Neutron Transport Calculations for ITER

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Summary

With the development of the upcoming International Thermonuclear Experimental Reactor (ITER), analysis is being done into the neutron behaviour in a fusion reactor. This is an important consideration for reactor shielding and power production. Many of the neutron analysis techniques used in fission reactors such as multi-group energy approximations and diffusion theory approximations of the neutron transport can still be applied to calculate neutron flux distributions in fusion reactors [1,2]. As demonstrated in fission reactor analysis, the terms in the diffusion equation can be divided into Production, Scattering, Absorption and Leakage terms. Using these four neutron interactions, the neutron behaviour in a fusion reactor can be analyzed.

1.0 Introduction

The distribution of neutrons in a fusion reactor obey a diffusion equation that is very similar to that of a fission reactor. The diffusion equation is given by [1,2]:

$$-\nabla\cdot D(r,E)\nabla\varphi(r,E)+\Sigma_t(r,E)\varphi(r,E)+\int dE'\,\Sigma_s(r,E'\rightarrow E)\varphi(r,E)+S(r,E)=0 \qquad (1)$$

where:

$\varphi(r,E)=$ Neutron Flux
$\Sigma_t(r,E)=$ Total Neutron Interaction Cross Section
$D(r,E)=$ Diffusion Coefficient
$S(r,E)=$ Source of Neutrons
$\Sigma_s(r,E)=$ Scattering Cross Section

Although this equation appears similar to that of a nuclear reactor, the interactions of neutrons will differ in a fusion reactor when compared to a fission reactor. This is mainly due to the difference in material composition and neutron energy spectrum’s present in both reactor types.

2.1 Production:

Nuclear fusion will be the primary source of neutrons in ITER. The fusion reaction between Deuterium-Tritium is given by [3,4,5]:

$$^{2}_{1}D+^{3}_{1}T=^{4}_{2}He+^{1}_{0}n \qquad (2)$$

The neutron released from this fusion reaction will have an energy of 14.1 MeV [3].   One can determine the 14.1 MeV neutron production rate in a fusion reactor by calculating the reactor rate of Equation 2 [3,4,5]. The calculation of the fusion reaction rate differs from the fission reaction rate. In a fission reactor, the fission rate is given by [6]:

$$R_{fission}(E)=\Sigma_f(E)\Phi(E) \tag{3}$$

The reaction rate in fission is proportional to the fission cross section and the neutron flux. In contrast the fusion reaction rate is given by:

$$R_{fusion}=n_D n_T<\sigma v>=\frac{1}{4}n_e^2<\sigma v> \tag{4}$$

The fusion reaction rate is independent of the neutron flux. The fusion reaction rate is dependent only on the densities of the two fusion reactants, their relative velocities and their fusion cross section. As the fusion cross section is a function of the ion energies, the <σv> term in Equation 4 is usually stated as the reaction rate. Deuterium-tritium fusion has the highest reaction rate compared to other fusion reactions such as deuterium-deuterium and deuterium-helium fusions. Overall, from Equation 4 it is apparent that the distribution of neutron production in the Tokamak will be a function of the distribution of the plasma temperature and density[3].

The walls of the Tokamak are the best suited area to compare the neutron flux spectrum of a fusion and fission reactor. This is because the neutron flux at the first wall of a fusion reactor will determine the amount of heat generation that will occur [7]. Calculations using the MCNP neutron code have been done to calculate what the projected neutron flux will be at the first wall of DEMOnstration Power Plant, the proposed fusion power plant which is to be ITER's successor. Figure 1 displays their results comparing the simulated neutron flux of a 3.0 GW fusion reactor to that of the 3.8 GW fission reactor in Paluel, France [7].

