma reach to maximum values. Several constraints were considered during study design. This include a maximum beam line length of 6 m, a reasonable thermal neutron flux at the image plane (>10^6n.cm^{-2}.s^{-1}). The location of the aperture in the beam tube entrance was calculated to be 140 cm.

2.3 Materials

The proposal neutron beam collimator as shows in Fig. 3. It consists of the following parts:

- The first section of the collimator is convergent to focus neutron on the single crystal silicon filter which are made from cylindrical polyethylene and are lined with cadmium slabs of 1 mm thickness. The angle has been selected in order to optimize the homogeneity of the flux entering the collimator to be 3.05^0
- At the filter position, a cylindrical Bi with the diameter of 50 mm was inserted to shield gamma ray from the reactor core, because Bi is a good material to shield gamma ray since it has large gamma absorption coefficient and its neutron capture cross section is smaller than that of lead. A Si single crystal filter is the next convergent collimator section and plays as the moderator role. Because single crystal Si has thermal neutron cross section is much small (0.3 barn), therefore it serves as moderator to produce thermal neutron [19]. The collimation system consists of an aluminium pipe assembly and a set of diverging collimators which are made from conical polyethylene and lead and are lined with cadmium slabs of 1 mm thickness. The aperture of the collimation system is 30 mm and the beam diameter on sample is 220 mm.

2.4 MCNP simulation

The MCNP 4-C2, developed at the Los Alamos National Laboratory, is a general purpose Monte Carlo code. The code can be used to model 3-D transport of neutrons, photons, coupled neutron/photons, coupled photons/electrons [21]. ORIGEN-RA is a modified version of the ORIGEN code developed by Oak Ridge National Laboratory. This code is used to perform isotopically detailed nuclide transmutation calculations based on the flux history. In addition to nuclide inventories, this code is used to estimate radiation emission characteristics and decay power for irradiated reactor constituents.

The simulations were performed in two steps: the first one was performed to calculate the neutron spectrum using MCNP 4C2 code and gamma spectrum using ORIGEN-RA for input data of second step. The computed results including neutron spectrum and gamma spectrum, were shown in the fig. 2, 3. The second step was performed to determine the length of the Bismut and Silicon filters, the inlet aperture diameter of the collimator D.

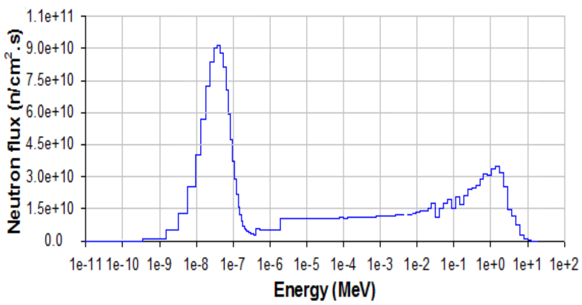

Fig. 2: Neutron spectrum calculated by using code MCNP 4C2

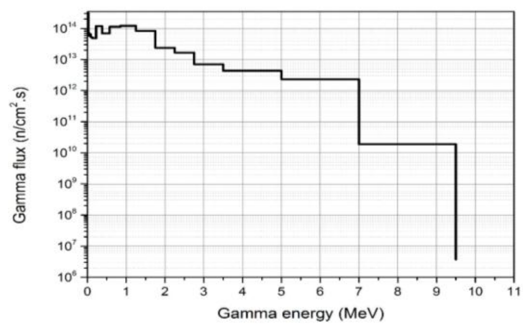

Fig. 3: Gamma spectrum calculated by using ORIGEN code

Gamma ray spectrum calculated by using ORIGEN code to use in MCNP simulation. Thông lượng gamma được xác định là 1,17 x 10^{15} g.cm^{-2}.s^{-1}.

