EN_05

FUSION-FISSION HYBRID SYSTEM – LAYER TRANSMUTATION ANALYSIS AFTER DIVERTOR INSERTION

Natália G. P. L. Oliveira, Carlos E. Velasquez and Claubia Pereira

Departamento de Engenharia Nuclear
Universidade Federal de Minas Gerais - UFMG
Av. Antonio Carlos, 6627 Pampulha
31270-901, Belo Horizonte, MG, Brazil
nataliagplofis@gmail.com

Palavras-Chave: Fusion-Fission Hybrid System; Divertor; Transmutation Layer

ABSTRACT

Currently, the most used magnetic confinement fusion technology worldwide is called Tokamak and based on this technology, the experimental nuclear fusion reactor project called ITER, has been developed in Cadarache, south of France. One of the most important components of this project is the Divertor system, whose main function is to extract the heat and ashes that were generated as a product of the fusion reactions and other impurities in the plasma. From a hybrid reactor model developed at DEN and based on the ITER reactor, it analyzed the transmutation of the transmutation layer after the insertion of the Divertor component in the system. Spectrum of neutron flux and cross sections for three modeled systems were examined using the MONTEBURNS code that links MCNP5 and ORIGEN2.1 codes. Preliminary results indicate that the insertion of the Divertor component affects the initial flux of neutrons in transmutation layer, impacting the transmutation of certain groups of fuel materials.

1. INTRODUCTION

Hybrid fusion-fission reactors are currently being studied due to their ability to transmute actinides through fission reactions. Because it has a high hardened neutron flux (about 14.1 MeV of energy) originating from the deuterium and tritium (D-T) fusion reactions in the fusion reactor core, it increases the probability of inducing fission in the transuranic nuclides decreasing its high radiotoxicity and long decay half-life.

The fission system coupled to the fusion reactor is inserted after the Plasma Chamber in the core of the reactor operating in subcritical mode [1,2]. This region, loaded with reprocessed fuel from LWR plants, is submitted to two spectra of neutron fluxes: the first, corresponding to the fission reactions occurred in the transmutation layer (TL) and the second one is due to the D-T fusion reactions which produces neutrons with high energy and flux. The combination of these neutrons sources increases the probability of transuranic transmutation.

Previous studies on hybrid fusion-fission systems (FFS) and developed at the Department of Nuclear Engineering - UFMG, indicate that the hybrid fusion systems based on Tokamaks is more efficient at transmutation compared to other hybrid systems [3]. From this hybrid model FFS, it will analyze the insertion of the Divertor component and its influence on the TL. The Divertor component is located along the bottom of the Vacuum Chamber and has the main function of extracting the heat and ashes generated as a product of the fusion reactions and other impurities in the plasma. It consists of two parts: the stainless-steel support structure and the plasma interface components (PFC: Plasma Facing Components). Two models were proposed for the Divertor component, based on the ITER Divertor under development [4,5], in order to evaluate if the insertion of this component can affect the characteristics of the neutron flux in TL and, consequently, the transmutation of the fuel.

2. METHODOLOGY

Fig. 1 shows the three-dimensional modeling of the hybrid fusion-fission reactor, without the Divertor component. The geometry is represented by the intersection of cylinders and planes limiting the different fusion device layers, as well as the TL [6]. The materials used were according to the ITER guidelines [5] and the paper [7].