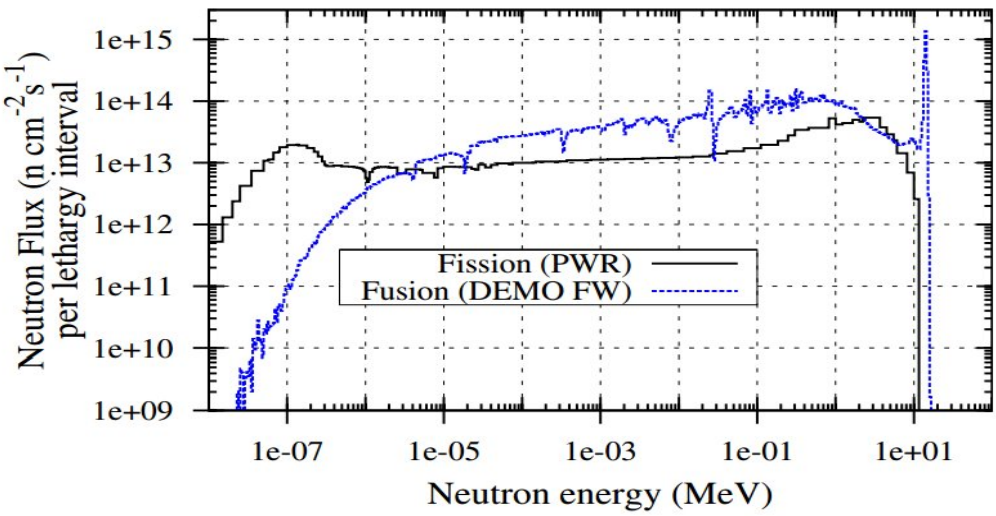


Figure 1: Comparison of neutron flux in a fission and fusion reactor. [7]

Note that the results displayed in Figure 1 are only reliable for neutron fluxes above the thermal energy range [7]. From Figure 1, it is observed that at the First Wall there will be a spike of 14.1 Mev neutrons. However there will also be a considerable amount of neutrons in the 10 eV to 1 MeV range. Clearly, fusion reactor analysis will be concerned primarily with neutron energies in the fast neutron energy range, unlike fission reactors where the focus in on thermal neutrons.

2.2 Scattering:

Neutron scattering in fission reactors is a crucial phenomenon and must occur in order for fission reactors to operate in steady state [7]. Unlike fission reactors however, scattering is not a desired effect in fusion reactors. Fusion reactors want to maximize the energy of the outgoing neutrons as the energy of the neutrons is eventually converted to heat.

After production in the high density plasma, neutrons will have the opportunity to scatter with the deuterium and tritium ions or other neutrons in the plasma. The neutrons can either be scattered to higher or lower energies. Cross-sections for neutron scattering with deuterium and tritium are displayed in Figure 2[8].

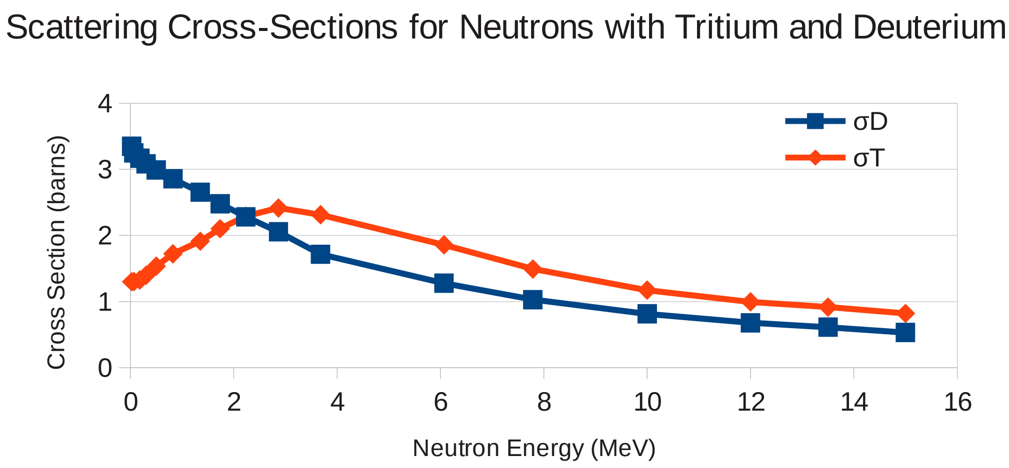


Figure 2: Neutron scattering cross-sections for Tritium and Deuterium[8].

From Figure 2 it is observed that the scattering cross sections are low for high neutron energies (E>10MeV). The cross-sections increase for deuterium as the neutron energy decreases and for tritium, the cross-section reaches a maximum at around 3.68 MeV [8]. With this data along with the group scattering probabilities, the neutron scattering cross-sections for Equation 1 can be calculated.

