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TRANSMUTATION BLANKET DESIGN FOR A TOKAMAK SYSTEM

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ABSTRACT

Sub-critical advanced reactor with a D-T fusion neutron source based on Tokamak technology is an innovative type of nuclear system. Due to the high quantity of neutrons produced by fusion reactions, it could be well spent in the transmutation process of the transuranic elements. Nevertheless, to achieve a successful transmutation, it is necessary to know the neutron fluence along the radial axis and its characteristics. In this work, it evaluated the neutron flux and interaction frequency along the radial axis changing the material of the first wall. W-alloy, beryllium and the combination of both were studied and regions more suitable to transmutation were determined. The results demonstrated that the better zone to place a transmutation blanket is limited by the heat sink and the shield block. Material arrangements W-alloy/W-alloy and W-alloy/Beryllium would be able to hold the requirements of high fluence and hardening spectrum needed to transuranic transmutation. The system was simulated using the MCNP5 code, the *ITER Final Design Report, 2001*, and the FENDL/MC-2.1 nuclear data library.

1. INTRODUCTION

Transmutation of high-level waste (HLW) utilizing D–T fusion neutrons is a good choice for an early application of fusion energy. Transmutation is the process of bombarding a material with particles (typically neutrons) to form new atoms with higher masses and/or to fission the materials into atoms with smaller masses. In principle, transmutation can convert those isotopes in spent nuclear fuel that pose a radiological hazard to humans to isotopes that pose less of a hazard. It can reduce the mass, volume, activity, heat load, and/or radiotoxicity of waste that must be sent to a repository. High level waste can be distinguished: (1) long-lived fission products (LLFPs: ^{129}I, ^{99}Tc, ^{135}Cs, etc.) and (2) transuranium (TRU) elements (Z>92), which mainly include plutonium isotopes and minor actinides (MAs: isotopes of Np, Am and Cm) [1,18]. Although fission products comprise a significant portion of the radiotoxicity risk for the first few hundred years, the primary contributors over thousands of years are actinides [18]. Since all of the actinides are potentially radiotoxic and since neutron capture (n, y) reactions in the actinides just produce other actinides, the mainly effective way to incinerate actinides is by neutron fission (n,f) reactions. Some of the actinides are effectively not fissionable in a thermal neutron spectrum, such as the neutron spectra in almost all commercial nuclear reactors, and the probability of fission per neutron absorbed is greater for all the actinides in a hard neutron spectrum. With fast neutrons, the fission-to-capture ratios,

σ_f/σ_c of plutonium or MAs is often larger than when the neutrons are slower. To achieve transmutation it is need that high energetic neutrons released from fusion reactions enter into a sub-critical blanket containing the fission products for induction of transmutation reaction [2]. To enhance the transmutation efficiency, it requires high neutron wall loading (high neutron fluence), with a width energy spectrum in the fast energy region. On the order hand, the high neutron flux and heat fluxes induced for the high temperatures produced by the fusion process makes necessary to study the behavior of materials when submitted to these special conditions [3]. So, it is being studying different materials in the design of Power Plant Conceptual Study (PPCS) and fusion experimental devices, especially in the first walls that are subjected to extreme conditions. Beside these conditions, it is also necessary that the materials have some desirable properties such as high melting point, high thermal conductivity, high resistance to sputtering and particle fluencies and erosion [4-6]. Tungsten fulfills these requirements and is considered as the main component in different alloys. So W-alloys are considered for various plasma-facing components [4]. Nevertheless, to transmutation, a certain amount of neutron multiplication is required and the most used neutron multiplier is beryllium (Be), which is necessary for the high demand of neutrons fluence in the transmutation blanket [7]. The main goal of this work is to study the influence in the neutron flux variation for the different coatings in the first wall. To help the understanding of how the influence of using different coatings is taken in count, the interaction frequency at which reaction cross section occurs. W-alloy, beryllium or the combination of both were studied for this purpose and the most suitable position for a transmutation blanket are showed in this paper.

For the simulations the MCNP5 (Monte Carlo N-particle) code [8], the ITER Final Design Report 2001 [9], and FENDL (Fusion Evaluated Nuclear Data Library) data library were used [10].

These results will allow a comparison of the behavior from the neutron fluence passing through the materials and the neutron fluence along neutron trajectory was followed for each case, in order to find a suitable region with high neutron fluence and width energy spectrum.

2. METHODOLOGY

The modeling used in this work was the same adopted by Araujo, et al., 2009 [11], described following.

