Optimization of tritium breeding ratio in ARC reactor

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Affordable Robust Compact reactor is a conceptual design for a Tokamak conceived by Massachusetts Institute of Technology (MIT) researchers. The design of this tokamak is under development and update. One of the key parameters for fusion reactor power plants is the tritium breeding ratio (TBR), which has to guarantee the tritium self-sufficiency.
The tritium inventory circulating in a fusion power plant must be minimized. In the meantime, to enhance plant's economics, the amount of tritium generated and stored should be maximized, since it would be used to startup new reactors. Both of the aforementioned trends meet their best in a TBR as high as possible. In this work, ARC tritium breeding ratio is studied and optimized.
Taking advantage of Monte Carlo neutron transport codes, several configurations of ARC's blanket and vacuum vessel have been analyzed in order to find the most effective one for a high TBR. The study takes into account different materials for the structure, such as Inconel718, V-15Cr-5Ti and Eurofer97. Moreover, it scans different width of coolant's channels and evaluates the effect of lithium-6 enrichment in the blanket looking for the best configuration in terms of TBR.

Keywords: Affordable Robust Compact (ARC), Tokamak, Tritium Breeding Ratio, Blanket, Neutronics, Monte Carlo

1. Introduction

Affordable Robust Compact (ARC) reactor [1, 2] is a relatively small tokamak designed to achieve 525 MW of steady state fusion power. It takes advantage of high temperature superconductors as main magnet technology, lower hybrid technology for current drive and log-leg divertor configuration for helium ashes exhaust. ARC machine is designed to be a pilot plant with a full-scale autonomous fuel cycle, including tritium breeding, transport, extraction and injection. In this framework, ARC is provided with a liquid blanket made of the FLiBe ($2LiF - BeF_2$) molten salt, that fully surrounds the Vacuum Vessel (VV) and hence the confined plasma. It has FLiBe channels flowing poloidally inside the double walled vacuum vessel and the VV itself is immersed in a bulk FLiBe tank, to maximize tritium breeding and magnets shielding [1, 2].

So far, the VV design mainly focused on structure integrity [1, 3] while looking to fulfill the tritium breeding ratio (TBR) > 1 requirement. The outcome was a double walled vessel with two structural layers of Inconel 718, a tungsten first wall and it was found the necessity of a Beryllium layer for overcoming the minimum TBR requirement, which was finally found to be 1.1 [1] and lately 1.08 [2].

However, every fusion reactor must undergo to a TBR analysis for optimization, as that parameter plays a central role in a broad range of fields, from safety to plant's economics. More specifically, a fusion machine's TBR directly affects the exceeding tritium build up over time and the time-independent circulating tritium inventory [4]. For instance, a TBR increase would make the exceeding tritium rise, accelerating the build up for a new fusion power plant, which is good for economics, being tritium the most high-priced element on the planet. Additionally, a high TBR would cause a drop of the time-independent circulating inventory, making the plant way safer in case of accident and release [4].

This work analyses ARC's TBR and points out the main aspects that play a role in its variation, namely materials, geometries and main breeder element's enrichment. It then identifies which of these aspects have room for modifications without undermining ARC's core design. Parametrizing these main elements is possible to come up to the best configuration in view of an optimized TBR, as upstream parameter for future works on tritium systems in ARC.

2. Model description

While first ARC neutronic studies have been carried out with a full size VV design [2], for this study, the decision made was to build an independent fast-running and easy-to-parametrize model by means of the MCNP neutron transport code [5].

The original VV configuration is characterized as follows: 0.1 cm of tungsten as first wall; 1 cm of Inconel 718 as structural material (here referred as STR1); 2 cm of flowing FLiBe as blanket and coolant; 1 cm of beryllium as neutron multiplier (here referred as Nmult layer); 3 cm of Inconel 718 as second structure (here referred as STR2) and roughly 1 m of bulk FLiBe in a tank [2].

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Also, based on ARC given fusion power output (525 MW) its neutron production rate has been computed to be 1.86E+20 n/s [2][3].

The model (Fig. 1) simplifies the vessel geometry to a cylinder having the same first wall surface of reference model's main chamber [2].

The choice of the geometry is related to the necessity, for the study, to be able to quickly change the parameter and run the simulations several times.