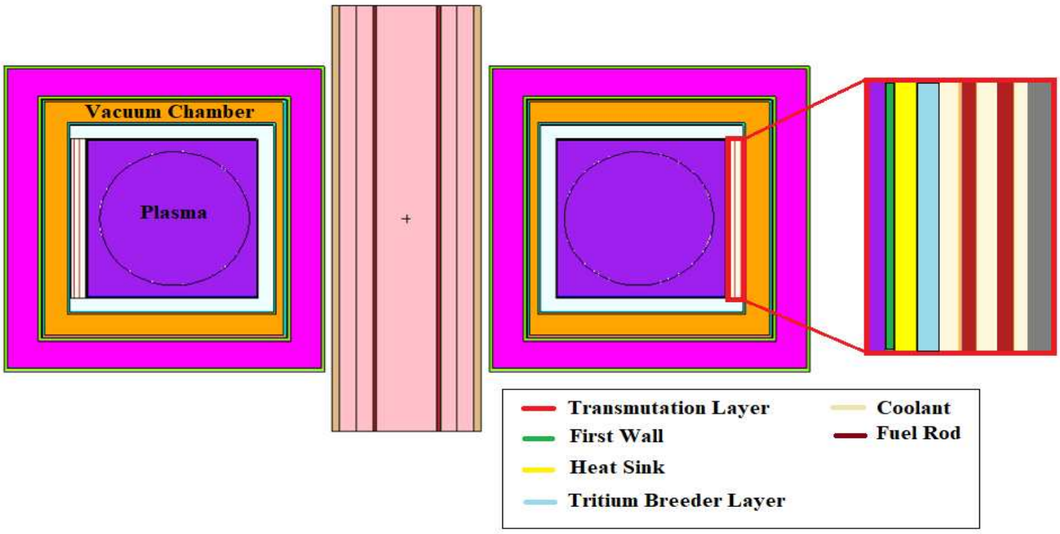

Fig. 1. System 1 with the transmutation layer and no Divertor.

The model above was modified to insert the Divertor component in the lower part of the Plasma Chamber and after several attempts, two possible models were reached, based on the reference ITER Divertor [4,5]. The first model (System 2) proposed for the Divertor component, has geometry made up of intersections of flat surfaces and circular torus; and the second model (System 3), is represented by intersections of flat and cylindrical surfaces. The last model was proposed in order to simplify the modeling of the Divertor component, not using surfaces like the circular torus in its geometry. This is because these surfaces are described by quartic equations, which makes calculating their roots more complicated to determine the particle positions by MCNP5, resulting in losses of particles during the program executions. Therefore, the System 2 has a limitation in the number of stories (nps) for its execution to 1.0E+06 total. For Systems 1 and 3, the nps values were 1.0E+08. Fig. 2 and 3 show the three-dimensional modeling of the FFS with the models represented for the Divertor component.

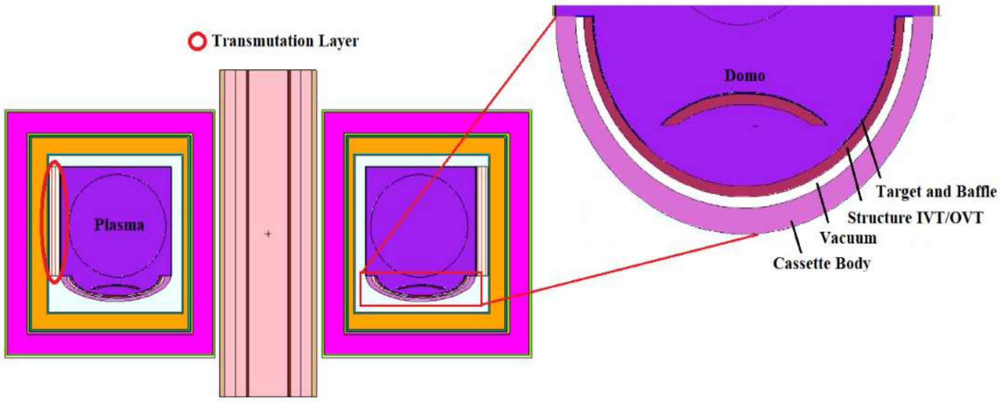

Fig. 2. System 2, the modeled Divertor with torus and planes

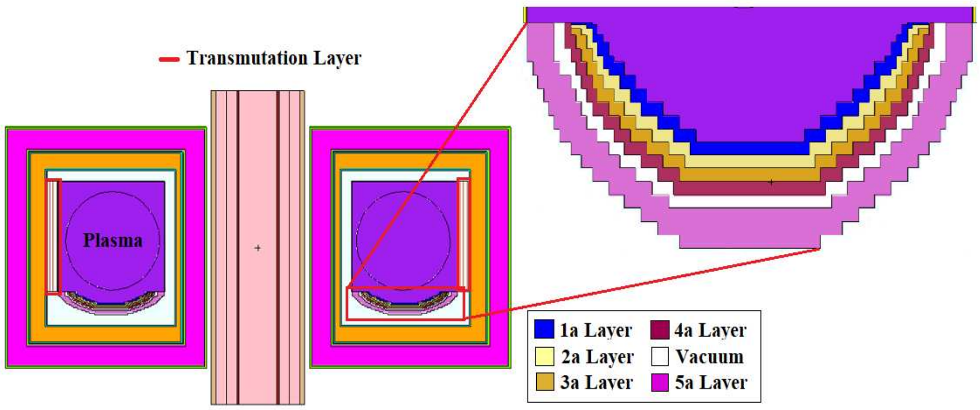

Fig. 3. System 3, the modeled Divertor with cylinders and planes

Tab. 1 describes the systems and layers of the two Divertors components modeled in more detail, based on research and projects for the ITER Divertor under development [4,5].