2.3 Absorption:

Neutron absorption is an area of major importance to the ITER reactor. The walls of the fusion reactor is where the neutron absorption will primarily take place [3,5]. The walls will be composed of modular components called blanket modules. Together the modules will comprise the ITER blanket [5,6]. Figure 3 illustrates a conceptual design of the geometry ITER blanket[9].

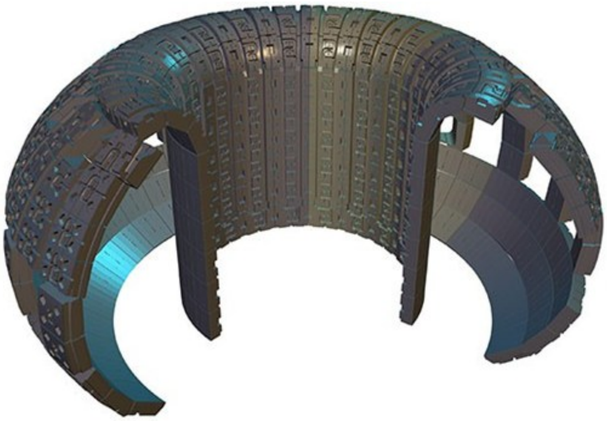


Figure 3: Conceptual design of ITET blanket module[9].

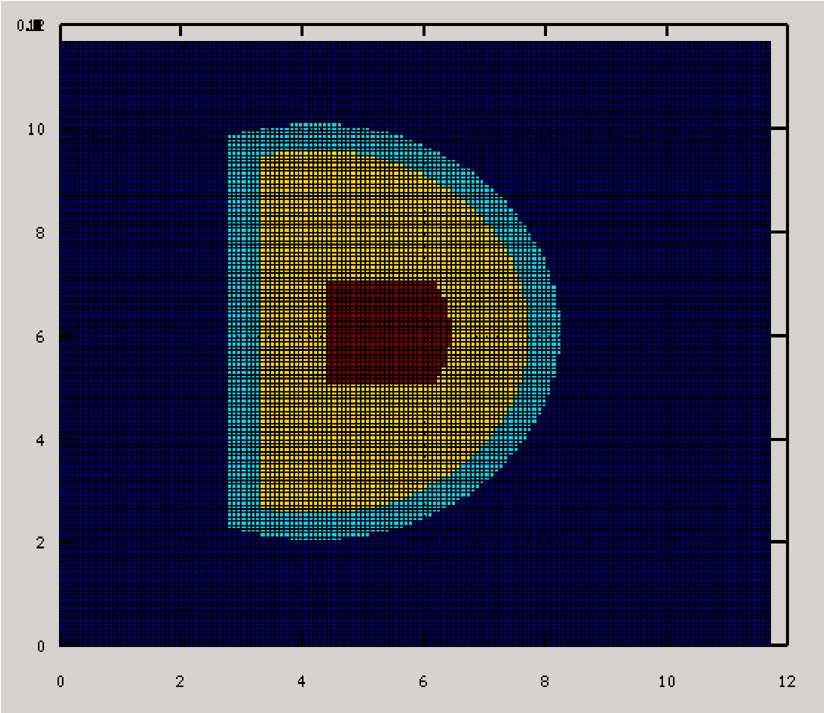
The ITER blanket encloses the fusion plasma and is the first material to be facing the plasma. The goal of the blanket is to extract the energy carried by the neutrons, while withstanding the harsh environment created by the plasma. Tests on tritium production through lithium will also be conducted using blanket modules. The blankets composition will be of a combination of beryllium, steel, copper and lithium[10]. The ITER blanket will have window sections as shown by empty spaces in the blanket. These windows are where external heating systems will be placed [9]. These heating systems are to heat the plasma and will not be included in the following analysis. Using the proposed material compositions of the reactor blanket, absorption cross sections at the Tokamak first wall can be calculated.