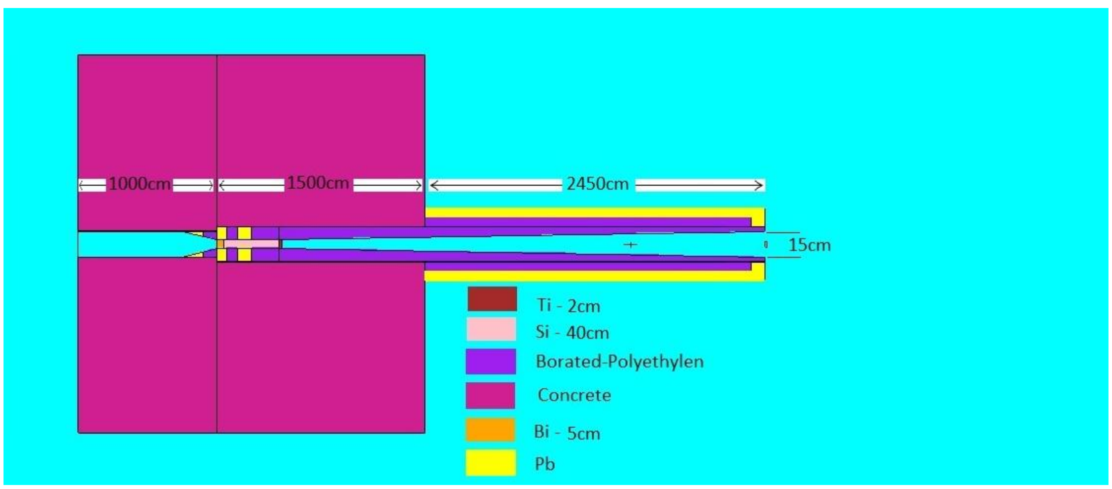

Fig. 3: Longitudinal section of collimator from MCNP simulation.

For second step simulation, after choosing the material to build the collimator, the calculation simulation have been performed the varying of the thermal neutron flux, ratio of thermal neutron flux to epithermal neutron flux at group of three data of the length of Si filters at 4, 10, 15, 20, 25, 30, 35, 40 cm; the length of Bi filter at 1, 2, 3, 4, 5 cm; and the diameter of Si and Bi filters at 4, 5, 6. The calculated results are shown in tables 1, 2, 3. Comparing with the need criteria of the beam quality (neutron flux $\geq 10^6$n.cm^{-2}.s^{-1}, $\varphi_{tot}/\varphi_{epi}$ = 80÷120, L/D = 100÷150), the group of Si filter length 20 cm, Bi filter length 5 cm and diameter of Bi and Si 4 cm is satisfy.

There is a darkroom facility for developing neutron radiographs. Other facilities includes a microdensitometer, neutron radiography camera of different sizes with different converter foils and vacuum cassettes.

Table 0.1. Neutron flux, ratios ϕ_{tot}/ϕ_{epi} and L/D (D=4cm) varying to thickness in cm of Bi and Si.

	Si / Bi	5	10	15	20	25	30	35	40
N_Flux	1	2.68E+06	2.36 E+06	2.08E+06	1.84 E+06	1.63 E+06	1.45 E+06	1.28 E+06	1.14 E+06
$\varphi_{tot}/\varphi_{epi}$		36.1	40.5	46.0	51.3	58.0	65.5	74.0	83.7
L/D		129.8	128.5	127.3	126.0	124.8	123.5	122.3	121.0
N_Flux	2	2.36E+06	2.08 E+06	1.83 E+06	1.62 E+06	1.44 E+06	1.27 E+06	1.13 E+06	9.99 E+05
$\varphi_{tot}/\varphi_{epi}$		40.7	45.6	51.6	57.8	65.3	73.8	83.4	94.3
L/D		129.5	128.3	127.0	125.8	124.5	123.3	122.0	120.8
N_Flux	3	2.07E+06	1.83 E+06	1.61 E+06	1.43 E+06	1.27 E+06	1.12 E+06	9.91 E+05	8.79 E+05
$\varphi_{tot}/\varphi_{epi}$		45.5	51.6	58.2	65.1	73.5	83.1	93.9	106.1
L/D		129.3	128.0	126.8	125.5	124.3	123.0	121.8	120.5
N_Flux	4	1.82 +06	1.61 E+06	1.42 E+06	1.26 E+06	1.11 E+06	9.87 E+05	8.72 E+05	7.74 E+05
$\varphi_{tot}/\varphi_{epi}$		53.2	60.5	69.1	76.6	86.0	94.9	106.9	126.8
L/D		129.0	127.8	126.5	125.3	124.0	122.8	121.5	120.3
N_Flux	5	1.61E+06	1.42 E+06	1.25 E+06	1.11 E+06	9.80 E+05	8.69 E+05	7.67 E+05	6.81 E+05
$\varphi_{tot}/\varphi_{epi}$		59.5	67.7	77.4	85.8	96.4	106.3	119.8	142.0
L/D		128.8	127.5	126.3	125.0	123.8	122.5	121.3	120.0