The Divertor model for System 3 is much simpler when compared to System 2, due to complex components that composed the Divertor, such as the Dome, and also, the thin layers used to represent the system. Therefore, for the model 2, it has been chosen to sketch only the layers of the main materials that constitute the Divertors.

The three systems have the same volume for the TL of 105,194 m^3 and for the volume fuel about 74.05 m^3. The TL is load with a hexagonal lattice containing the fuel rods and the coolant, its location is inside the block shield and next to the heat sink component. Systems 1 and 3 have the same volume for the Plasma Chamber, 837.00 m^3 and for System 2, the approximate volume of 838.04 m^3, which results in a relative difference of 0.12%. This difference in the volumes of the Plasma Chamber stems from the difference in the volumes of the Divertor components of the two proposed models, since with the insertion of the Divertor, the volume for the cylindrical ring part of the Plasma Chamber decreases. So, the maximum effort was made to obtain the same volume for the two Divertor components modeled, contrary to the different surfaces used in these models.

Tab. 1. Divertor component specifications for Systems 2 and 3 [5,6].

	Components	Composition
Model 1 (System 2)	Target	W-1.1%TiC
		Pure Cu
		CuCrZr
	Baffle	W-1.1%TiC
		Pure Cu
		CuCrZr
	Domo Umbrella	W-1.1%TiC
		Pure Cu
		CuCrZr
	Structure Domo	SS316L(N)-IG, 55%; water, 45%
	Structure IVT / OVT*	SS316L(N)-IG, 55%; water, 45%
	Cassette Body	SS316L(N)-IG, 65%; water, 35%
Model 2 (System 3)	1^{a} layer	W-1.1%TiC
	2^{a} layer	Pure Cu
	3^{a} layer	CuCrZr
	4^{a} layer	SS316L(N)-IG, 55%; water, 45%
	5^{a} layer	SS316L(N)-IG, 65%; water, 35%

* Inner and Outer Vertical Target

To calculate criticality calculation and the fuel depletion were used the MONTEBURNS code, which links the MCNP5 with the depletion code ORIGEN2.1. For the criticality calculations, the number of cycles was 40, and for depletion calculations, the number of steps was fixed in 10 where each step has a range of 365 days, the fission power was 3000 MW and fusion power through D-T source was between 250 and 500 MW.

The fuel used in the TL was a spent fuel from a PWR after a burnup of 33000 MWd/t, then left 5 years in the spent pool. After that, the spent fuel was reprocessed by the GANEX technique and then spiked with thorium until reach 11.5% of fissile material, in order to convert the fertile material into fissile isotopes, such as uranium-233. The Tab. 2 presents its isotopic composition [8].

Tab. 2. Initial isotopic composition for fuel loaded in TL [8].

Nuclide	Mass Fraction	Nuclide	Mass Fraction	Nuclide	Mass Fraction
^{232}Th	7.1000E-01	^{239}Np	7.4344E-04	^{242}Cm	4.0902E-04
^{233}U	3.2927E-11	^{238}Pu	2.9197E-03	^{244}Cm	4.6819E-04
^{234}U	2.4438E-06	^{239}Pu	7.6402E-02	^{245}Cm	1.6335E-05
^{235}U	1.2746E-04	^{240}Pu	2.6110E-02	^{143}Nd	1.9550E-03
^{236}U	6.5212E-05	^{241}Pu	2.4567E-02	^{150}Sm	3.9101E-04
^{237}U	9.3123E-08	^{242}Pu	9.2866E-03	^{153}Eu	8.3219E-05
^{238}U	1.5563E-02	^{241}Am	1.3119E-03	^{16}O	1.2061E-01
^{237}Np	7.1643E-03	^{242}Am	2.4181E-06	-	-
^{238}Np	1.1769E-05	^{243}Am	1.7750E-03	-	-

3. RESULTS

Fig. 4 shows the values for the effective multiplication factor in the three systems. During burnup, Systems 2 and 3 present values higher than the values of System 1, indicating that the fission reactions are more frequent for systems with the Divertor component. Observing Fig. 5, these fission reactions occur more intensely in the region of the fast neutron spectrum, since the neutronic flux profile in the three systems is more hardened. The values of the relative errors for the k_{eff} calculations in Systems 1, 2 and 3, were around: 5.18E-04, 1.42E-03 and 1.28E-03, respectively.

