Neutronics Assessment for the Thailand Tokamak Upgrade*)

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Shielding configuration studies for the fusion plasma experiment of the Thailand tokamak upgrade are presented in this work. The neutron rate of 10^{14} n/s of DT fusion is determined to assess the next step operation in phase II of the Thailand tokamak upgrade in the future. In order to optimize the materials and dimensions of the shielding, a series of MCNP simulation was performed to assess the neutron streaming in order to enhance understanding of neutron and gamma transport in the plasma torus, hall and the pathways shielding. Effect of three commonly available concrete composition (ordinary concrete, barite concrete and boron frits-baryte concrete) have been investigated as a torus wall shielding and entrance maze. Four orders of magnitude of fast neutron flux reduction was observed at outside torus hall. The thermal neutron was significantly reduced using the labyrinth structure. The conceptual design of the biological radiation shielding is assessed and presented. This study provides support for the future neutron and gamma radiation safety at the Thailand tokamak upgrade facility.

Keywords: Thailand tokamak, shielding, neutron, MCNP

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1. Introduction

It is important to understand the neutron and gamma radiation distributions in the thermonuclear fusion device study [1–4]. Neutrons are uncharged particles which escape the magnetic field and interact with the surrounding structure through the elastic and inelastic scattering, neutron capture and other events. Gamma rays are mainly produced by the interaction of the neutron and surrounding structure of the tokamak. The information of radiation flux distribution in fusion device allows the prediction of other quantities such as radiation dose, radiation heating, radiation damage, neutron activation and other parameter necessary for safety studies [1]. For the radiation safety, many parameters in building construction become important to protect against radiation damage to operating and casual personnel. The design of biological shielding and building construction depends on the operating parameters, physics and engineering requirements specified for the machine. Many types of concrete, ordinary, heavyweight, barite, etc., have been widely used for radiation protection in nuclear power plants, medical field and other application where radioactive shielding is required [5, 6].

For Thailand, the Thailand tokamak will be constructed based on the HT-6 M tokamak and installed at Thailand Institute of Nuclear Technology (TINT), Ongkharak site in Nakorn Nayok under the guidance of Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) and the collaboration of the Center for Plasma and Nuclear Fusion Technology (CPaF) in 2019-2020. The machine was previously developed and operated by the ASIPP in Hefei [7]. It was originally designed for the study of auxiliary heating (neutral beam injection and ion and electron cyclotron resonance heating), transport process and diffusion process of the impurity [8–10]. In phase I operation at TINT, hydrogen plasma will be used. However, the neutron flux is determined to assess the next step operation in phase II of the Thailand tokamak which can be upgraded to fusion plasma. For such small tokamak, total neutron up to 10^{14} n/s is estimated to be generated. With such high neutron flux, there is potential hazard to workers and environment. Therefore, the emitted neutron and gamma-rays must be shielded more effectively in the tokamak vessel and the building. In this work, the design of the Thailand tokamak upgrade biological shielding is investigated. A series of neutronics analysis have been performed for Thailand tokamak upgrade based on the existing HT-6 M geometry and parameters as shown in Table 1. The calculations are carried out using the Monte Carlo method based on Monte Carlo N-Particle (MCNP5) [11] and nu-

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Table 1 Main parameters of HT-6 M [7].

Parameter	Value
Major radius, R (cm)	65
Minor radius, a (cm)	20
TF on axis, B_t (kG)	15
Plasma current, I_p (kA)	150 (q = 3)
Flat-top time, t_{ft} (ms)	150
Ion temperature, T_i (eV)	400
Electron temperature, T_e (eV)	800
Plasma density, n (cm^{-3})	1×10^{14}
Confinement time, τ_E (s)	0.01

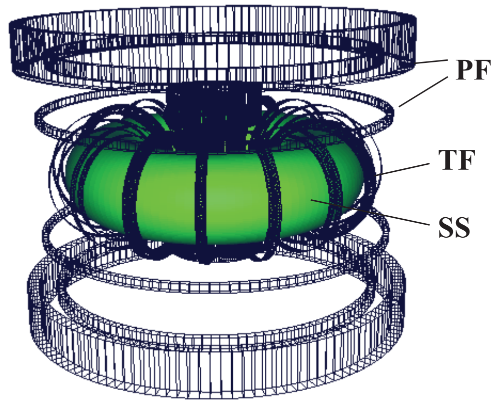

Fig. 1 3-D calculation model of the Thailand tokamak upgrade for estimating neutron streaming at the plasma torus and surrounding structure.