2.1. Geometry Model

The geometric model used concentric finite cylinders as can be seen in the Fig. 1. The cylindrical surfaces are 24 meters high and they have the same axial alignment. Each region between two successive cylindrical surfaces was filled with the appropriate material in order to represent the different layers of each component along the radial reactor direction.

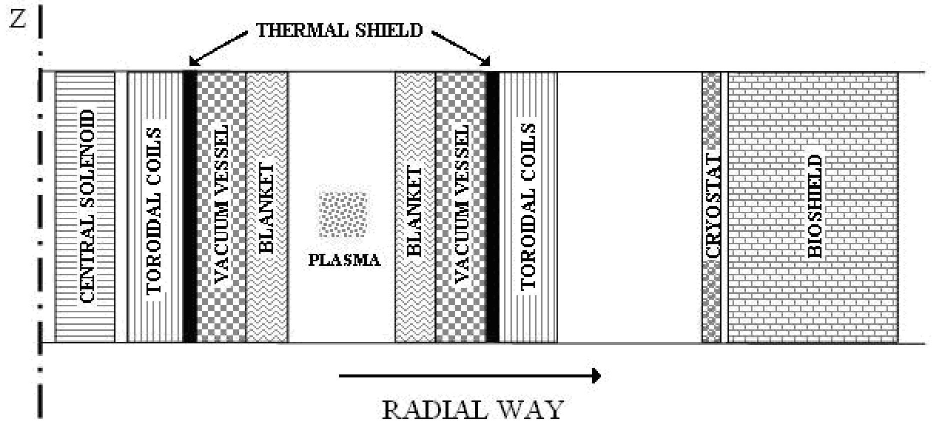

Figure 1. Radial one-dimensional model profile (scale out). The blank spaces are vacuum areas.

This simplified model disregards the detailing of components that are more complex, omits the vertical and horizontal slits between blanket modules, and does not consider components that do not involve the whole machine. The top view of the geometry used in the modeling is shown in the Fig. 2.

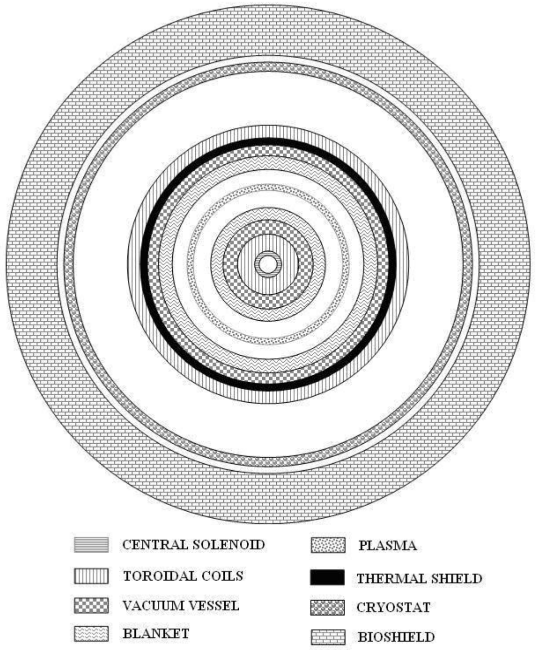

Figure 2. Top view of geometric model (scale out). The blank spaces are vacuum areas.

2.2. Materials

The MCNP code performs the transport of neutrons, photons and electrons, or the combined transport of these particles, where the random path of the particles is simulated based on the stochastic laws with interaction probability inserted from libraries of nuclear cross section. The accuracy obtained with the MCNP simulation depends on several uncertainties involved in the data from nuclear cross sections and the uncertainty of the statistical calculation.

Therefore, the detailing of the material composition for each reactor component is highly relevant to obtain a reliable prediction to the individual history of each neutron in the simulation.

Table 1 presents the reactor systems used in this present study with the thickness and materials for each one of them: central solenoid (CS), blanket (BLK), vacuum vessel (VV), vacuum vessel thermal shield (VVTS), toroidal field coils (TFC), cryostat (CRY) and bioshield (BSD). Focusing the study on the material of the first wall located inside the blanket.

In agreement with ITER guidelines and the article of Fusion Engineering and Design [8-10], stainless steel SS316L(N)IG was used in the filling composition of the blanket shield block. The vacuum vessel was filled with 60% of stainless steel SS304B7 and 40% of water. Due to the CS composition complexity, such module was assumed to be composed by 27% Nb_3Sn + 30% Incoloy 908 + 30% SS316 + 10% resins + 3% Al_2O_3. The small details of the CS composition were not considered in the present model to simplify. The composition of the material filling the CS coils and TF coils was assumed to be 45% Nb_3Sn + 50% Incoloy 908 + 5% Al_2O_3. The composition of the bioshield [12] is described in the Table 2.

