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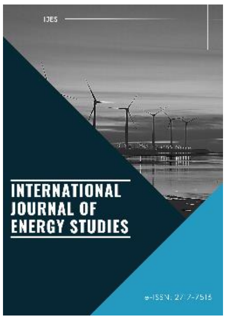

Research Article

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Effect of the various tritium breeding materials on the tritium breeding ratio in ARC fusion reactor

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Highlights

- D-shaped ARC fusion reactor modelling and simulations have been performed to determine the effect of tritium breeding ratio (TBR) of the different molten salts.
- The TBR performance of molten salts has been evaluated according to the effect of the Li-6 enrichment ratio.
- The TBR performances of the molten salts have been re-evaluated by removing the neutron multiplication zone.
- The FLiBe and FLiNaBe molten salts showed that the better TBR performance according to other candidate tritium breeding materials.
- The V4Cr4Ti first wall material more contributed than SiC composite to produce more tritium.

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ABSTRACT

This study deals with TBR (Tritium Breeding Ratio) performance of the four different types of molten salt (FLiBe, FLiNaK, FLiNaBe, FLiNaRb) which has four different Li-6 enrichment ratios (0%, 30%, 60%, 90%) Moreover, two different vacuum vessel materials (SiC composite and V4Cr4Ti alloy) have been used in ARC reactor geometry. In models with TBR ≥1.05, it has been desired to examine the sustainability of the tritium production of the reactor by removing the neutron multiplication layer from the design without using the toxic Beryllium element. The neutronic performance studies have been examined in OpenMC, which is an open-source Monte Carlo neutron and photon transport code. The TBR values of the different models obtained and the change of these values according to Li-6 enrichment were examined. Obtaining result showed that the FLiBe molten salt and V4Cr4Ti alloy vacuum vessel wall material could be the best choice for the ARC reactor.

Keywords: Fusion reactor, ARC reactor, Tritium breeding ratio, Molten salts

1. INTRODUCTION

To meet the energy needs of human beings, studies on fusion reactors have started since the second half of the 20th century. There are ongoing studies on obtaining net fusion power from magnetic compression fusion reactors and establishing a commercially viable reactor model for tokamak reactors, whose research studies are currently ongoing. In the D-T reaction, making the tritium production sustainable is vital for the reactor to be able to serve. This depends on the amount of lithium isotopes present in the reactor layer. In addition to all these, there are various alternatives for a reliable fusion reactor model that is compact, cost-effective, and technically trouble-free. One of them, the ARC reactor, is a conceptual tokamak modeled to study the behavior of materials and reactor structural elements under the influence of radiation.

Reactions in which two lighter and fewer stable nuclei are fused under certain conditions to produce at least one heavier and more stable nucleus with a mass number of less than 56 are called "fusion reactions". In a plasma environment where ideal ignition temperature and Lawson criteria are met with poloidal and toroidal magnetic fields. Reactors in which controlled energy output is obtained by controlling the particles resulting from the D-T reaction are called magnetic confined (compression) fusion reactors [1]. Among these types of fusion reactors, there are tokamak reactors, which are the most well-known and are still being researched today. The Tokamak Fusion Test Reactor (TFTR) was built in the USA in 1982, the Joint European Tokamak (JET) facility in 1983, the Japanese Torus (JT-60) facility in 1985, and the Tore Supra facility in France in 1988. By using D-T fuel in JET reactors in 1991 and TFTR in 1993, megawatt fusion output power was obtained [2]. To implement a fusion reactor design, several technical and financial difficulties must be overcome. The fusion power produced in the plasma should be higher than the energy consumed, the lithium production should be sustainable, the neutronic performance of the reactor building materials should be at a sufficient level, and the construction time and costs should be optimum [3]. For this reason, the production of ARC reactor was started in 2021 with the cooperation of MIT Plasma Science and Fusion Center and Commonwealth Fusion Systems (CFS).

Sorbom et al. have been designed plasma structure, structure of its components (magnet system, neutron moderation layers, tritium breeding layers, shielding layer), dimensions and other parameters of the ARC reactor, which is considered as a pilot fusion reactor design [4]. Segantin et al. have been studied with pure Li, PbLi, FLiBe, FLiNaBe, FLiNaK, LiF-LiBr-NaBr, LiF-LiBr-

NaF, LiF-LiI and LiF-NaF-ZrF_4 blankets in a compact and commercial tokamak ARC fusion reactor. Neutronic analysis has been performed using the OpenMC nuclear code. Except for the heavy and radioactive uranium-containing Be content, FLiBe outperformed other blanket models due to its TBR value close to 1.2, its good neutron moderation, radiation shielding and activation properties [5]. Segantin et al. have been simulated a D-shaped 2D model of the ARC tokamak fusion reactor by Monte Carlo technique supported by OpenMC open-source code. In their study, radiation accumulations for different armor materials were investigated in order to ensure the continuity of operation of the ARC reactor, between the TBR values between 1.055 and 1.065, in order to minimize the exposure of the magnet and other external structure to the radiation effect [6]. Bocci et al. have been investigated neutronic performances of different materials in the mantle layers of the ARC reactor and the radiation effect resulting from exposure to neutron fluxes have been numerically investigated using MNCP and FISPACT-2 codes. It has been demonstrated that the best alternative to Inconel-718 alloy steel in vacuum vessel as one of the reactor mantle layers is Vanadium alloy steel (V-15Cr-5Ti) in terms of adequate neutron moderation and low dose deposition values, and FLiBe as blanket layer is a good choice [7].

