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Neutron Damage in the Plasma Chamber First Wall of the GCFTR-2 Fusion-Fission Hybrid Reactor

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Abstract. The successful development of energy-conversion machines based on either nuclear fission or fusion is completely dependent on the behaviour of the engineering materials used to construct the fuel containment and primary heat extraction systems. Such materials must be designed in order to maintain their structural integrity and dimensional stability in an environment involving high temperatures and heat fluxes, corrosive media, high stresses and intense neutron fluxes. However, despite the various others damage issues, such as the effects of plasma radiation and particle flux, the neutron flux is sufficiently energetic to displace atoms from their crystalline lattice sites. It is clear that the understanding of the neutron damage is essential for the development and safe operation of nuclear systems. Considering this context, the work presents a study of neutron damage in the Gas Cooled Fast Transmutation Reactor (GCFTR-2) driven by a Tokamak D-T fusion neutron source of 14.03 MeV. The theoretical analysis was performed by MCNP-5 and the ENDF/B-VII.1 neutron data library. A brief discussion about the determination of the radiation damage is presented, along with an analysis of the total neutron energy deposition in seven points through the material of the plasma source wall (PSW), in which was considered the HT-9 steel. The neutron flux was subdivided into three energy groups and their behaviour through the material was also examined.

Keywords: **Hybrid Reactors, Fusion Reactors, Neutron Damage, GCFTR-2, MCNP-5**
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1. Introduction

Hybrid subcritical reactors, as the Gas Cooled Fast Transmutation Reactor (GCFTR-2), or even Accelerator Driven Systems (ADS), are recently being widely studied since they would offer a range of important advantages over conventional fission reactors. The greater security due to the subcritical core is one of the strongest points in favor of hybrid reactors, along with the greater public acceptance of nuclear energy. Hybrid systems would also offer minor problems with respect to proliferation, significantly reduction of nuclear waste production and the possibility of transmutation of the existent nuclear waste. In this case, neutrons might be used to “transmute” long lived radioactive nuclei into much more short-lived ones [1,2,3,4,5,6].

In a fusion reactor, energy will be mainly produced by the fusion reaction between Deuterium (D) and Tritium (T) nuclei: $D + T \rightarrow {}^{4}He + n$. It is important to notice that this kind of system has a large neutron excess in comparison to fission reactors. Since neutrons produced by fusion reactors do not contribute for fusion reactions, the neutron leakage is complete. On the other hand, in a fission reactor the neutrons maintain the chain reaction. Despite the fact that in a fission reaction more neutrons are produced than in a fusion reaction, their leakage from the system is always kept to a minimum. In view of the high number of neutrons produced by fusion reaction without being appropriately exploited, conceiving a system in which neutrons may be utilized for other purposes is then possible. The peak of the neutron emission occurs at ~14 MeV, energy in which ^{239}Pu and ^{238}U undergo fission, enabling the utilization of fusion neutron excess as neutron source in a subcritical fission system. Therefore, a hybrid fusion-fission reactor may be seen as a coupled system; a subcritical fission reactor which has as source of neutrons a fusion reactor core [7].

1.1. The Fast Neutron Damage Problem

Damaging effects due to high-energy neutrons are considered crucial in fusion reactors, since a large number of neutrons are produced and escape from the system. In structural steels, as the one studied in this work, the main radiation damage mechanism is the displacement of atoms (DPA) from their lattice positions [8,9]. When radiation such as fast neutrons displaces atoms, vacancies are formed, which may be concentrated and create voids within the material, leading to void swelling phenomena. With the accumulation of damages, structural material may be deformed or even lose its integrity due to the high degradation of its properties. Unfortunately, currently there is no sufficient information which could be used to establish absolute damage limits for structure materials in fusion reactors. However, it is acknowledged that ferritic steels are less susceptible to displacement damage effects than austenitic steels, which led us to concentrate our study on the HT-9 steel, proved to be one of the most resistant and a strong candidate to be a structural material in fusion facilities [10,11].