Table 1. Material and thickness adopted for the simulated component models.

COMPONENT		THICKNESS (cm)	MATERIAL
CS	Insertion Module	80 to 90	27% Nb_3Sn + 30% Incoloy 908 + 30% SS316 + 10% resins +3% Al_2O_3
	Superconductor and insulator	90 to 180	45% Nb_3Sn + 5% Al_2O_3 + 50% Incoloy 908
	Support	180 to 200	SS316L(N)IG
TFC	Wall Box	220 to 229.5	SS316L(N)IG
	Superconductor and insulator	229.5 to 310.5	45% Nb_3Sn + 5% Al_2O_3+ 50% Incoloy 908
	Wall Box	310.5 to 320	SS316L(N)IG
VVTS	Wall	320.6 to 322.8	SS304L
VV	Wall	322.8 to 328.8	SS316L(N)IG
	Filling	328.8 to 350.5	SS304B7-60%, water-40%
	Wall	350.5 to 356.5	SS316L(N)IG
BLK	Shield Block	357 to 399	SS316L(N)IG
	Heat Sink	399 to 401	CuCrZr-IG
	First Wall	401 to 402	Material to be Studied
Plasma Chamber		402 to 853	Vacuum
BLK	First Wall	853 to 854	Material to be Studied
	Heat Sink	854 to 856	CuCrZr-IG
	Shield Block	856 to 898	SS316L(N)IG
VV	Wall	898.5 to 904.5	SS316L(N)IG
	Filling	904.5 to 967.5	SS304B7-60%, water-40%
	Wall	967.5 to 973.5	SS316L(N)IG
VVTS	Wall	973.5 to 975.5	SS304L
TFC	Wall Box	976 to 985.5	SS316L(N)IG
	Superconductor and insulator	1085.5 to 1165.5	45% Nb_3Sn + 5% Al_2O_3+ 50% Incoloy 908
	Wall Box	1165.5 to 1176	SS316L(N)IG
CRY	Wall	1400 to 1410	SS304L
BSD	Wall	1455 to 1655	Concrete

Table 2. Concrete composition used.

Elements	Composition Br3 (ρ = 2.43 $g.cm^{-3}$)
H	0.34
O	32.9
Na	0.71
Mg	0.43
Al	1.4
Si	5.5
K	0.15
Ca	6.7
Fe	10.1
Eu	0.0001
S	7.5

In order to evaluate the neutron flux in different materials based on the Tokamak design, the coatings surrounding the fusion plasma were changed (Fig. 3). To help the understanding of what kind of reaction happens along the neutron trajectory for each blanket, it was followed the rate at which different reactions occur. In the first analysis, it was placed the beryllium material in 1-coating and 2-coating surrounding the fusion plasma, owing to the fact that beryllium is an excellent neutron multiplier. On the other hand, W and W-alloys (W-1.1TiC) are being considered due to its desirable structural properties: high melting point, high thermal conductivity, and high resistance to sputtering and erosion. In the second one, it changed the beryllium coating for tungsten alloy (W-1.1TiC) material in 1-coating and 2-coating to verify the different reactions due to the neutron production induced by fusion reactions. The last one was an arrangement of both materials: for the material 1-coating it was used tungsten alloy (W-1.1TiC) and for the 2-coating it was used beryllium to perform a comparison and evaluation of the neutron multiplier parameters. The measure of the neutron fluence was made along the radial axis for both materials, using tally point detectors from the MCNP code. One detector was placed before 2-coating surrounding fusion plasma and so on detectors are placed before and after each blanket, following the radial axis. It will be needed to find width spectrum energy in order to study a possible position for a transmutation blanket. The combination of coating materials evaluated was: beryllium (1-coating) and beryllium (2-coating); W-1.1TiC (1-coating) and W-1.1TiC (2-coating); W-1.1TiC (1-coating) and beryllium (2-coating).