In general, the three systems have a similar neutron flux profile, in the range above 1.0E-10 MeV region. The System 2 presents some peaks between the energy range of 1.0E-11 to 1.0E-10 MeV. The System 3 has the highest neutron flux over the TL, followed by System 2 and System1, as can be seen in Tab. 3, which displays the total flux values for the energy intervals in the systems and the calculated values for the weighted average energies. In the three systems, the weighted average energy for the neutron corresponding to the fast range of the spectrum and although they have a more hardened neutron spectrum, Systems 2 and 3 also present a good part of their population located in the intermediate energy range, which explains the smaller values for the weighted average energies. Then, the insertion of the Divertor component in these systems, increases the neutron scattering in the lower region of the Plasma Chamber, contributing to the increase in flux. Further analysis, such as the tracking of these neutrons and their spectrum on the initial surface of the TL, will be performed. The softening and hardening of neutrons in the systems with Divertor, are responsible for the differences in the transmutation capacity of the three systems.

The impact of the insertion of the Divertor component during the burnup, can be seen in Tab. 4. Analyzing by material group: the System 1 consumes 0.69% more fissile material than System 2 and 0.16% more than System 3; the System 2 consumes about 0.09% more actinides than System 1 and 0.08% more than System 3; it also produces more fission products, about 7.99% more than System 1 and 0.39% more than System 3; and finally, System 3 consumes about 0.05% more minor actinides than System 1 and 0.06% more than System 2. Comparing some of these results presented with those of Figs. 6 and 7, the probabilities of neutron fission absorbed in the fissionable materials for System 1 are higher compared to Systems 2 and 3, however, it is the systems with the Divertor component that exhibit the highest values for transmutation of the minor actinides and actinides. As analyzed in Fig. 5, the largest population of fast neutrons in systems with a Divertor component, allows the best consumption of the nuclides of these groups. Consequently, they are also the ones that present a relative increase in the production of fission products, since the amount of mass of non-fissile actinides in the fuel, exceeds the mass of fissile materials.

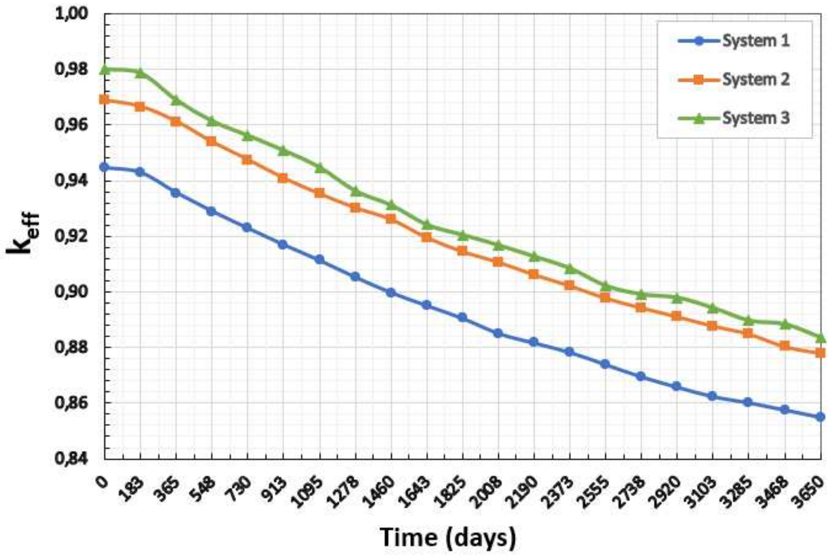

Fig. 4. Values for the effective multiplication factor in the three systems during burnup of the fuel.