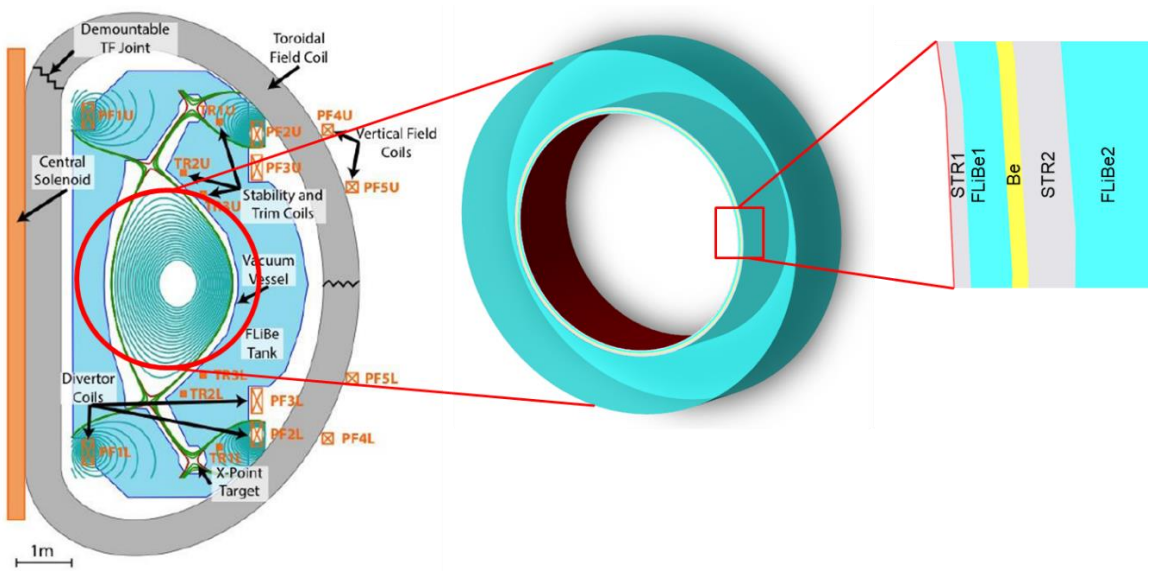

Fig. 1. Original model (left) [2], simplified model (center) and zoom in of the original configuration, namely tungsten first wall (red), structural layers (STR1, STR2), beryllium as neutron multiplier (Be) and FliBe's volumes (FLiBe1, FLiBe2).

After an analysis on the runtime required for the full geometry model, a simple toroidal model and a cylindrical model, the last one has been considered having the best computational time – result's quality tradeoff. In this context, it is important to point out that this work main objective is to develop a consistent and fast running code, in order to carry out preliminary parametric studies aimed to understand whether a configuration or material increases or decreases the TBR, rather than giving an exact value. To check the consistency, simulations on the original configuration are in good agreement with the main model [2], showing a TBR of roughly 1.07. In addition, neutron's flux on the different layers do show consistency as well. In order to further accelerate the runtime, the model stops to 70 cm of FLibe behind the vessel strucutre. In most configurations it has been noticed that 70 cm of FLiBe was enough to reduce the neutron flux of more than two order of magnitudes with respect its first wall value, which has been considered acceptable as it is comparable to the Monte Carlo simulation's relative error. Cylinder height has been set to 100 cm, which corresponds to roughly 1/20 of the vessel's length at its major radius, leading to a 9.3E+18 n/s of source intensity. Few simulations have been run at different cylinder heights (up to 200 cm) showing results consistent with the 100 cm model, which thus was chosen for the parametric studies, as it is less time consuming. ENDF/B-VII [6] library for energy dependent neutron cross sections has been applied. The source has been modeled as a line standing in the cylinder's central axis and emitting 14.1 MeV neutrons isotropic. In addition, 20-40 cm radius cylinder sources have been also tried showing no significant differences in the output. Cylinder's surroundings have been set as a whole void while its sides have been modeled as reflectors, in order to simulate the axisymmetric tokamak geometry. For a good result precision-computational time tradeoff, 1.5E+7 random walks have been simulated taking 4-5 hours computing time on an average performance machine [5]. Furthermore, the code has the capability of directly computing the tritium rate production and therefore the tritium breeding ratio. Hence, a single shot of one second and 9.3E+18 neutrons was modeled and tritium production in each of the FLiBe volumes was noted for the final TBR evaluation.