Table 0.2. Neutron flux, ratios ϕ_{tot}/ϕ_{epi} and L/D (D=5cm) varying to thickness in cm of Bi and Si.

	Si / Bi	5	10	15	20	25	30	35	40
N_Flux	1	4.13E+06	3.64 E+06	3.20 E+06	2.83 E+06	2.49 E+06	2.20 E+06	1.94 E+06	1.71E+06
$\varphi_{tot}/\varphi_{epi}$		36.1	40.5	46.0	51.3	58.0	65.5	74.0	83.7
L/D		103.8	102.8	101.8	100.8	99.8	98.8	97.8	96.8
N_Flux	2	3.62 E+06	3.20 E+06	2.81 E+06	2.48 E+06	2.19 E+06	1.93 E+06	1.70 E+06	1.50 +06
$\varphi_{tot}/\varphi_{epi}$		40.7	45.6	51.6	57.8	65.3	73.8	83.4	94.3
L/D		103.6	102.6	101.6	100.6	99.6	98.6	97.6	96.6
N_Flux	3	3.19E+06	2.82 E+06	2.49 E+06	2.19 E+06	1.93 E+06	1.70 E+06	1.50 E+06	1.33E+06
$\varphi_{tot}/\varphi_{epi}$		45.5	51.6	58.2	65.1	73.5	83.1	93.9	106.1
L/D		103.4	102.4	101.4	100.4	99.4	98.4	97.4	96.4
N_Flux	4	2.82 E+06	2.49 E+06	2.20 E+06	1.94 E+06	1.71 E+06	1.51 E+06	1.33 E+06	1.17E+06
$\varphi_{tot}/\varphi_{epi}$		52.3	59.1	66.8	75.5	85.3	96.4	108.9	123.0
L/D		103.2	102.2	101.2	100.2	99.2	98.2	97.2	96.2
N_Flux	5	2.50 E+06	2.21 E+06	1.95 E+06	1.73 E+06	1.53 E+06	1.36 E+06	1.20 E+06	1.06E+06
$\varphi_{tot}/\varphi_{epi}$		60.0	67.7	77.4	8.8	96.4	106.3	119.8	142.0
L/D		103.0	102.0	101.0	100.0	99.0	98.0	97.0	96.0

Table 0.3. Neutron flux, ratios ϕ_{tot}/ϕ_{epi} and L/D (D=6cm) varying to thickness in cm of Bi and Si.

	Bi \ Si	5	10	15	20	25	30	35	40
N_Flux	1	6.00E+06	5.30E+06	4.68E+06	4.14E+06	3.67E+06	3.25E+06	2.87E+06	2.55E+06
$\varphi_{tot}/\varphi_{epi}$		36.1	40.5	46.0	51.3	58.0	65.5	74.0	83.7
L/D		86.5	85.7	84.8	84.	83.2	82.3	81.5	80.7
N_Flux	2	5.28E+06	4.67E+06	4.12E+06	3.65E+06	3.23E+06	2.86E+06	2.53E+06	2.25E+06
$\varphi_{tot}/\varphi_{epi}$		40.7	45.6	51.6	57.8	65.3	73.8	83.4	94.3
L/D		86.3	85.5	84.7	83.8	83.0	82.2	81.3	80.5
N_Flux	3	4.64E+06	4.11E+06	3.62E+06	3.21E+06	2.84E+06	2.52E+06	2.23E+06	1.98E+06
$\varphi_{tot}/\varphi_{epi}$		45.5	51.6	58.2	65.1	73.5	83.1	93.9	106.1
L/D		86.2	85.2	84.3	83.5	82.7	81.8	81.0	80.2
N_Flux	4	4.09E+06	3.61E+06	3.19E+06	2.82E+06	2.50E+06	2.22E+06	1.96E+06	1.74E+06
$\varphi_{tot}/\varphi_{epi}$		53.2	60.5	69.1	76.6	86.0	94.9	106.9	126.8
L/D		86.0	85.2	84.3	83.5	82.7	81.8	81.0	80.2
N_Flux	5	3.60E+06	3.18E+06	2.80 E+06	2.48 E+06	2.20 E+06	1.95 E+06	1.72 E+06	1.53 E+06
$\varphi_{tot}/\varphi_{epi}$		59.5	67.7	77.4	85.8	96.4	106.3	119.8	142.0
L/D		85.8	85.0	84.2	83.3	82.5	81.7	80.8	80.0