This work presents a study of the displacement per atoms and the energy deposition in the first plasma source wall (PSW) composed by High-Cr martensitic HT-9 steel due to the high fast neutron flux in the Gas Cooled Fast Transmutation Reactor (GCFT-2) facility [12,13,14]. Studies of this nature are essential to evaluate which materials may be employed in fusion facilities, the thickness of material needed and also the lifetime of the structures, contributing to the understanding of these technological challenges.

2. Computational Simulation

2.1. The MCNP-5 Gas Cooled Fast Transmutation Reactor (GCFTR-2) Simulation

As the name suggests, the Gas Cooled Fast Transmutation Reactor (GCFTR-2), is a helium-cooled, fast and subcritical reactor which uses coated transuranic (TRU) fuel particles enclosed in SiC matrix pins. The GCFTR-2 was entirely reproduced using MCNP-5 simulations. The Figure 1 shows a side and an upper view scheme of the reactor.

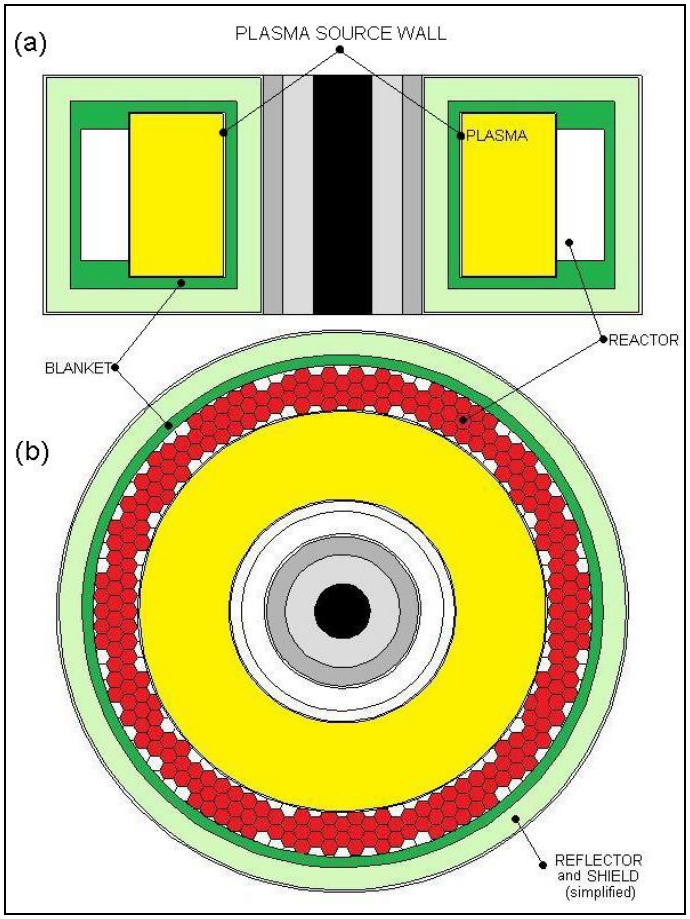

Figure 1 – (a) The side view and (b) the upper view of the Gas Cooled Fast Transmutation Reactor (GCFTR-2) simulated in the MCNP-5. In the picture, the word "reactor" corresponds to the fission core.

The PSW has a thickness of 3.5 cm and separates the fission core and plasma regions. All the calculations concerning neutron damage presented on this work were precisely made considering this wall. In order to perform those calculations coherently, a 300 ºC temperature was assumed and gas and heat production were also considered. The cross sections needed were generated by the NJOY99 Nuclear Data Processing System, broadly used when it is necessary to convert Evaluated Nuclear Data Files (ENDF) format into useful information for practical applications, as fission and fusion nuclear reactor analysis.

2.2. Fuel Element, Fuel Pin, Matrix and Triso Particles

The fuel element consists of a hexagonal arrangement of 384 fuel pins, each of them encapsulated with ODS steel, containing Triso particles enclosed by an inert matrix of SiC [14].

The Triso particles have a very interesting composition. They are constituted of five layers, the inner shell being TRU oxide and the other shells being, respectively, Zirconium carbide, Tungsten Carbide, Silicon Carbide and Tungsten carbide. In order to achieve a high burn up and no fuel failure this special configuration is required.