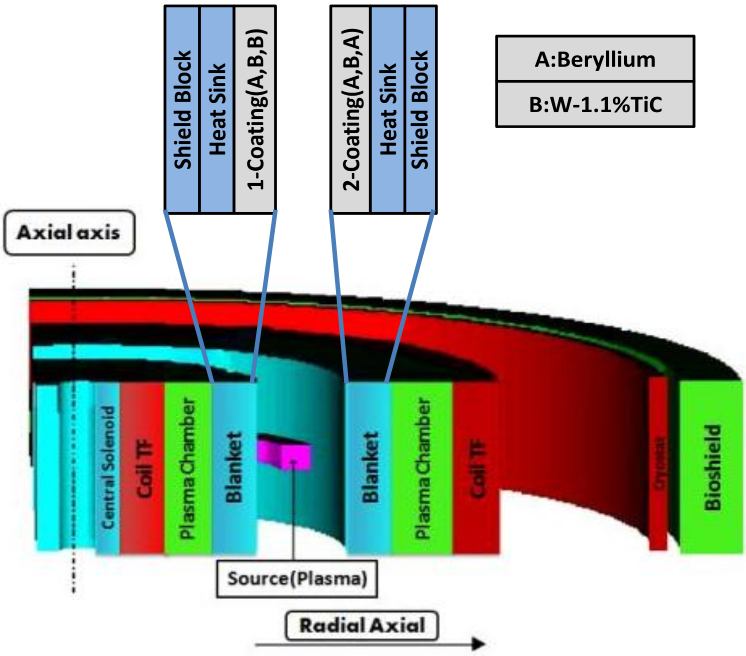

Figure 3. System blanket design

2.3. Source

To simplify, the source used in the simulation emits neutrons symmetrically. The neutrons source used is isotropic and has a ring shape with square cross section being 0.60 m height and 0.60 m wide, occupying the central part of the plasma chamber. This source does not take into account the plasma emissions asymmetries in the poloidal and toroidal directions. Considering the aims of this study, this simplification is acceptable. The parameters of emission spectrum were adjusted automatically by MCNP through the choice of standard source for DT fusion. The plasma temperature was adjusted for 10 keV [13].

3. RESULTS AND ANALYSIS

3.1. Neutronic Evaluation for Different Coating Materials

For each case, the neutron fluence measured “N” by the detectors is divided by the initial neutron fluence measured “N_0”, this is located where the neutron source is placed. Therefore, the analysis will be made using (N/N_0), i.e., it will analyze the rate of change in the neutron population that passes through the walls. To have a better understanding, it was followed the interaction frequency for the different reactions cross section along the radial axis and the reactions cross section considered were: elastic collision, inelastic collision, radiative capture, neutron production, (n,n') n' in excited state and the total cross section. For each distance, it was normalized with respect to the total cross section to know at what proportion each reaction cross section occur.

3.1.1. The effect using beryllium coating

In the first case, it was taken place a beryllium coating surrounding the fusion plasma chamber. The results are displayed in the Fig. 4, showing the detector measurement of the neutron fluence along the radial axis for each chosen distance.

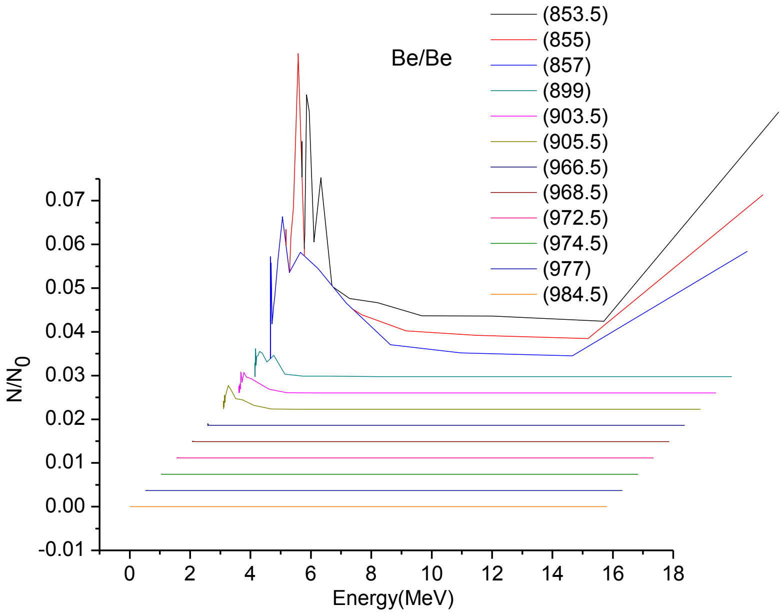

Figure 4 - Neutron spectrum for Be-Be coating.

The Fig. 4 describes a high intensity at 855cm from the centre (Table 1) where the second detector is located (heat sink). This peak means that there is a high neutron production but it is missing a wider energy spectrum. Nevertheless, the next relevance zone located at 857cm has wider energy spectrum, with a significantly neutron fluence becoming a suitable zone to place a transmutation blanket. The Table 3 presents the type of reaction and their interaction frequency at which each reaction occur for the different distance.

