2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-1256-3

Doppler Effect Analysis of a Fast Neutron Reactor for a Fusion-Fission System

R. V. A. Marques, C.E. Velasquez, C. Pereira

renatovam@ufmg.br, carlosvelcab@nuclear.ufmg.br, claubia@nuclear.ufmg.br

Departamento de Engenharia Nuclear
Escola de Engenharia – UFMG
Av. Antônio Carlos, 6627 - Pampulha - Belo Horizonte – MG, Brazil
CEP 31270-901 +55 (31) 3409-6666

1. Introduction

The Nuclear Engineering Department at Universidade Federal de Minas Gerais (DEN/UFMG) has been studying subcritical nuclear reactors for transmutation of transuranic (TRU), such as, accelerator driven system (ADS) and fusion-fission system (FFS) [1-5]. Previous works studied the FFS based on a Tokamak, which uses deuterium (D) and tritium (T) as fuel in the fusion device producing 14.1 MeV energy neutrons, which are used as an external source to drive a subcritical fission blanket with fertile and/or fissionable materials. These neutrons increase the probability to induce transmutation in transuranic nuclides by fission reactions due to the probability of fission per neutron absorbed being greater for all the actinides in a hard neutron spectrum [1-3, 5].

In addition, coolant materials studies for FFS, suggest that lead-bismuth eutectic (LBE) liquid metal would be the best material option to enhance transmutation of transuranic nuclides and tritium production on the system [6]. In addition, a tritium breeder layer was placed before the transmutation layer for tritium production purpose [7]. To optimize the geometry system, it was considered the geometry utilized on an ADS [8] replacing the photon beam and spallation target in the reactor center by a D-T fusion neutron source spectra from the FFS [6, 7]. Therefore, it was modeled a Fusion-Fission Fast Reactor (FFFR), using the materials of the FFS [6, 7] such as the cladding, coolant, first wall and heat sink in the FFFR modeled system with the purpose to obtain a harden neutron spectrum to induce TRU transmutation on the FFFR.

In this context, the aim of this work is to evaluate the Doppler Effect and criticality analysis in the FFFR with the external fusion neutron source [7] by using two different fuel matrices at different fuel temperatures. Furthermore, this work also studied the evaluated nuclear data processing cross section generated by the NJOY Nuclear Data Processing System-Version 2012 [9] using Jointly Evaluated Fission and Fusion File (JEFF-3.3) [10] and Fusion Evaluated Nuclear Data Library (FENDL-3.2) [11] in FFFR. It was used GANEX spike with Thorium (Th) and GANEX spiked with Depleted Uranium (DU) as nuclear fuels in the FFFR core using Lead-Bismuth Eutectic (LBE) as coolant material. Thorium oxide was used as breeder material in the breeder core. The respective analysis was provided by Monte Carlo N-Particle-Version 5 code (MCNP5) [12].

2. Methodology

2.1. FFFR Geometry and Materials

The FFFR geometry parameters are shown in Table 1 [8]. It consists of an iron tank cylinder [8] with a D-T fusion source at the center of the system, a first wall and a heat sink surrounded the fusion device, respectively, with a subcritical core (transmutation layer) divided in inner core, outer core and breeder core as shown in Figure 1. The fusion source device was supply by the neutron spectra from previous studies at the FFS [6, 7] described in

Simulation section in this work. It has 7.5 cm in radius and both first wall and heat sink have 1 cm thickness. The core simulated has 41.47 m³ filled with a hexagonal lattice formed by 162 fuel assemblies including the breeder core. The nuclear fuel pin radius is 0.365 cm, the clad thickness is 0.01 cm, and the fuel assembly dimensions are 11.6 cm in radius and 150 cm in active length. The materials used were according to the ITER guidelines [13] and the article of Fusion Engineering and Design [14]. The FFFR fuel work temperature is 1200 K and 300 MWt at fuel power. The LBE was used as coolant and also reflector material. The LBE work temperature at the system is 613 K [6]. The HT-9 was used as cladding, Be S-65C as first wall material and CuCrZr-IG as heat sink, which the work temperatures are 900 K, 1013 K and 723 K, respectively [6, 7, 13, 14].