2.4 Leakage:

Neutron leakage in a fusion reactor occurs when neutrons are not attenuated by the blanket described above. These neutrons will escape the containment of the Tokamak. This is very undesirable for two main reasons. First, the energy carried by a neutron that escapes the Tokamak is lost and cannot be converted to heat. As the leakage increases, the efficiency of the reactor decreases. The other main concern regarding neutron leakage is the effect the neutrons will have on the equipment surrounding the Tokamak. Directly outside the walls of the Tokamak are the superconducting magnets generating the magnetic field to contain the plasma. In order to protect these magnets from being damaged through neutron activation, the leakage from the Tokamak must be minimized [4,10]. Using measurements of the neutron attenuation coefficients of the materials comprising of the ITER Blanket, the neutron leakage rate of the Tokamak can be calculated.

2.5 Approach to Solution:

A finite difference approach was used to solve Equation 1. The method was first verified by applying it to solve the diffusion equation for a nuclear reactor. The mesh geometry was then modified to model the cross-section of the ITER tokamak. Figure 4 shows the mesh used to model the ITER tokamak cross-section. The dimensions of the axis are in meters. The grid is 150 x 150 cells in size.



Legend		Radius (m)	Width (m)	Height (m)
Inner Plasma		2.2	2.22	1.0
Outer Plasma		3.5	3.38	-
Beryllium Outer Wall		4.0	5.3	-
Steel			Else	

Figure 4:Grid used to model tokamak cross-section. The cross-section was divided into four zones as shown in the legend. Each zone has unique diffusion properties.

In order for fusion to be achieved in ITER, the plasma will have to be near toroidally symmetric [11]. This allows for the two dimensional cross-section approximation to be accurate for when the reactor is in steady state operation. The finite difference method applied solves for the flux in each cell in the grid displayed above. The leakage from one cell into another is then calculated making the grid a coupled system. This process is iterated until convergence is achieved. As the plasma is assumed to be toroidally symmetric, the neutron flux is also assumed to be toroidally symmetric. This assumption allows the leakage calculations to only be preformed in two dimensions.

3.0 Results:

A two-group approximation was made for the neutron energy distribution in the reactor. The fast neutron group consists of neutrons with energy greater than 2.70 MeV. For the two energy groups, the system of diffusion equations is:

$$-\nabla D_1 \nabla \varphi_1 + (\Sigma_{a1} + \Sigma_{1-2})\varphi_1 - P_1 \Sigma_{a1} \varphi_1 - S_1 = 0$$

$$-\nabla D_2 \nabla \varphi_2 + \Sigma_{a2} \varphi_1 - (P_2 \Sigma_{a1} + \Sigma_{1-2})\varphi_1 = 0$$

where:

1 = fast neutron property, 2 = slow neutron property, φ = neutron flux, D = diffusion coefficient
Σa = absorption cross section, Σ_{12} = downscattering cross section, S = Source of neutrons
P_i = probability of being multiplied into i^{th} energy group

With this system of equations the following assumptions are made:

1) Two Energy Groups: The cut off for the two energy groups was 2.70 MeV. This was done to account for the cross-section for neutron multiplication in beryllium [12,13].
2) No up-scattering. Although, the probability of a 14.1 MeV neutron to up-scatter from deuterium or tritium is roughly equal to that of it down-scattering, the probability of a neutron with energy <2.70 MeV up-scattering is small [8].
3) Neutron multiplication and down-scattering are the only sources of slow neutrons.
4) There is no neutron absorption in the plasma and the plasma only consists of deuterium, tritium, neutrons and electrons.

Figures R1 and R2 on the following page show the results of the calculation. The colour scale located to the right of the diagram shows the relative flux intensities. After the flux distribution was calculated, both fluxes were normalized to have a maximum value of 1.

The fast neutron flux closely resembles the temperature distribution inside the ITER tokamak shown in Figure 5 [5]. From this figure it is observed that although the density of the plasma is predicted to be fairly constant throughout the tokamak, the temperature spikes in the centre of the tokamak, causing the neutron production to also spike.