Table 3. Interaction frequency at which the different cross section occur for Be/Be

Distance	Reaction Type	Interaction frequency (particles/s)	Normalized
853.5	elastic collision	1.87659E+09	0.89118
	Inelastic collision	0	0
	Radiative capture	8.00067E+04	3.79946E-5
	Neutron production	1.62307E+05	7.70784E-5
	(n,n') n' in excited state	6.34246E+05	3.01199E-4
	Total cross section	2.10574E+09	1
855	elastic collision	8.78642E+08	0.68332
	Inelastic collision	0	0
	Radiative capture	3.42448E+06	0.00266
	Neutron production	1.53811E+08	0.11962
	(n,n') n' in excited state	1.46913E+08	0.11425
	Total cross section	1.28585E+09	1
857	elastic collision	3.36108E+08	0.60728
	Inelastic collision	1.35762E+06	0.00111
	Radiative capture	7.44902E+05	0
	Neutron production	4.79211E+07	0.08543
	(n,n') n' in excited state	9.80197E+07	0.17615
	Total cross section	5.52983E+08	1

3.1.2. The effect of using tungsten alloy coating

In the second case, tungsten coating surrounded the plasma chamber. In recent evaluations [14-15], the tungsten alloy was considered for various plasma-facing; therefore replacing the beryllium by tungsten alloy, the evaluations indicate that tungsten alloy could be a suitable option.

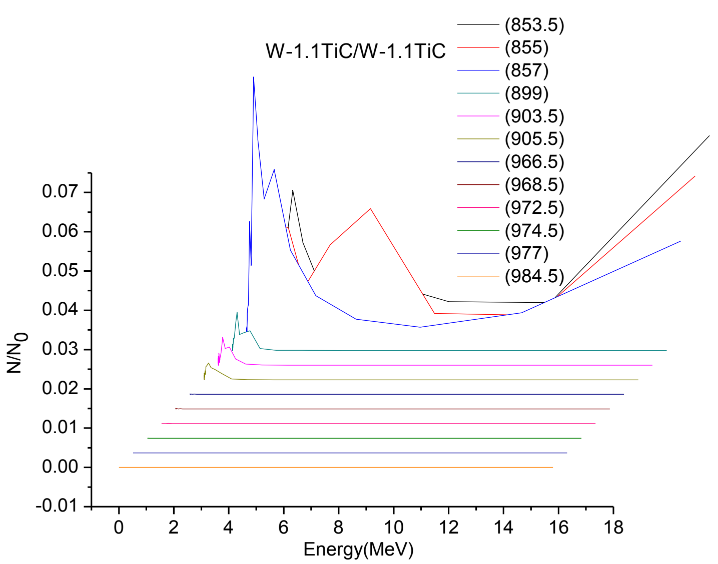

Figure 5. Neutron spectrum for W1.1TiC/W1.1TiC coating.

According to the results in the Fig.5 it could be appreciate two important peaks the first one located inside the heat sink at 855cm and the other one inside the shield block at 857cm. So a suitable region for placed a transmutation blanket would be limited by these two regions. The Table 4 presents the type of reaction and their interaction frequency at which each reaction occur for the different distance.

Table 4. Interaction frequency at which the different cross section occur for W1.1TiC/W1.1TiC

Distance	Reaction Type	Interaction frequency (particles/s)	Normalized
853.5	elastic collision	3.08081E+09	0.70764
	Inelastic collision	0	0
	Radiative capture	3.45950E+07	0.00795
	Neutron production	8.13846E+05	1.86935E-4
	(n,n')	8.24294E+07	0.01893
	Total cross section	4.35363E+09	1
855	elastic collision	8.19653E+08	0.70964
	Inelastic collision	0	0
	Radiative capture	2.54904E+06	0.00221
	Neutron production	1.27194E+08	0.11012
	(n,n')	1.19205E+08	0.10321
	Total cross section	1.15503E+09	1
857	elastic collision	3.17346E+08	0.63917
	Inelastic collision	1.19919E+06	0.0013
	Radiative capture	5.55145E+05	0
	Neutron production	3.96457E+07	0.07887
	(n,n')	8.07312E+07	0.16177
	Total cross section	4.96187E+08	1

3.1.3. The effect of using tungsten and beryllium coating

As showed in the Fig.4 and Fig.5 the beryllium has higher neutron fluence but a narrow energy spectrum than tungsten at 855cm. Instead the tungsten alloy has higher neutron fluence with the same width than the one for the beryllium at 857cm. Therefore, it conduces to evaluate the feasibility to use both materials. For this last case, it was placed a combination of both materials coating as shown in Table 5. This arrangement was made due to the evaluated properties of each material that shows that the tungsten alloy has a larger absorption and inelastic reaction rate than beryllium (the Table 3). Therefore, the tungsten alloy was placed in the inner position and, due to its multiplier features, the beryllium would be better placed in the outer position surrounding the plasma vacuum as shown in Table 5.