Table 1 – Geometry parameters of FFFR.

Core Regions	Inner Core	Outer Core	Breeder Core
Fuel pin/assembly	331	397	397
Number of fuel assemblies	54	66	42
Pitch (mm)	12.43	11.38	11.38

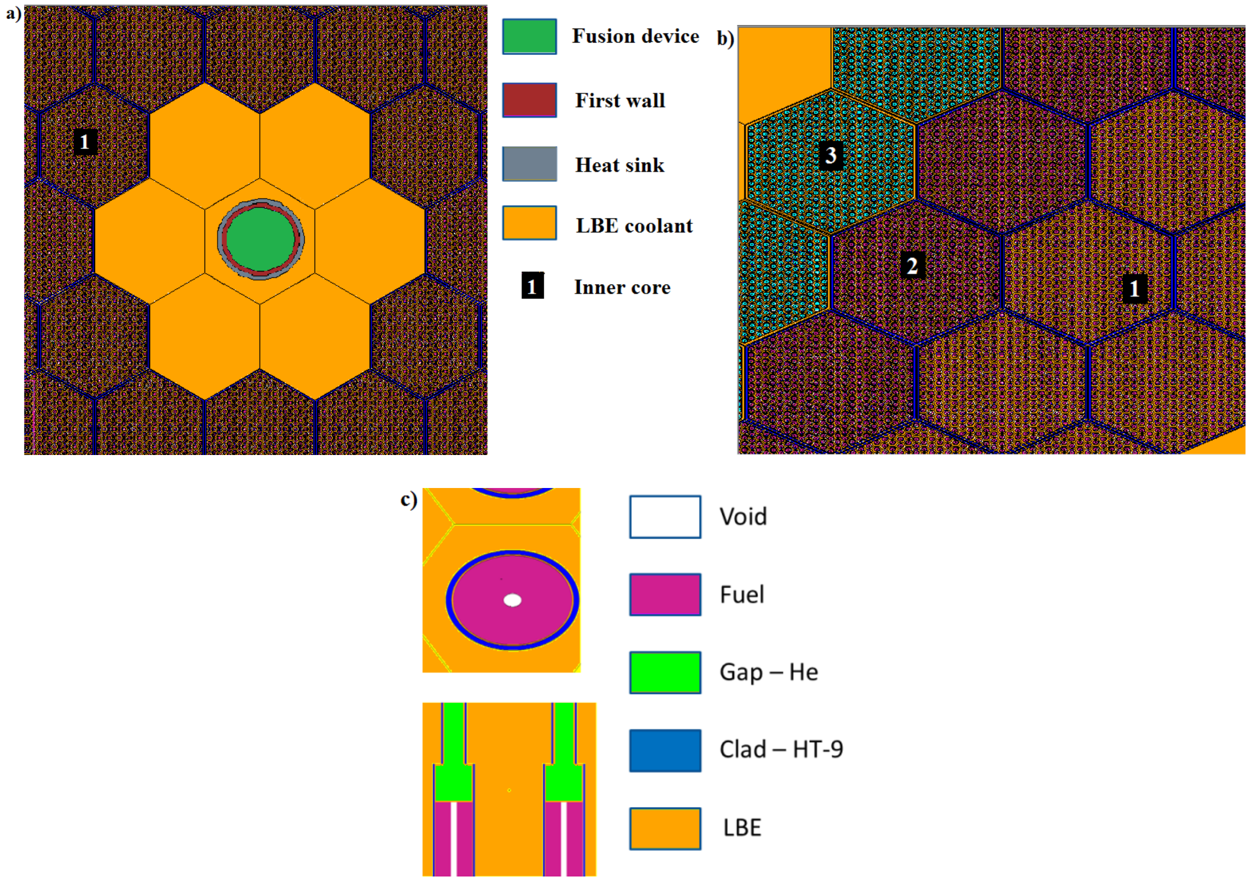

Figure 1 – a) Overview of FFFR system; b) FFFR transmutation layer: 1-inner core, 2-outer core, 3-breeder core; c) Fuel rod design at FFFR.