2.3. Determination of Radiation Damage

As previously mentioned, the DPA is a standard parameter considered for determination of radiation damage in materials. It considers the number of times in which an atom is displaced for a

given neutron flux fluence. Furthermore, it is possible to extract information about the material that is under effect of the flux, and from the own flux.

The two variables that can determine the DPA rate are the number of displacements per unit volume, denoted by R divided by the atomic density of the material (HT-9 steel in this case). Equation (1) expresses the DPA rate (R_{DPA}):

$$R_{DPA} = \frac{R}{N} = \int_{Em}^{EM} \sigma_D(E_i)\Phi(E_i)dE_i \quad (1)$$

In the integral, the upper and the lower limits are denoted respectively by EM, the maximum energy of the incoming particle and Em, the minimum energy of the incoming particle. The $\Phi(E_i)$ is the energy-dependent particle flux per unit energy, and $\sigma_D(E_i)$ is the energy-dependent displacement cross-section [9,15].

Through the MCNP-5 Nuclear Reactor Physics code, the neutron flux $\Phi(E_i)$ was calculated as function of energy in the PSW and then combined with the DPA cross-section $\sigma_D(E_i)$ of the HT-9 steel. Utilizing equation (1), the computation of the R_{DPA} was possible. The achieved results are presented at the section below.

3. Results

The total neutron energy deposition in the PSW is expressed in Figure 2. It is possible to notice that the R_{DPA} (in fluence per year, FPY) presents the maximum value at the inner surface of the PSW, in the position of 0.5 cm, as expected. Due to attenuation effects, the neutron damage decreases when the R_{DPA} is calculated for other position through the PSW.

For all calculations it was considered that the neutron source strength for the GCFTR-2 was equal to 7.1×10^{19} (number per second) [13].

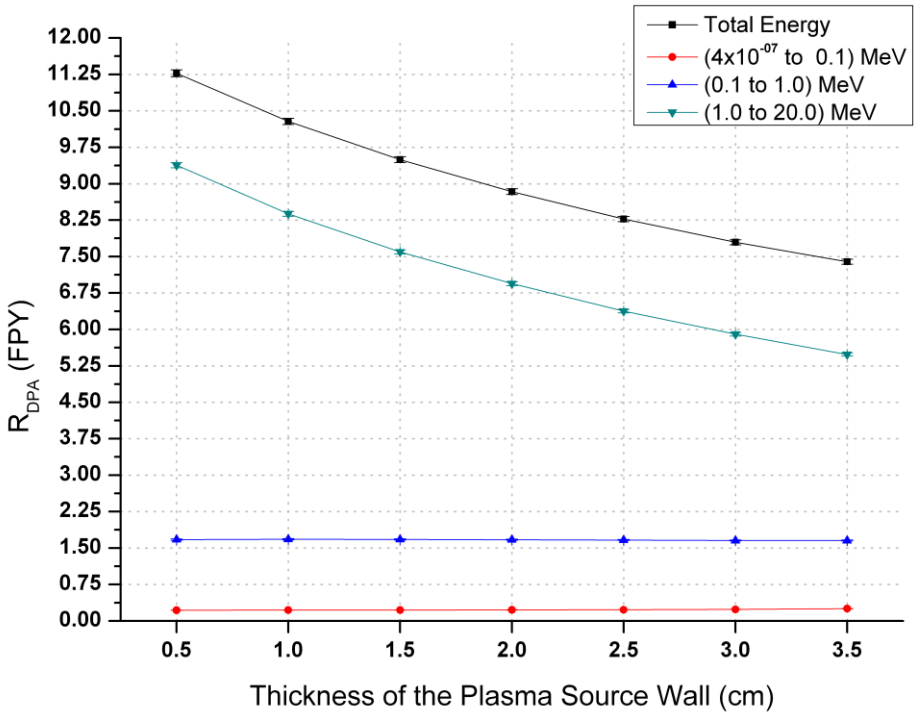

Figure 2 - Neutron energy deposition expressed in R_{DPA} (FPY) in function of seven positions within the PSW.