Table 5. Data changed for new design.

Centre		0	Vacuum
Blanket	Shield Block	357 a 399	SS316L(N)IG
	Heat sink	399 a 401	CuCrZr-IG
	First wall	401 a 402	W-1.1TiC
Plasma Chamber		402 a 853	Vacuum
Blanket	First wall	853 a 854	Beryllium
	Heat sink	854 a 856	CuCrZr-IG
	Shield Block	856 a 898	SS316L(N)IG

In accordance to the analysis made for each material, the region showing a high neutron fluence and width energy spectrum. As it is verified in the Fig. 6 is located between 855cm to 857cm, limited by the heat sink and the protector block.

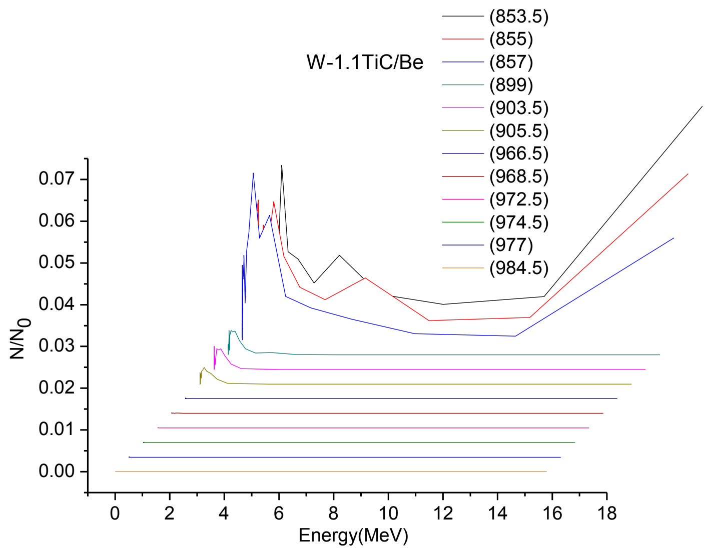

Figure 6. Neutron fluence results for W-Be arrangement.

According to these preliminary results, a suitable area to place a transmutation blanket could be between 855cm to 857cm where it is found the main requirements. These results shows that the W1.1TiC/Be arrangement as located in the Table 5 is a suitable coating option. The Table 6 presents the type of reaction and their interaction frequency at which each reaction occur for the different distance.

Table 6. Interaction frequency at which the different cross section occur for WTiC/Be

Distance	Reaction Type	Interaction frequency (particles/s)	Normalized
853.5	elastic collision	1.74528E+09	0.88536
	Inelastic collision	0	0
	Radiative capture	7.18623E+04	3.6455E-5
	Neutron production	3.30068E+04	1.6744E-5
	(n,n') n in excited state	2.23634E+05	1.13447E-4
	Total cross section	1.97126E+09	1
855	elastic collision	9.29500E+08	0.69768
	Inelastic collision	0	0
	Radiative capture	3.63000E+06	0.00272
	Neutron production	1.52679E+08	0.1146
	(n,n') n in excited state	1.44866E+08	0.10874
	Total cross section	1.33228E+09	1
857	elastic collision	4.12944E+08	0.65715
	Inelastic collision	1.65199E+06	0.0015
	Radiative capture	7.08024E+05	0
	Neutron production	4.54232E+07	0.07128
	(n,n') n in excited state	9.80240E+07	0.15513
	Total cross section	6.28018E+08	1

3.2. A detailed analysis

The following results present the most relevant fluence peaks associated to a suitable position for a transmutation blanket, for the different studied cases.

3.2.1. Beryllium

As described in the Fig. 7 the neutron fluence through beryllium was higher than tungsten fluence. This behavior is due to tungsten alloy has a larger reaction rate than beryllium material. This was deduced from the reaction cross section from Table 3 and Table 4 and the Fig. 7 that shows that beryllium has higher neutron fluence [16-17].