3. Methodology

The methodology was to set changeable parameters while keeping the whole configuration as simple as possible. In particular, the work focused on changing layers' thicknesses and materials where it was possible. First wall was unchanged as very few materials other than tungsten are suitable as plasma facing component and the thickness of 0.1 cm was a choice of the last ARC work that avoids first wall's temperature peaks [2]. STR1 and STR2 thicknesses have been kept constant for structural integrity [1]. FLiBe channel's width (here referred as FLiBe1) is the first main parameter. It has been sequentially increased from 2 cm up to 7 cm of

width, with 0.5 cm steps. Model does not go any further than 7 cm since it is a geometric limit set to the demountability of the VV, which is designed to be pulled out from the top of the blanket tank. The choice has been made also because the STR2 structure is supposed to bear most of the structural loads [7], then it was decided to shield it better from neutrons while looking to improve the tritium production rate in the channel. The other main parameter is the STR1 and STR2 material: the aim was not only to enhance the TBR but also to start investigating the feasibility of low activation materials. Therefore, moving from Inconel 718 to V-15Ti-5Ti and Eurofer97, which is the reference low activation material for DEMO [8]. Material's physical properties and chemical composition applied in the Monte Carlo model can be found for the three chosen structural material in [9, 10, 11], respectively. For what concerns the liquid blanket, FLiBe's composition can be found in [12]. Its Li-6 enrichment has been kept constant to 90% for first simulations [2], then it has been parametrized in 0-100% enrichment range as last parameter. In addition, the neutron multiplier layer has been set as last parameter: from no layer to 0.5 cm and 1 cm of thickness and beryllium or tungsten as materials. Since ARC's magnets and plasma geometry are well fixed it is not possible to change VV and tank's shapes as well. Therefore, in the model the total minor and major radii of the cylinder have been kept constant while changing layers thicknesses. Meaning that the FLiBe in the tank was losing or gaining volume while other layers' thicknesses were being increased or decreased, respectively.

Table 1 summarizes the main parameters implemented, as described above, showing the number of simulations run. In particular, FLiBe channel's width, the beryllium layer thickness and blanket's lithium-6 enrichment have been parametrized and simulated with the three different structural materials as cross parameter.

Table 1. Number of simulations run for each parameter considered. In particular materials, thicknesses and enrichment.

	Channel width	Beryllium thickness	FLiBe Li-6 enrichment
Inconel718	11	3	12
V-15Cr-5Ti	11	3	12
Eurofer97	11	3	12

4. Results and discussion

As previously mentioned, first simulations focused on the channel width and the structural material. Results are plotted in Fig. 2.

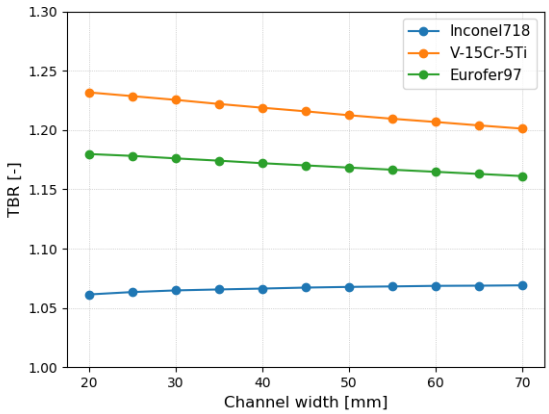

Fig. 2. TBR as a function of channel width and Inconel 718 (blue), V-15Cr-5Ti (orange) and Eurofer97 (green) structures. Each configuration has a 1 cm Beryllium layer for neutron multiplication.

It is possible to notice that from the tritium production viewpoint both vanadium alloy and Eurofer97 behave way better than Inconel 718. This can be explained by alloys' neutron transparency and main element's nuclear properties (here listed in table 2). The V-alloy and Eurofer97 are less dense than Inconel 718. In addition, at high neutron energies (i.e. 14 MeV) vanadium and iron show a higher (n, 2n) cross section while a lower absorption cross section (n, γ) than nickel at low energies [13]. Hence, the vanadium alloy and Eurofer97, compared to Inconel 718 let more neutron get through the structure and reach the blanket while multiplying more of those neutrons that experience and interaction with them.

Table 2. Some physical and nuclear properties of the structure alloys considered [9, 10, 11 and 13].

Alloy main elements	Alloy density [g/cm^3]	σ (n, tot) @ 14 MeV [b]	σ (n, 2n) @ 14 MeV [b]
Inconel-Ni28	8.2	4	0.04
V-alloy-V51	6.1	2.5	0.6
Eurofer-Fe56	7.8	2.7	0.4

Studies of element cross-sections and neutron fluxes in the beryllium and STR2 layers show the competitive effects of (n, 2n) and (n, γ) reactions. Table 3 shows the result of the multiplication and absorption tallies set to the STR1 cell. In addition, the nmult Be cell has been equally tallied as well.