A new mechanical sample transfer system is designed to permit the transportation of samples from the outside the exposure cell to the sample position, which is fixed on the holder table. This system can transfer a radiograph object and the cassette up to 5 kg in weight. The sample transfer time from outside to sample position of this system is 2 seconds, which is faster than the old one. A heavy and/or big object is to be inserted on the neutron beam separately from the cassette.

A beam catcher of dimension 100 cm × 100 cm × 80 cm having a diameter 60 cm and length 40 cm cylindrical hole in the middle of the front face, a 30 cm × 30 cm ×15 cm lead block is placed at the back of the hole for gamma shielding. The cylindrical hole is lined with 2mm thick boron carbide sheet for neutron shielding.

3. Conclusion

A study design of a new neutron beam collimator of neutron imaging facility at Dalat reactor is done to construction of the facility for both neutron radiography and tomography for various scientific, engineering and industrial application, non-destructive testing and industrial inspection. The MCNP code has been used to simulate the collimator. Many sectors of collimator have been optimized by simulation.

- The optimal thickness of the single-crystal silicon filter is fixed at 70 cm.
- The length of the collimator was simulated to be 3.4 m.

- The kind of materials for construction of the collimator were selected.

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TÍNH TOÀN THIẾT KẾ CHO THIỀT BỊ CHỤP ẢNH NƠTRON TẠI LÒ PHẢN ỨNG HẠT NHÂN ĐÀ LẠT

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Tóm tắt: Trong bài báo này chúng tôi trình bày kết quả tình toán thiết kế cho thiết bị hình ảnh notron mới đặt tại kênh số 3 của lò phản ứng hạt nhân Đà lạt. Bản thiết kế gồm có hai phần, gồm ống chuẩn trực dòng nơtron và phần bảo vệ an toàn bức xạ. Đối với ống chuẩn trực dòng nơtron, các kết quả tính toán các tham số như thông lượng nơtron, tỷ số thông lượng nơtron toàn phần trên nơtron nhiệt và tỷ số liều nơtron trên liều bức xạ gamma được trình bày. Chúng tôi cũng trình bày kết quả tính toán về kích thước hình học, lựa chọn vật liệu sử dụng để xây dựng ống chuẩn trực, tỷ số L/D, trong đó L là chiều dài ống chuẩn trực và D là đường kính lối vào của ống chuẩn trực. Đối với thiết bị che chắn an toàn bức xạ, chúng tôi trình bày kết quả tính toán mô phỏng để tìm ra kích thước hình học và vật liệu sử dụng để xây dựng, phù hợp với các tiêu chuẩn an toàn bức xạ. Các phần mềm MCNP-4C2 và ORIGEN đã được sử dụng để tính toán mô phỏng. Dựa theo các chuẩn của ASTM, kết quả tính toán cho thấy thiết bị đề nghị đạt được loại IA

Từ khóa: Hình ảnh nơtron, ống chuẩn trực dòng nơtron, tỷ thông lượng nơtron toàn phần /nơtron nhiệt gamma, tỷ số liều nơtron/liều bứcxạ gamma, tỷ số L/D.