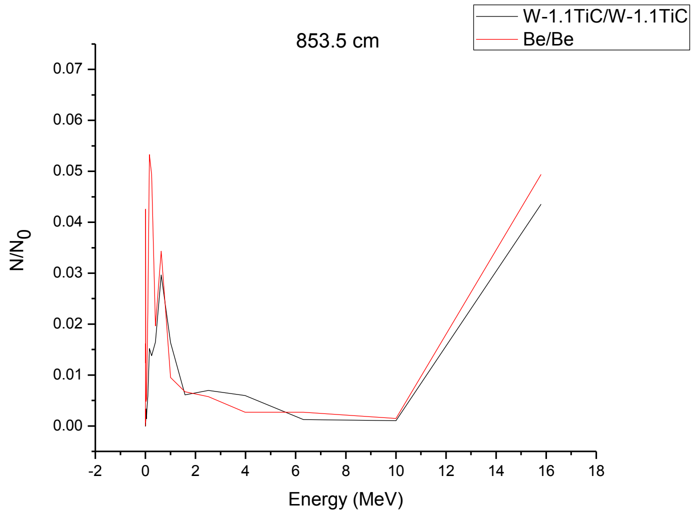

Figure 7. Comparison between Beryllium and Tungsten at 853.5cm.

As illustrated in the Fig. 4, there are two relevance peaks. The first one is located at 855cm from the centre, where it presents the highest neutron fluence; which is 0.065 from the initial fluence and a width energy spectrum between 0.0398 to 0.631MeV. The second one is about 857cm; this peak has a bit lower neutron fluence than the one at 855cm as illustrated in Fig.8 but has a wider energy spectrum between 0.0398 to 3.98MeV showing itself as suitable zone. Due to the abruptly neutron fluence fell from 855cm to 857cm and the high deficiency in the width energy spectrum, these conditions limited the main purpose which is to have a high probability of transmutation. Although it is the best choice for placed a transmutation blanket the results does not satisfy the main requirements.

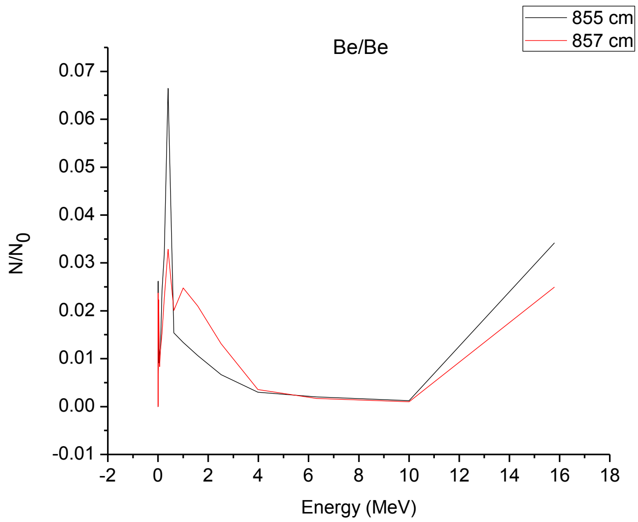

Figure 8. Neutron fluence at 855cm and 857cm from the centre.

3.2.2. Tungsten alloy

This evaluation was performed for tungsten alloy coating, but first of all, to have a better understanding of what is happening for farther distance from the centre, it is done a comparison between the cases where was used only beryllium and the tungsten alloy. As showed the Fig. 4 and Fig. 5, the most representative peaks in those figures were located at 899cm. The Fig.9 describes the neutron fluence at 899cm for both cases. The neutron fluence for both cases are to lower to achieve transmutation due to the neutron fluence is less than 0.01 from the initial fluence with a width energy spectrum between 0.00631 to 1 MeV.

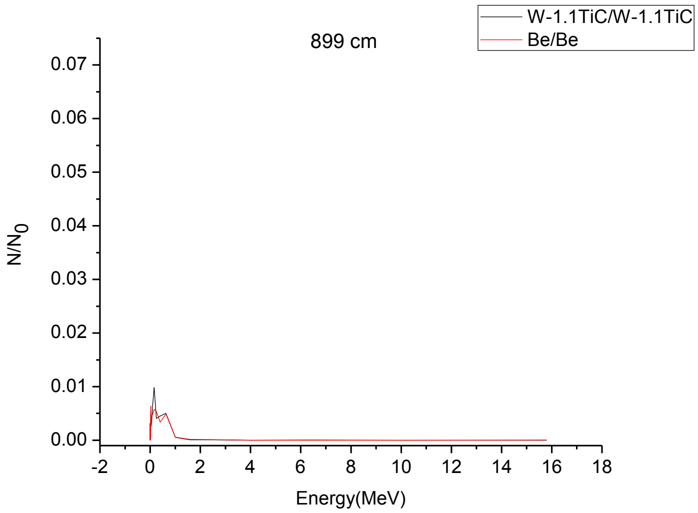

Figure 9. Neutron fluence at 899 cm from the centre.