Table 3. Results of multiplication and absorption ratio tallies on STR1 and nmult cells. FLiBe at 90% Li-6 enrichment.

	Inconel718	V-15Cr-5Ti	Eurofer97	Be
(n, 2n)	3.48E-2	5.41E-2	4.70E-2	8.92E-2
(n, γ)	5.38E-2	1.32E-2	2.73E-2	9.64E-3
2n/ γ ratio	0.65	4.10	1.72	9.25

From table 3 it is clear that, as far as the spectrum peaks in the range 10-14 MeV, vanadium and Eurofer have a positive multiplication-absorption ratio, enhancing the TBR values. Contrarily, Inconel718 could be considered an absorber at any fusion spectrum. Beryllium, on the other hand, confirms its effectiveness as neutron multiplier.

For Inconel 718 increasing the width means that both beryllium and STR2 Inconel 718 are reached by less neutrons, therefore while beryllium multiplies less neutrons, Inconel 718 absorbs even lesser neutrons. The result is a TBR increment. This does not apply for Eurofer97 and, especially, the vanadium alloy: increasing the width just less neutrons get multiplied by both beryllium layer and the STR2 layer, systematically decreasing the TBR. That observation can be also confirmed by figure 3, where spectra are plotted for the two different structural layers and two widths of the FLiBe1 channel (i.e. 2 and 5 cm).

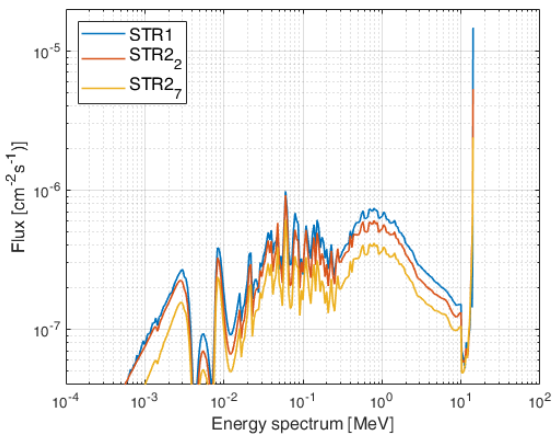

Fig. 3. Examples of neutron spectra in STR1, STR2 with 2cm of channel width ($STR2_2$) and STR2 with 7 cm of channel width ($STR2_7$). Spectra are normalized over 1 neutron source.

As the channel width increases, flux on STR2 decreases and gets a more effective moderation. Indeed, In Fig. 3 $STR2_7$ shows a lower peak in 14.1 MeV with respect $STR2_2$. In addition, this causes vanadium to multiply less neutrons, both for the lower flux and the moderated spectrum, as vanadium (n, 2n) cross section is observable just over 8 MeV [13].

Even though the highest TBR are experienced at 2 cm, 2 cm and 7 cm of FLiBe1 width for vanadium, Eurofer97 and Inconel 718, respectively, it has been chosen to apply to the three of them a channel width of 5 cm. The choice was made in order to decrease the neutron flux (roughly by 20-30% on average) on STR2 and therefore the damage. Furthermore, 5 cm leaves few centimeters for vessel's vertical demountability, taking into account room for thermal deformation and swelling.

Starting from these assumptions, the third parametrization has been made on the neutron multiplier layer's thikness: no Nmult layer at all, 0.5 cm and 1 cm are the parameter's values. It has been decided not to go any thicker than 1 cm because of beryllium cost [14] and thus, the unlikely addition of this material from the first design [1]. TBR results of this study are listed in table 4.

Table 4. TBR values for different beryllium thicknesses and structural materials.

Structural material	w/o multiplier	Be 0.5 cm	Be 1 cm
Inconel718	1.01	1.04	1.07
V-15Cr-5Ti	1.16	1.19	1.22
Eurofer97	1.11	1.14	1.17

Beryllium's multiplication capability sensitively increases TBR. Hence, V-alloy as structure and beryllium as multiplier are both effective elements for raise the TBR. Moreover, a thin channel would help increasing TBR as well. Therefore, in order to increase as much as possible TBR, a good investigation should start from 2 cm FLiBe1 width, vanadium as structural material and 1 cm or more of beryllium, and probably iterate over other tritium breeding-effective parameters (e.g. Li-6 enrichment). However, because of beryllium's high price [14], neutron induced activation and toxicity [15], it is more plausible that future research would look for removing the layer.

Vanadium as structural material still shows the best behavior, in TBR viewpoint. Assuming that reactor's economics and safety studies suggest beryllium removal where possible, the last analysis picks different material structure, 5 cm of channel width and no beryllium; and it studies the Li-6 enrichment effect.