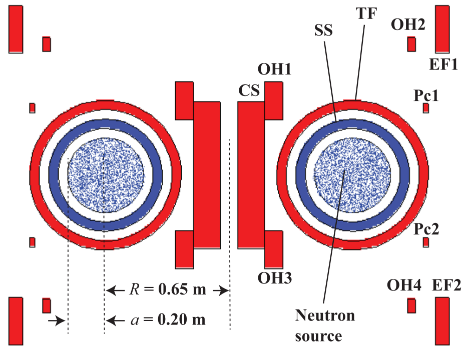

Fig. 2 A cross-section view of the Thailand tokamak with TF and PF coils and neutron source.

clear library ENDF-VI for the simple torus geometry and shielding for the torus hall. The results of neutron and gamma fluences around the tokamak device have been estimated. The conceptual design of the biological radiation shielding is investigated. The study provides results that can be used for neutron and gamma radiation safety in the Thailand tokamak upgrade commission and operation in the future. This paper consists of the following sections: section 2 represents the tokamak and shielding geometry, section 3 represents the results and section 4 represents summary of this work.

2. Tokamak and Shielding Geometry

In this work, the 3-D transport method calculations based on the MCNP code are performed to estimate of radiation streaming at the plasma torus and surrounding structure of the Thailand tokamak upgrade. Detailed geometrical model of Thailand tokamak upgrade and torus hall have been created and described in this section. The model consists of approximately 40 cells defined using about 70 surfaces. The vacuum vessel and magnetic field coil have been modeled using the existing parameters of HT-6 M tokamak [7].

2.1 Thailand tokamak upgrade model

Thailand tokamak upgrade is set to be developed from the existing tokamak chamber of HT-6 M tokamak. The main parameters are shown in Table 1. To prepare for the installation and operation, J. Promping et al. [12] have studied the relevant plasma scenarios that will be operated using this tokamak by using turbulent transport models e.g. Multi mode model (MMM95) and Mixed Bohm/gyro-Bohm (Mixed B/gB) with BALDUR code. The results provide the background plasmas in range of $n_e(0) \sim 1.2 \times 10^{19}$ m^{-3}, $n_e(a) \sim 0.6 \times 10^{18}$ m^{-3}, $T_e(0) \sim 600$ eV and $T_e(a) \sim 10$ eV where a is the minor radius [12].

In phase II, the Thailand tokamak is aimed toward operation using plasma which is estimated to generate total neutron up to 10^{14} n/s. Therefore, the machine requires the construction of radiation shielding. The 3-D simple torus geometry is shown in Fig. 1. The model consists of plasma facing components, vacuum vessel made of stainless steel, toroidal field coils made of copper, poloidal field coils (PF), including of equilibrium field coils and displacement feedback control coil, made of copper and concrete shielding walls. Figure 2 shows a cross-sectional view of the torus with the major radius (R) of 65 cm and minor radius (a) of 20 cm, stainless steel vessel (SS), 16 toroidal field coils (TF) and 9 poloidal field coils (CS, OH1-OH4, EF1-EF2, Pc1-Pc2). In the hydrogen plasma operation stage in phase I, the existing vacuum vessel of stainless steel welding with two insulation gaps with the major radius of 0.65 m, minor radius of 0.25 m and thickness of 5 mm is used. In the upgraded design for the fusion plasma, the vacuum vessel wall is implemented with a thick layer of stainless steel and iron wall in order to minimize the fast neutron fluence and displacement damage to the coil. Due to the limitation space between vacuum vessel and the TF coil, the combination of stainless steel and iron is limited at 10 cm thick toward the TF coil direction.