2.2. Nuclear Fuels

The FFFR uses as fuel material transuranic nuclides with the transmutation purpose, decreasing the level of long-lived highly toxic actinides. The fuel composition was provided by reprocessed spent nuclear fuel (SNF), obtained from a Pressurized Water Reactor (PWR) standard fuel with initial enrichment of 3.1% after a fuel burnup of 33000 MWd/t and kept over five years in a spent fuel pool for decay heat dissipation [15]. The SNF was reprocessed by GANEX technique [16, 17]. Then, the reprocessed fuel was spiked with Depleted Uranium (DU) –

which had 0.2% of ^{235}U - and Thorium (Th).

The two different fuels GANEX-DU and GANEX-Th were used separately in the FFFR to analyze the Doppler Effect for each of them in the proposed system. The inner and the outer core are loaded with each reprocessed fuel and the breeder core is loaded with thorium oxide (ThO_2) for both of them. The work temperature of fuel and breeder materials is 1200 K. The GANEX-DU had 7.5% of fissile material and GANEX-Th had 9.5% in order to achieve the multiplication factor around $k_{eff} \approx 0.95$ [18].

2.3. Simulation

The FFFR was design using the MCNP5 for criticality and temperature coefficient of reactive calculations, where the number of particles (nps) was 10^8 to minimizing the relative error - approximately 10^{-4}. The cross sections were generated by NJOY using JEFF-3.3 and FENDL-3.2 as nuclear data base for coolant and fuel materials at 300 K - except for LBE coolant due to its melting point of 398 K [6], 600 K, 900 K, 1200 K, 1500 K and 1800 K temperatures. The analyzes were carried out keeping the full power and the LBE temperature constant (at the work temperature) and changing the fuel temperature in order to evaluate the Doppler Effect in FFFR for both GANEX-DU and GANEX-Th fuel matrices. It also was made a similar analysis maintaining the fuels temperature constant (1200 K) and varying the coolant temperature. The neutron spectra of D-T fusion source from FFS was obtained using a MCNP5 tally [12] which calculated the neutron flux over the surface surrounding the FFS D-T fusion source for 10^{-8} to 14.1 MeV energy range. The obtained FFS neutron spectra were implemented as external source in the FFFR.

3. Expected results

Over the results, it is expected that an increasing in the temperature causes a broadening of spectral lines of resonances. Although the area under the resonance remains the same, the broadening of spectral lines causes an increase in neutron flux in the fuel, which in turn increases the absorption as the temperature increases as shown in Figure 2 [19, 20]. In fast neutron reactors, the Doppler Effect becomes less dominant (due to the minimization of the neutron moderation), but strongly depends on the neutron spectrum and the type of the fuel matrix [19].

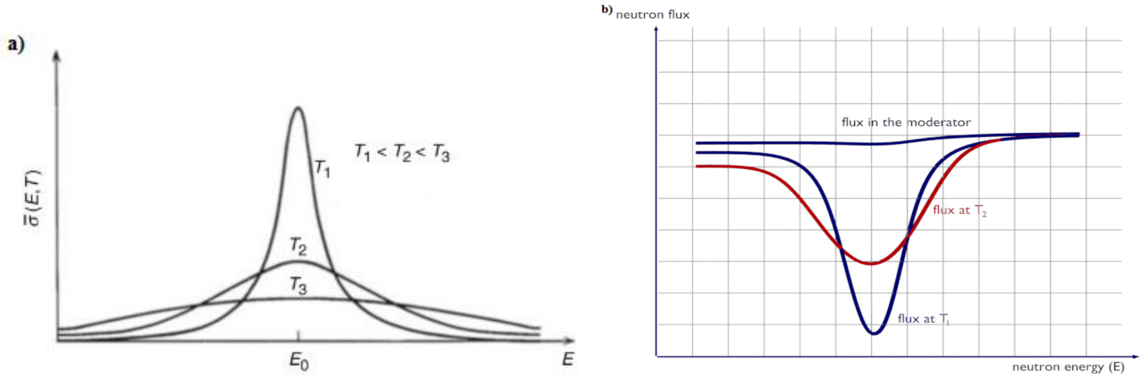

Figure 2 – a) Doppler broadening of a resonance with increasing temperature; b) Neutron flux for different fuel temperatures.