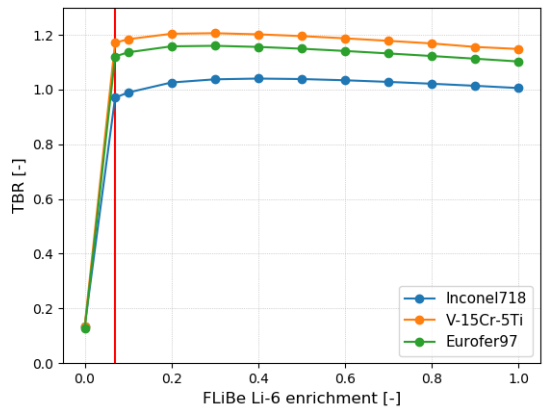

Fig. 4. TBR as a function of Li-6 enrichment degree in the blanket and Inconel 718 (blue), V-15Cr-5Ti (orange) and Eurofer97 (green) structures. Vertical red line identifies Li-6 natural abundancy [16].

Fig. 4 shows that is not necessary to achieve a Li-6 enrichment of 90%, as previously assumed. Actually, results show that a range of 20-50% of Li-6 enrichment would be the best choice for all the three types of structural material. This is due to a Li-6 and Li-7 simultaneous effect. Namely, Li-6 has a way higher (n, T) cross section but Li-7 releases a n' neutron in its (n, T) reaction, ultimately generating a triton without reducing the neutron population. This lead to the

necessity of identifying the best ratio between the two lithium isotopes.

5. Discussion

Concerning ARC's vacuum vessel configuration, channel's thickness, structural material, beryllium thickness and FLiBe's Li-6 enrichment have been found to be suitable parameters for the study. They sensitively affect the tritium production while not playing any critic role on other main design issues, such as plasma shape, magnetic configuration and divertor exhaust geometry. Inconel718 as structural material turned out to be a questionable choice from TBR's viewpoint. The nickel-based alloy shields and absorbs too many neutrons, leading to the necessity of a multiplier like beryllium, which is potentially harmful and extremely costly. Differently, lighter materials, such as Eurofer97 and V-15Cr-5Ti, do not need a neutron multiplier. In particular, the vanadium alloy revealed to be the best one, as it is lighter than others, it is known for being a low-activation alloy, and shows the best TBR behavior as well. Hence, the best structural choice from nuclear viewpoint is V-15Cr-5Ti, or other vanadium based alloys. Results suggest that the highest TBR configuration is a V-alloy structure, with a neutron multiplier layer, a low-width FLiBe1 channel and a blanket's 30% Li-6 enrichment. Such configuration could achieve a TBR considerably higher than 1.2. However, such configuration is not supposed to be the first choice for ARC. Awareness of beryllium-related issues drives the purpose of reducing its inventory, being such element present in the liquid salt as well. In this respect, the solid layer of beryllium will most likely avoided in the case of vanadium structure. Therefore, the suggested configuration has vanadium as structure, no neutron multiplier, a 30% Li-6 enriched blanket and a channel width of 5 cm in order to better shield STR2, which is the main structure. This vessel arrangement leads to a TBR equal to 1.2.

5. Conclusions

The main goal of the work was to optimize ARC's vacuum vessel and blanket in view of the highest tritium breeding ratio achievable. The study aimed to identify the elements that had some room for parametrization and build and run a versatile and fast-running neutronic model for TBR evaluations.

Results shown that the type of structural material and the blanket's Li-6 enrichment heavily affect TBR outcomes. The analysis revealed that a vanadium alloy would be a good choice and will probably be applied for the structure, as it also has good nuclear properties other than TBR enhancement. The application of vanadium revealed that it could not be necessary a high Li-6 enrichment degree in FLiBe nor a beryllium layer, which has been considered the most promising result and surely worth further investigations. Additional analysis on FLiBe channel's width revealed that it affects TBR too but it is likely that the actual wall distance's choice will be based on outer wall shielding and vessel ease of extraction from the tank.

Hence, it is possible to conclude that an upgrade on ARC's vacuum vessel is recommended and will probably be implemented. The main chamber will maintain a 1 mm tungsten first wall, there will be a swich on vanadium alloys for the structural materials, the beryllium layer will be removed and the distance between the two walls will be increased to 4-6 cm.

In future works the suggested configuration will be tested in a model that implements the full ARC's core geometry in order to confirm the TBR results and to analyse the effect on the neutron flux reaching the machine magnets, which is the last main aspect being affected by a change in core configuration.

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