The uniform 14.1 MeV neutron source from deuterium-tritium (D-T) fusion plasma with the minor radius of 20 cm by assuming toroidal and poloidal symmetries has been developed in the model as shown in the poloidal cross section view in Fig. 2. The statistical weight of the particle is set as 1×10^{14} n/s. The scrape-off layer (SOL) has been set to 5 cm.

2.2 Torus hall

The biological shielding and building construction have been implemented to quantify radiation streaming during the fusion plasma operation. The purpose is to ensure a low level external radiation flux. Aim of the design in this work is to reduce worker exposure in the Thailand tokamak upgrade building and to reduce the displacement damage to the various equipment. The toroidal and poloidal view of the torus hall is shown in Fig. 3. The torus hall layout occupies area of 10 m × 10 m including free space for the additional systems (diagnostic system, heating system, various equipments, etc.). The entrance maze is located at the corner of the torus hall. One of the design requirements for the Thailand tokamak is that neutron flux outside the torus hall be low enough to permit human working activities. For this purpose the torus model was complemented by the design of ordinary concrete structure all around the torus facility. The thickness of the ordinary concrete wall, floor, roof and entrance maze is 30 cm as depicted in green in Fig. 3. Additionally, the effect of the concrete composition (ordinary concrete with density of 2.35 g/cm^3, barite concrete with density of 3.35 g/cm^3 and boron frits-baryte concrete with density of 3.10 g/cm^3) is determined for different neutron and gamma attenuation purpose and is presented in this paper.

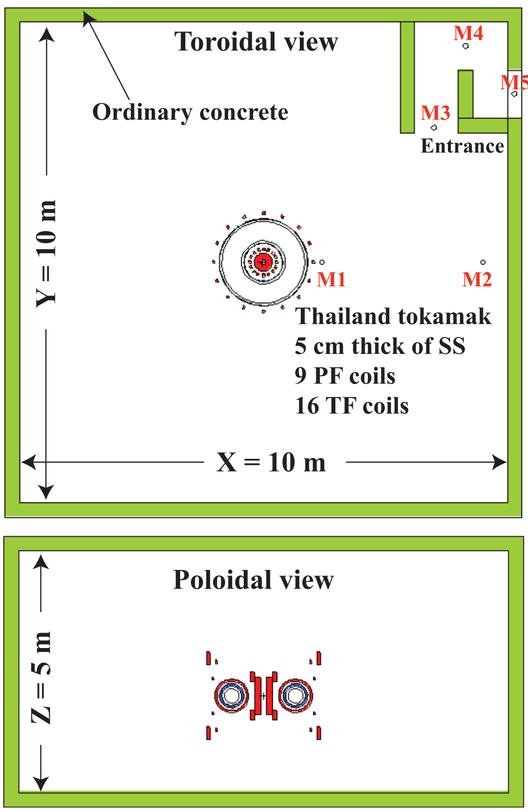

Fig. 3 MCNP geometry of the torus hall with ordinary concrete wall.

3. Results

3.1 Vacuum vessel shield

In the present work, the neutron transport in the torus and neutron streaming through the TF coils, PF coils and vacuum vessel are evaluated. The neutron streaming through the torus, torus hall and entrance maze is shown in Fig. 4. It is clearly seen in the figure that the neutron stream is attenuated by the designed ordinary concrete wall in the model. The neutron rate of ~ 5×10^8 n/s is observed at the plasma core and is reduced by two orders of magnitude approximately outside the concrete wall.

Figure 5 shows the midplane neutron fluence profile (at Z = 200 cm) in radial direction between the torus centre (X = 0 cm) and outside the torus hall (X ≥ 500 cm). The neutrons that are directed towards the thick vacuum vessel wall are scattered back to the plasma. It can be seen the increasing peak of the neutron flux in the plasma core when the thickness of the stainless steel (SS) and iron (Fe) is increased. There is no significant reduction of the neutron streaming in the torus hall for different vacuum vessel shielding thickness and material. However, it can be seen that the neutron flux in the torus hall is lower than in the vacuum vessel about two orders of magnitude.