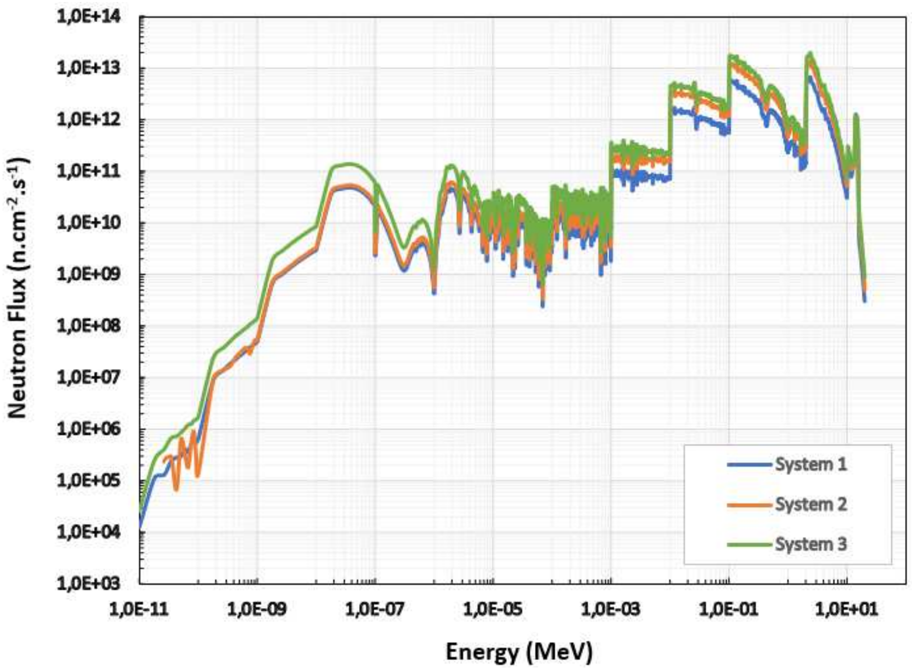

Fig. 5. Neutron fluxes for the three systems in the TL region and for fresh fuel.

Tab.3. Neutron fluxes, weighted average energies and relative errors calculated for fresh fuel systems.

	System 1	System 2	System 3
Thermal Neutrons (%)	0,037	0,020	0,036
Intermediate Neutrons (%)	69,642	70,675	70,186
Fast Neutrons (%)	30,321	29,305	29,779
Total Flux ($n.cm^{-2}.s^{-1}$)	1.619E+15	3.376E+15	4.799E+15
Total Flux Relative Error	7.000E-04	9.500E-03	1.200E-03
Weighted Average Energy (MeV)	5.935E-01	5.610E-01	5.660E-01

Tab.4. Mass transmuted (-) or produced (+) after 10 years of burnup, for the three systems.

Material Group	Mass Variation (kg)		
	System 1	System 2	System 3
Fissile Material	-8.66940E+04	-8.60956E+04	-8.65532E+04
Actinides*	-6.01984E+05	-6.02552E+05	-6.02081E+05
Minor Actinides**	-4.46613E+06	-4.46565E+03	-4.46853E+03
Fission Products	4.50689E+02	4.89850E+02	4.87930E+02

* Corresponds to Th to Cm nuclides, except their fissile isotopes.

** Corresponds to Np, Am e and Cm except their fissile isotopes.

Due to the greater production of fission products in systems with a Divertor component at the end of the burnup, they have a lower value for fuel mass variation. The total net consumption for Systems 1, 2 and 3, respectively, are: -6.916E+08 kg, -6.914E+08 kg and -6.913E+08 kg.

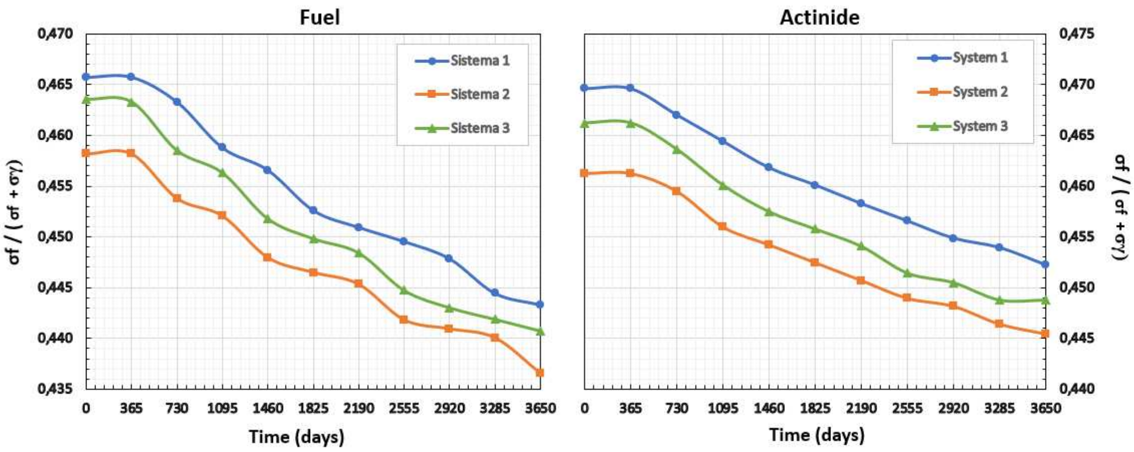

Fig. 6. Variations for probability of neutron fission absorbed during burnup, for the three systems. Values obtained for the total fuel composition (left) and for the actinide group (right).