In this case, the neutron flux analysis in different fuel matrices at different temperatures and using different nuclear data libraries it will be important to neutronic parameters evaluating. The neutron spectra at different temperatures, the Doppler Effect and criticality using both JEFF-3.3 and FENDL-3.2 will be performed for analyze and comparison purpose after the proposed simulations.

Acknowledgements

The authors are grateful to the Brazilian research funding agencies, CNEN (Brazil), CNPq (Brazil), CAPES (Brazil) and FAPEMIG (MG/Brazil) for the support.

References

[1] Velasquez, C.E. et al. (2016), “Fusion–Fission Hybrid Systems for Transmutation”, Journal of Fusion Energy, Volume 35 – Number 1, pg 1-134.

[2] C.E. Velasquez et al., “Axial Neutron Flux Evaluation in a Tokamak System: a Possible Transmutation Blanket Position for a Fusion Transmutation System”, Nuclear Physics 42:237– 247, Sociedade Brasileira de Física (2012).

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

[4] Barros, G., et al., GANEX and UREX+ reprocessed fuels in ADS. International Journal of Hydrogen Energy, 2016. 41(17): p. 7132-7138.

[5] C. E. VELASQUEZ et al., “Layer Thickness Evaluation for Transuranic Transmutation in a Fusion–Fission System,” Nucl. Eng. Des., 286, 94 (2015);

[6] Marques, R.V.A., “Fusion-Fission Hybrid System: Neutronic Evaluation of Coolant Materials and of the Tritium Breeder Layer”, Master’s Thesis, (2019), 136 pages, UFMG-Brasil;

[7] Renato Vinícius A. Marques, et al., (2020) Tritium Breeder Layer Evaluation of Fusion-Fission Hybrid System, Fusion Science and Technology, 76:2, 145-152, https://doi.org/10.1080/15361055.2019.1704594;

[8] Rubbia, C., et al., Conceptual design of a fast neutron operated high power energy amplifier. 1995.

[9] MacFarlane, R.E. (2012), "The NJOY Nuclear Data Processing System, Version 2012", Los Alamos National Laboratory, LA-UR-12-27079.

[10] Nuclear Energy Agency, JEFF-3.3 evaluated data library. https://www.oecd-nea.org/dbdata/jeff/jeff33/index.html.

[11] International Atomic Energy Agency (IAEA), FENDL-3.2 Nuclear Data Services, https://www-nds.iaea.org/fendl/.

[12] X-5 Monte Carlo Team, Mcnp, A General Monte Carlo N-Particle Transport Code, Version 5, vol. II. User’s Guide University of California, Los Alamos National Laboratory (2003).

[13] International Thermonuclear Experimental Reactor (ITER) - Final Design Report (2001), http://www.naka.jaea.go.jp/ ITER/FDR/.

[14] Wu, Y. and F.D.S. Team, “CAD-based interface programs for fusion neutron transport simulation.” Fusion Eng. Des. 84, 1987–1992 (2009).

[15] Cota, S., Pereira, C. (1997), “Neutronic evaluation of the non-proliferating reprocessed nuclear fuels in pressurized water reactors”, Annals of Nuclear Energy, Vol.24, nº10, pp. 829-834.

[16] Aneheim, E.H.K. (2012), Development of a Solvent Extraction Process for Group Actinide Recovery from Used Nuclear Fuel, Department of Chemical and Biological Engineering, CHALMERS UNIVERSITY OF TECHNOLOGY, Gothenburg, Sweden.

[17] Miguirditchian M. et al. (2008), Development of the GANEX Process for the Reprocessing of Gen IV Spent Nuclear Fuels, ATALANTE Conference 2008, Montpellier (France).

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

[19] Zohuri, B., Neutronic Analysis for Nuclear Reactor Systems (2017), DOI:10.1007/978-3-319-42964-9.

[20] Doppler Broadening–Doppler Effect, Nuclear Power, https://www.nuclear-power.com/glossary/doppler-broadening/ [accessed August 28, 2021].