3.2 Torus hall shield

Originally, 30 cm-thick ordinary concrete structure (wall, floor, roof and entrance maze) was modeled as shown in green in Fig. 3. The neutron fluence was deter-

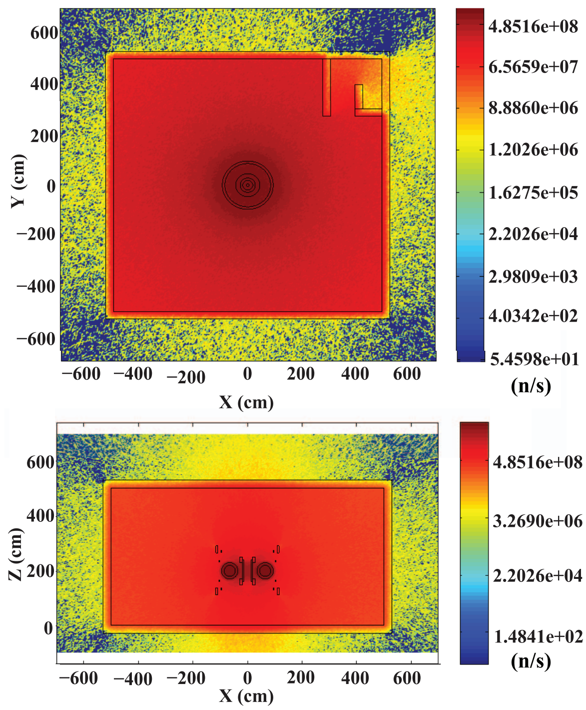

Fig. 4 Top: top view, at Z = 200 cm, of neutron streaming through the torus, torus hall and entrance maze. Bottom: poloidal cross section view of neutron streaming through the torus and torus hall.

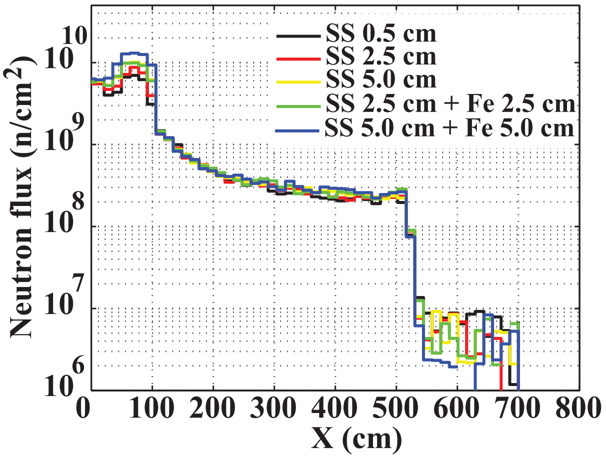

Fig. 5 Midplane neutron flux profile (Z = 200 cm) with different vacuum vessel wall thickness and material.

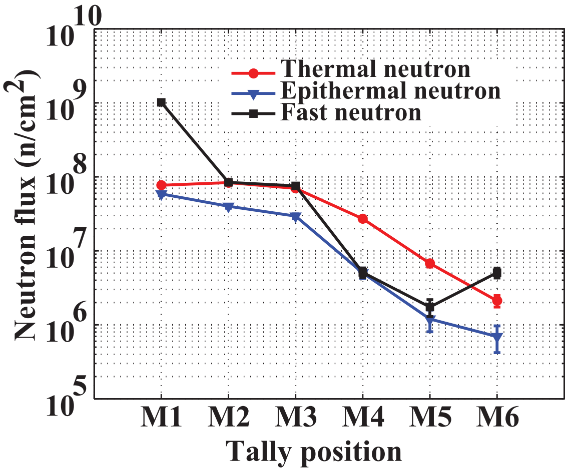

Fig. 6 Neutron flux at M1-M6 tallies position (as shown in Fig. 3) with the 30 cm-thick ordinary concrete wall.