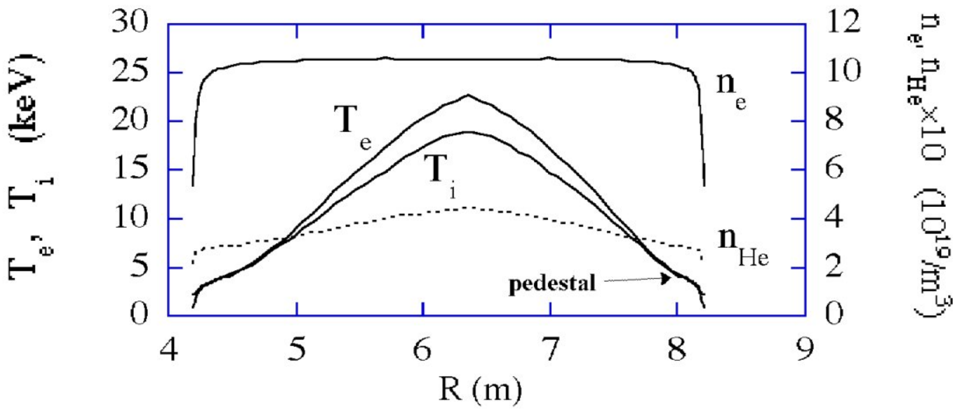


Figure 5:Proposed temperature and density profiles for ITER[5].

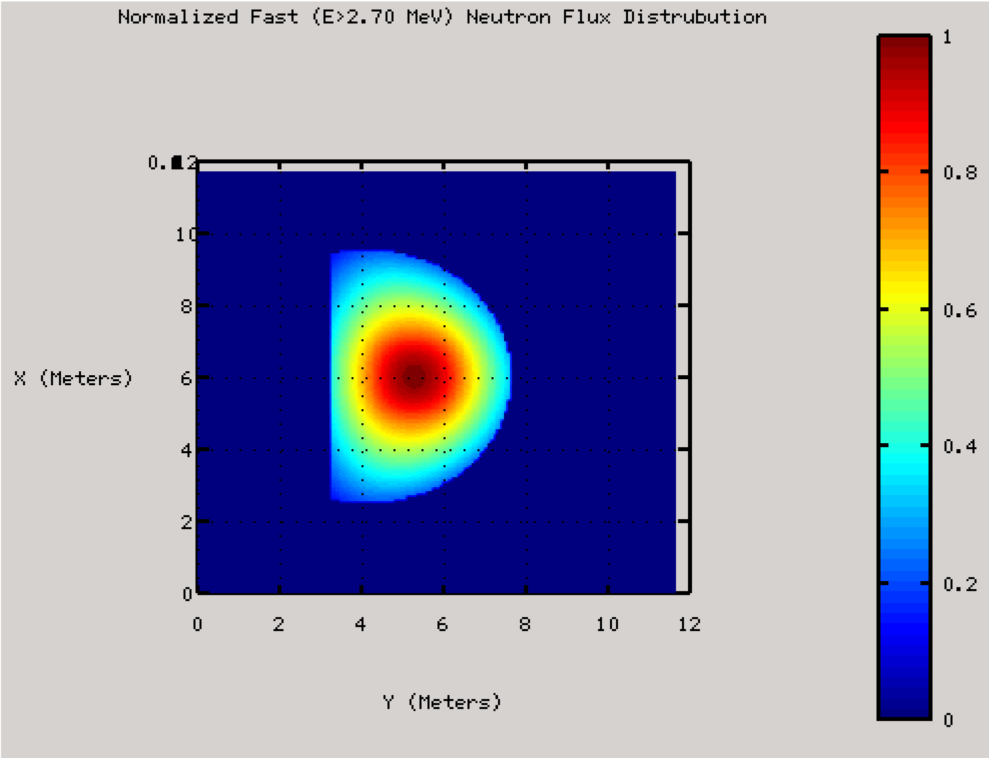


Figure R1: Fast neutron flux.