Besides the information concerning the total neutron energy deposition, Figure 2 also indicates the energy deposition according to the neutron energy group. Neutrons between 0.4 eV and 0.1 MeV are considered in the second epithermal energy group; between 0.1 MeV and 1 MeV in the first epithermal energy group and between 1 MeV and 20 MeV in the fast energy group [15]. Neutrons with energy up to 0.4 eV, in which thermal neutrons are included, presented no energy deposition within the material according to MCNP-5 simulations - indicating a non-interaction - and therefore are not represented in tables neither in graphs. The graph shows clearly that the major part of the neutron energy deposition was due to fast neutrons, followed by a small contribution of first epithermal group. Second epithermal group contribution was negligible.

By evaluating the energy deposition in various points through the PSW it was possible to determine which points of the material would be more affected by the radiation. The maximum energy deposition due to fast neutrons occurred at the inner points of the wall, and presented a decreasing along the material thickness. On the other hand, the first epithermal group energy deposition was practically constant, not presenting any decrease regardless of the position within the PSW.

More details may be appreciated in Tables 1 and 2, which presents, respectively, the neutron flux spectrum and the R_{DPA} for three neutron energy groups (second epithermal, first epithermal and fast) in two points (the most inner and outer) evaluated within the PSW.

Table 1- Flux spectrum for the PSW inner surface (0.5 cm) and for the outer PSW surface (3.5 cm)

Energy Group	**Energy Interval** (MeV)	**Flux Spectrum** PSW 0.5 cm surf. n / cm² / s	%f	PSW 3.5 cm surf. n / cm² / s	%f
2nd Epithermal	4E-7 to 0.1	2.17(1)E+14	30.4%	2.17(1)E+14	33.8%
1st Epithermal	0.1 to 1	2.89(2)E+14	40.5%	2.82(2)E+14	43.9%
Fast	1 to 20	2.08(1)E+14	29.1%	1.43(1)E+14	22.3%
	Total	7.14(1)E+14	100%	6.43(1)E+14	100%

Table 1 shows the neutron flux at the most inner and outer points considered within the PSW. This flux is also subdivided into three energy groups: second epithermal, first epithermal and fast. %f represents the percentage representatively correspondent of each component of the neutron flux - reminding that neutrons up to 0.4 eV were excluded from the analyses due to its non-interaction and, consequently, no energy deposition.

Table 2- R_{DPA} for the PSW inner surface (0.5 cm) and for the outer PSW surface (3.5 cm)

Energy Group	**Energy Interval** (MeV)	**R_{DPA}** PSW 0.5 cm surf. FPY	%f	PSW 3.5 cm surf. FPY	%f
2nd Epithermal	4E-7 to 0.1	0.221(2)	1.9%	0.253(2)	3.4%
1st Epithermal	0.1 to 1	1.67(1)	14.8%	1.66(1)	22.4%
Fast	1 to 20	9.38(5)	83.3%	5.49(3)	74.2%
	Total	11.28(7)	100%	7.39(5)	100%

Table 2 shows the R_{DPA} in fluence per year (FPY) at the most inner and outer points considered within the PSW. The R_{DPA} is also subdivided into three energy groups: second epithermal, first epithermal and fast. %f represents the percentage representatively correspondent of each component of the fluence.

By subdividing the study into three energy groups it was possible to evaluate the behaviour of neutrons within the material. Analysing the Table 1, it was possible to notice that at the most outer position within the PSW the first and second epithermal fluxes were enhanced by 3.4% each, while the fast flux presented a 6.8% of decrease. The behaviour may be explained by the thermalization of fast neutrons, which interact with the nuclei of the material.

From table 2, as seen in Figure 2, it may be observed that the larger contribution to R_{DPA} on the inner surface of the PSW (position of 0.5 cm) corresponds to the fast neutron flux (83.3% of R_{DPA}). The first and second epithermal groups correspond to 16.7% of R_{DPA}. The contribution of the second epithermal group, in this case, is found to be negligible.