However, the main analysis will be focus between the regions where it can be found larger neutron fluence between 855cm to 857cm as showed in Fig. 5.

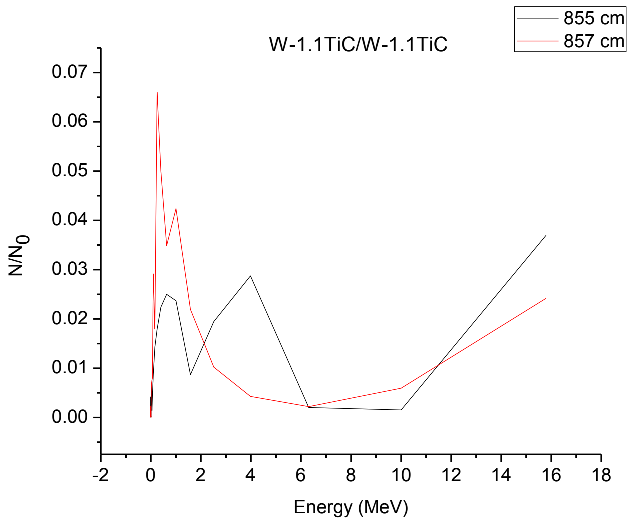

Figure 10. Neutron fluence at 855cm and 857cm from the centre.

The Fig.10 shows a peak with high neutron fluence at 855cm, the neutrons with high energies between 2 to 6 MeV reduce their energy just to pass through the heat sink (855cm) to the shield block (857cm). The fluence at 857cm seems to be accumulated between 0.158 to 2 MeV with a high fluence about 0.065 from the initial fluence. This abrupt change on energy is due to the increase in the inelastic reaction rate produced while the neutron was passing through the heat sink at 855cm. Therefore, a suitable zone to place a transmutation blanket could be located between this two region (heat sink and shield block) as previously Beryllium results shows.

3.2.3. Tungsten Beryllium Coating

This coating considers tungsten material in the inner position and beryllium material in the outer one, as indicated in the Table 5. According to the calculation results as was showed in Fig. 6, the maximum neutron fluence was 0.04 from the initial fluence at 857cm, and the width of interest was from 0.1 to 1.58MeV. This region between the heat sink (855cm) and the shield block (857cm) is showed as a suitable zone to place a transmutation blanket due to combined condition of high fluence and a larger width energy spectrum (Fig. 11).

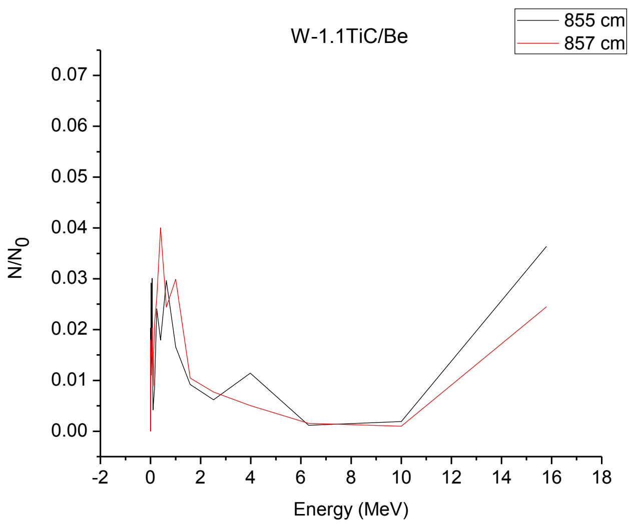

Figure 11. Neutron Fluence at 857cm from the centre in the shield block.

The result zone between the heat sink and the protector block as showed above could be a suitable solution for a transmutation blanket position, because accomplish the requirements of neutron flux, allowing a transmutation of nuclear waste, owing to the width energy spectrum and high fluence.

4. CONCLUSIONS

This work represents our initial efforts to simulate a Tokamak using MCNP5. In order to accomplish the effective transmutation, some coatings combinations were examined. The evaluated cases demonstrated that the better zone to place a transmutation blanket is limited by the heat sink and the shield block. Just these material arrangements W-alloy/W-alloy and W-alloy/Beryllium would be able to hold the requirements of high fluence and width energy spectrum. It is expected to achieve transmutation maintaining a sub-critical state $k_{eff} < 0.99$. The next step is going to design a transmutation blanket and study the behavior of the transuranium elements under the studied conditions. Also, introducing a transmutation layer and simulating this system using a depletion code, to analyze the transmutation layer evolution during an operation time

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