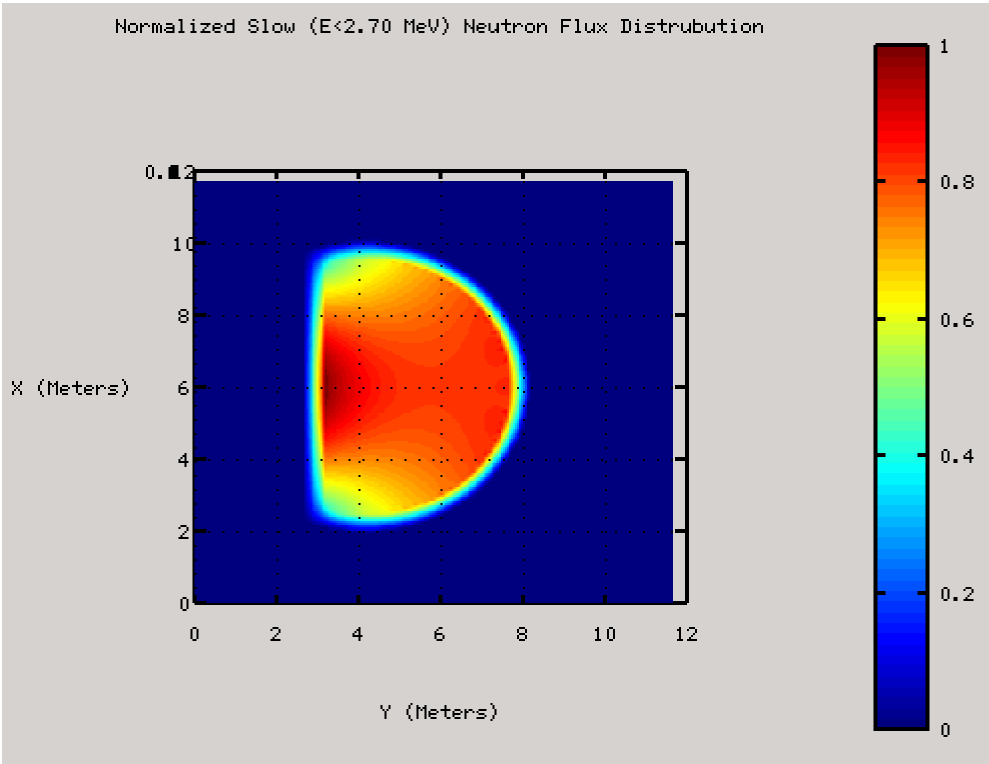


Figure R2: Slow Neutron flux.

The spike in neutron flux at the centre of the reactor is sharply peaked compared to similar simulations done using cross-sections of toroidal fusion reactions [1]. ITER however, is much larger than any toroidal fusion reactor operated before and has a large gradient in plasma temperature throughout the tokamak. A sensitivity analysis changing the size of the plasma zones in Figure 4 will be done to see how dependent the flux shape is on each plasma zone size.

The slow neutron distribution has an interesting shape. As there is no slow neutron production through fusion, one would expect that the slow neutron flux would be minimized in the centre of the tokamak and maximized at the edges. However the neutron flux is actually at a minimum in the upper and lower corners of the tokamak. The slow flux is at a maximum value at the vertical wall of the D. As this wall is the shortest path between the inner plasma and the outside wall, this could account for the high flux level. Calculations done on toroidal fusion reactors where the cross-section of the reactors is a circle have similar results where the slow neutron flux is maximized at the edges of the reactor [1]. Due to the difference in reactor shape between and toroidal and tokamak reactor, the slow neutron flux is not azimuthally symmetric around the tokamak reactor as it is with the toroidal reactor.

4.0 Conclusion:

The above discussion has illustrated the main neutron interactions that will take place in the ITER Tokamak during operation. A two-group calculation of the neutron flux shape was then completed. Due to the two group approximation, the diffusion properties of the materials are approximate. By modifying the input parameters, a sensitivity analysis of various scenarios of can be done to test which parameters have the largest affect in the tokamak flux. From the calculation already completed it is evident that the fast neutron flux closely resembles the temperature profile of the plasma in the reactor. This calculation also slows the slow neutron flux has hot and cold spots along the tokamak wall and that the maximum value of the slow neutron flux will be at the edges of the tokamak. Note that along with the assumptions stated above, this analysis excluded the divertor component of the Tokamak. This was done as a simplification. 80% of the fusion energy is extracted through neutron interacting with the blanket modules. The remaining 20% is extracted through the diverator [10]. A full detailed analysis would treat the divertor along with the other Tokamak components analyzed in this report.

5.0 References:

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