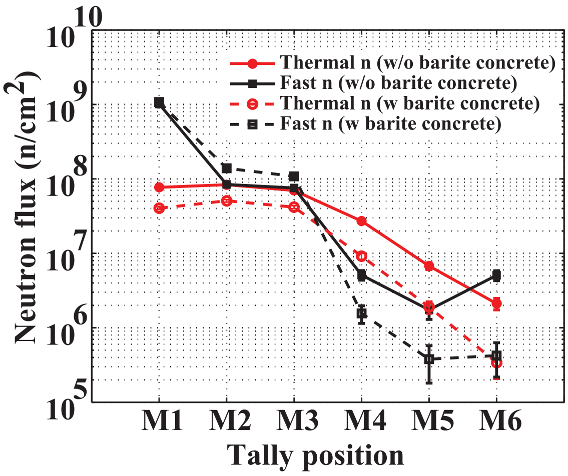

Fig. 7 Neutron flux at the M1-M6 positions with and without the 30 cm-thick barite concrete covering the 30 cm-thick ordinary concrete wall.

mined in the air using the MCNP track length estimation tallies of the neutron flux (F4:n). The tallies is set up using the spherical cells of 5 cm in radius and positioned at M1-M6 (depicted in Fig. 3) along the radial direction of torus and pathways of the entrance maze.

In Fig. 6, the neutron flux is presented in three energy groups: i) thermal neutron (E < 0.5 eV); ii) epithermal neutron (0.5 eV ≤ E ≤ 0.1 MeV); and iii) fast neutron (E > 0.1 MeV) for different positions of cell tallies (M1-M6). It can be seen that the neutron fluxes are attenuated by the ordinary concrete shield (between position M1, M2 and M6) by three orders of magnitude and by maze (between position M3, M4 and M5) by two orders of magnitude.

At horizontal position outside concrete wall (M6), the neutron flux is dominated by fast neutron (as shown in Fig. 6) therefore the additional fast neutron shield is needed. For the further design, the internal surface of the ordinary concrete wall is covered by 30 cm-thick layer of barite concrete in order to minimize the neutron streaming through the torus hall. The barite concrete has been considered as a heavyweight concrete shielding. The most important part of the design needs to determine fast neutron streaming and reducing through the biological shielding.

Figure 7 shows the comparison of thermal and fast neutron at different tally position by using the ordinary concrete wall with and without barite concrete layer. The thermal neutron flux reduction along the radial direction and pathways from position M1 to M6 was observed. The fast neutron flux of 3×10^5 n/cm^2 approximately are observed at position M6. Due to the high fast neutron absorption cross-section of barite, the fast neutron is attenuated by the barite concrete by one order of magnitude. There are no significant epithermal neutron flux reduction by using the heavyweight concrete wall.

3.3 Entrance maze

As can be seen on the red-circle-dashed line in Fig. 7 that the neutron flux in the entrance maze (at position M4 and M5) is dominated by thermal neutron. A further attenuation of neutron fluence can be achieved by using a layer of thermal neutron absorption material. The concrete, boron frits-baryte was implemented in the model as shown in blue in Fig. 8. The thickness of boron frits-baryte concrete is varied between 10 - 20 cm due to the limitation space of entrance maze. The pathway width is between 60 - 70 cm.

The results show that thermal neutron flux was attenuated by two orders of magnitude at the labyrinth position (M4) and by one order of magnitude at the exit maze (M5) as can be seen in Fig. 9.