The results for the neutron damage presented in Figure 2 and Table 2 are in agreement with the literature [11]. One important point that should be highlighted is that the previous studies concerning the HT-9 steel were experimental [10, 11]. Through the simulations presented in this work it was possible to achieve similar results, indicating that not only the present study contributes to the research and understanding of the irradiation effects on the HT-9 steel but also indicates that the theoretical approach may be utilized to the study of other materials with great accuracy.

4. Conclusions

The neutron damage determination was presented in this work with a special regard to the fast neutron damage problem applied to a hybrid reactor. Considering the calculated results, it was possible to confirm the predicted values of R_{DPA} in the Plasma Source Wall (PSW). The good agreement with the literature [11] indicates an excellent computational simulation of the system.

The work showed the total neutron energy deposition calculation in seven positions through the High-Cr martensitic HT-9 steel, demonstrating in which manner the energy loss may occur. Besides the total neutron energy deposition, the second epithermal, first epithermal and fast components were evaluated. As expected, according to MCNP-5 simulations, the thermal neutron energy deposition was not relevant to cause lattice damage in the steel and was not even considered in the analyses. As discussed in this work, the second epithermal group also presented negligible results.

The subdivision of the neutron flux into three energy groups was essential to demonstrate the thermalization effects. The work showed that principally neutrons belonging to the energy interval up to 0.4 eV and neutrons from the second epithermal energy group may be motive of concern from the shielding point of view, since not only they are not absorbed by the PSW but also the neutrons from the fast spectrum are thermalized, enhancing the number of low energy neutrons leaving the plasma wall.

In previous studies concerning the HT-9 steel, only mechanical tests were considered [10, 11]. In this context, computational simulations are needed to a better understanding of the experiment. The agreement between the previous results and the theoretical ones presented in this work indicates that not only the current study contributes to the research and understanding of the irradiation effects on the HT-9 steel but also indicates that the theoretical approach may be utilized to the study of other materials with great accuracy.

Studies of the same nature as the one presented are essential to evaluate which materials may be employed in fusion facilities, the thickness of material needed, the lifetime of the structures, and also exactly what kind of radiation must be shield both for biological and for instrumentation protection.

For future works, an improvement in the estimation of maximum R_{DPA} may be done by comparing other nuclear neutron data libraries, upgrading the computational code input by adding the magnets and increasing the number of the particle histories. A biological shielding study is also foreseen.

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References

[1] Waltar A E Todd D R Tsvetkov P V 2012 *Fast Spectrum Reactors* (Springer)
[2] Nifenecker H Meplan O David S 2003 *Accelerator Driven Subcritical Reactors - Series in Fundamental and Applied Nuclear Physics* (CRC Press)
[3] Oka Y Furuta K Kondo S 1989 *Fusion Engineering and Design* **7** pp 369-376.
[4] Salvatores M *et al* 1996 MUSE-1: A first experiment at MASURCA to validate the physics of

Subcritical Multiplying Systems relevant to ADS *2nd ADTT Conf*
[5] Rubbia C *et al* 2004 *PHYSOR-2004* **42** 4209647
[6] Maiorino J R dos Santos A Pereira S A 2003 *Brazilian Journal of Physics* **33** pp 267-272
[7] Freidberg J P Kadak A C 2009 *Nature Physics* **5** pp 370-372
[8] Kulctaski G L 1974 Radiation Damage to Materials in DT Fusion Reactors *Proc. of the Fifth Conference on Plasma Physics and Controlled Nuclear Fusion Research*.
[9] Koutsky J Kocik J 1994 *Radiation Damage of Structural Materials* (Elsevier Science Ltd)
[10] Smidt F A J Malmberg P R Sprague J A Westmoreland J E 1976 *Irradiation Effects on the Microstructure and Properties of Metals* **ASTM STP 611** pp 227-241
[11] Chen Y 2013 *Nuclear Engineering and Technology* **45** pp 311–322
[12] Stacey W M *et al* 2005 *Nuclear Technology* **150** pp 162-188
[13] Stacey W M *et al* 2006 *Nuclear Technology* **156** pp 99-123
[14] Stacey W M *et al* 2007 *Nuclear Technology* **159** pp 72-105
[15] Mascitti J A Madariaga M 2011 *Science and Technology of Nuclear Installations* **ID534689** pp 1-6