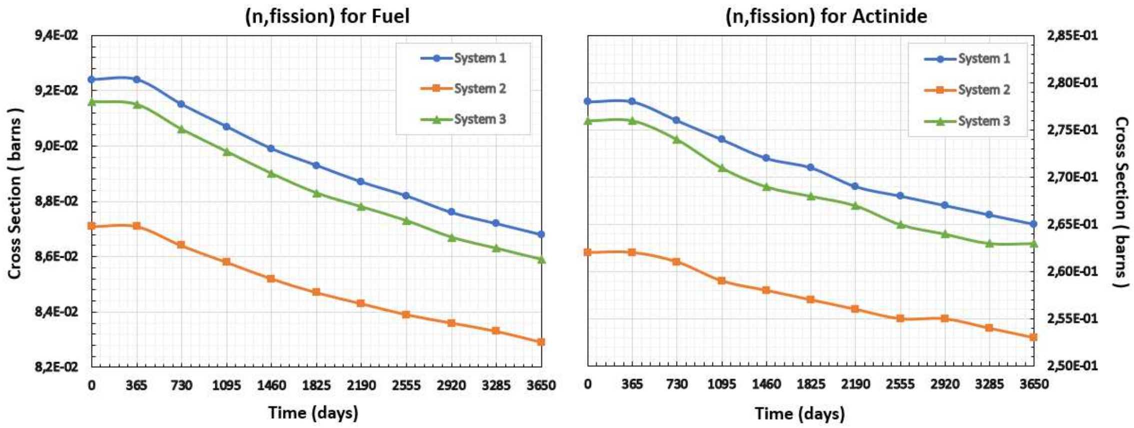

Fig. 7. Variations of the microscopic fission cross section during burnup, for the three systems. Values obtained for the total fuel composition (left) and for the actinide group (right).

4. CONCLUSION

The results obtained indicate changes in the neutron flux of TL and, consequently, in the transmutation of transuranic and production of fission products, when the Divertor component is inserted. Initially, in Systems 2 and 3, the fast neutron population in TL decreases and the intermediate neutron population starts to show a slight increase. However, these two systems have a higher neutron flux compared to System 1 and, consequently, a higher percentage of transmutation of minor actinides and actinides. The k_{eff} values shown in the graph also indicate the superior occurrence of fission reactions in fissionable nuclides for systems with a Divertor component, even though these exhibit the lowest values for the fission cross sections and probability of neutron fission absorbed. System 1 has values of relative errors for k_{eff} and total neutron flux, a lower order of magnitude compared to Systems 2 and 3, however, all values for relative errors in systems are small and are within the calculation quality, according to the MCNP manual. It is necessary to analyze the influence of the geometry of the fusion system and its impact on TL, especially the insertion of components such as Divertor, which has a high scattering cross section, and therefore exhibits greater moderating power, directly impacting capacity to induce fission in minor actinides. Future work will be carried out study of the neutron spectrum of the three systems throughout at different burnup step.

REFERENCES

[1] C.E. Velasquez *et al.*, Fusion–Fission Hybrid Systems for Transmutation, *Journal of Fusion Energy*, Vol. 35, N. 1, pp. 1-134 (2016).

[2] W.M. Stacey *et al.,* A Fusion Transmutation of Waste Reactor, *Fusion Science and Technology,* Vol. 41, (2002).

[3] C.E. Velasquez *et al.*, Evaluation of subcritical hybrid systems loaded with reprocessed fuel, *Annals of Nuclear Energy*, Vol. 85, pp. 633-642 (2015).

[4] T. Hirai *et al.*, ITER tungsten divertor design development and qualification program, *Fusion Engineering and Design*, Vol. 88, pp. 1798-1801 (2013).

[5] https://www.iter.org/ accessed on 01/01/2021.

[6] R.V.A. Marques, Tritium Breeder Layer Evaluation of Fusion-Fission Hybrid System, *Fusion Science and Technology*, Vol. 76, pp. 145-152 (2020).

[7] Y. Wu and FDS Team, CAD-based interface programs for fusion neutron transport simulation, *Fusion Engineering and Design*, Vol. 84, pp. 1987-1992 (2009).

[8] S. Cota and C. Pereira, Neutronic evaluation of the non-proliferating reprocessed nuclear fuels in pressurized water reactors, *Annals of Nuclear Energy*, Vol. 24, pp. 829-834 (1997).