Moreover, one of the most important issue of the neutronics calculation is to study the neutron capture gamma-ray stream because it causes heat in the tokamak components. The gamma-ray flux is generated due to thermal neutron capture in a surrounding structure (torus and

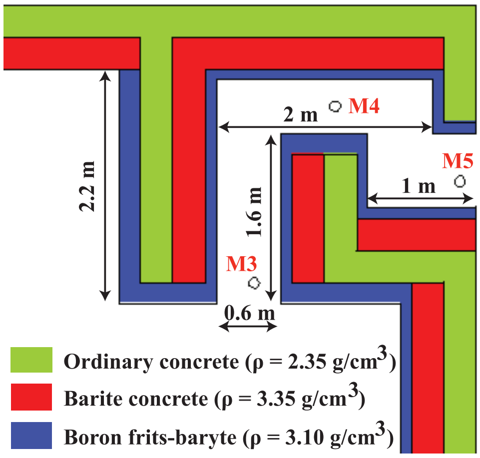

Fig. 8 Cross section view of the torus hall entrance maze.

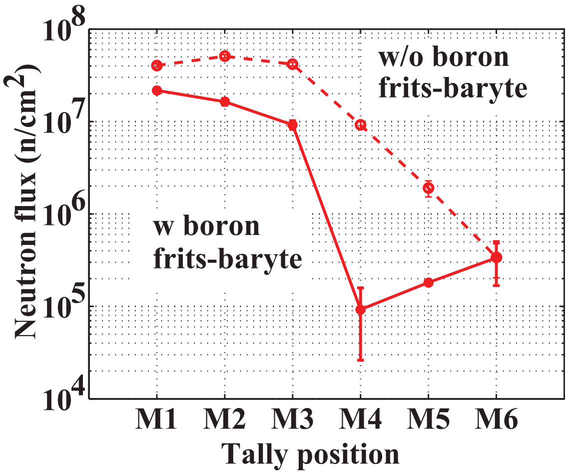

Fig. 9 Thermal neutron flux at M1-M6 tallies position with and without the implementation of boron frits-baryte concrete wall on the ordinary and barite concrete.

shielding). In this work, the calculation of the neutron capture gamma-ray flux due to neutron capture in a concrete combination shield have been concerned and presented in Fig. 10. The red-square-dashed shows the gamma flux generated by captured neutron around the torus structure and ordinary and barite concrete wall. About ~ 5×10^8 photon/cm^2 is observed near the torus (M1). The gamma fluxes reduce by one order of magnitude in radial direction in the torus hall (M2 and M3) and significantly decrease in the maze and outside torus wall (M4-M6). However, it can be seen that by covering the entrance maze with boron frits-baryte concrete, the gamma flux induced at the labyrinth position (M4) and exit maze (M5) reduce by one order of magnitude.

4. Summary

The neutron flux of the Thailand tokamak upgrade was evaluated using the MCNP code. The model consists

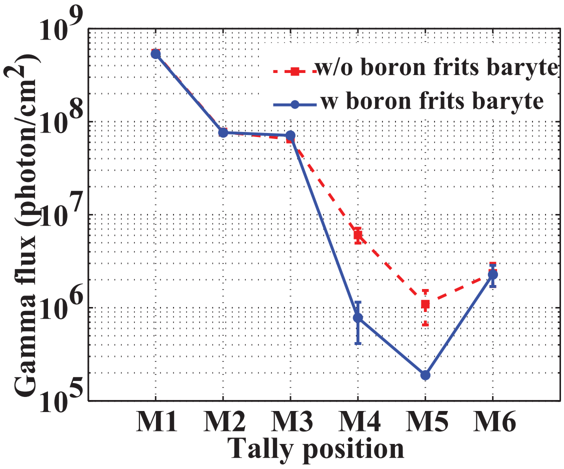

Fig. 10 Gamma flux at M1-M6 tallies position with and without the implementation of boron frits-baryte concrete wall on the ordinary and barite concrete.

of torus structure including the vacuum vessel, TF coils, PF coils, torus hall and biological shielding by using the different concrete compositions. The various thickness of stainless steel and iron were complimented to the HT-6 M existing vacuum vessel wall. The results show that the neutron flux is not significantly reduced in the torus hall when the layer of stainless steel and iron is added. The neutron and gamma streaming can be attenuated by the combination of different type concrete compositions wall. The radiation fluence along the labyrinth structure is significantly reduced. The design of biological shielding presented in this paper contributes to the installation, commissioning and upgrade design stages of the Thailand tokamak project.

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