Kuang et al. have been performed numerical simulations of the operating performance and neutronic analysis of the large ARC fusion reactor composed of toroidal field components, magnetic field coils, molten salt mantle layers, and vacuum fields. In the analysis made using the MNCP code, the tritium production amount (TBR) was found 1.08 and the output power of 525MW was obtained in the reactor, and it was demonstrated that the continuity of the plasma was ensured. In addition, with the FLiBe coolant channel design with tungsten swirl tube, heat is removed from the deflector with a heat load of up to 12 MW/m^2 [8]. Fausser et al. have been numerically investigated D-T neutron source formulas in high or advanced confinement (H & A) mode in a European demonstration fusion power plant (DEMO) context. They investigated arbitrary two-dimensional (radial and poloidal) neutron generation source maps for tokamaks using the Monte Carlo neutron particle code. It has been demonstrated that the vital neutronic parameters such as TBR and neutron amplification factor, which are considered in the DEMO reactor in the (H & A) mode, show improvement over those in the fusion reactor in the low (L) confinement mode [9]. Şahin et al. have been numerically performed the neutronic analysis of the material and thickness value selection in the first wall in an International Thermonuclear Experimental Reactor (ITER). Stainless steel (SS 316 LN-IG), oxide-enhanced steel alloy (PM2000 ODS), and low-activation Chinese martensitic steel (CLAM) as the initial wall material;

Fluoride-containing molten salt solutions and lithium oxide was used as a coolant and tritium production layer material. The considered fusion reactor was simulated in the MNCP5 code, and it was stated that the best TBR value was obtained in FLiPb coolant, and the initial wall replacement period varied between 6-11 years for all material selections selected depending on the thickness [10]. Sahin has been examined the neutronic performance of a hybrid reactor using different materials in the blanket layers using the MNCP5 nuclear code. Accordingly, the ratio of tritium production to consumption was determined as the net tritium breeding ratio (TBR), and it was stated that TBR should be greater than 1.05 to ensure self-sufficiency [11]. Segantin et al. have been numerically investigated neutron interactions of the materials used in the reactor vessels of the ARC reactor. It is stated that the first wall of the reactor is modelled from 1mm tungsten, the inner layer of the vacuum vessel is made of 1cm Inconel-718 material, the cooling channels are modelled from 2cm of FLiBe molten salt, the neutron propagation layer is modelled from 1cm of beryllium material, and the outer layer of the vacuum cup is modelled from 3cm of Inconel-718 material. FISPACT-2 programs were used to determine radiation damage and material isotropy, and OpenMC programs were used for flux and energy spectrum calculations [12]. Fenici et al. have been given information about the mechanical properties of SiC-based ceramic matrix composites such as low physical density, ability to work at high temperatures, as well as low neutron activation and resistance to radiation interaction [13]. Sahin has been compared the different structural materials in fusion reactors. Steels showed good performance as a building material up to 5 MW/m2 neutron wall load in the range of 500 – 600°C and the production technology is advanced, but the production technology of composite materials such as SiC has not yet reached a sufficient level; Although refractory materials containing vanadium-chromium alloys and tungsten are resistant to higher neutron wall loads and higher temperatures, production costs are high [14].

This study deals with the effect on the TBR value of the different first wall materials (SiC composite and V4Cr4Ti vanadium alloy) and different coolant channel-tritium production layer materials (FLiBe, FLiNaBe, FLiNaK, FLiNaRb) and different Li-6 enrichment rates (7.59 % (natural lithium), 30 %, 60 %, 90 %). In addition, tritium production values were analyzed again by removing the neutron multiplication layer (NML) and expanding the cooling channels for 12 models that met the TBR ≥1.05 condition.

2. MATERIALS AND METHOD

The ARC reactor is a conceptual tokamak design with the aim of exemplifying a fusion power plant and nuclear fusion science applications using the D-T reaction to study the behavior of materials and reactor structural elements under radiation [15]. In the ARC reactor, there are detachable layers around the plasma where the reaction occurs and a high temperature superconducting (HTS) magnet structure. Figure-1 shows the internal structure of the ARC reactor. It is planned to be a tokamak reactor with a main radius of 3.3 m and a small radius of 1.1 m, with a fusion output power of 9.2 T and 525 MWe [4].

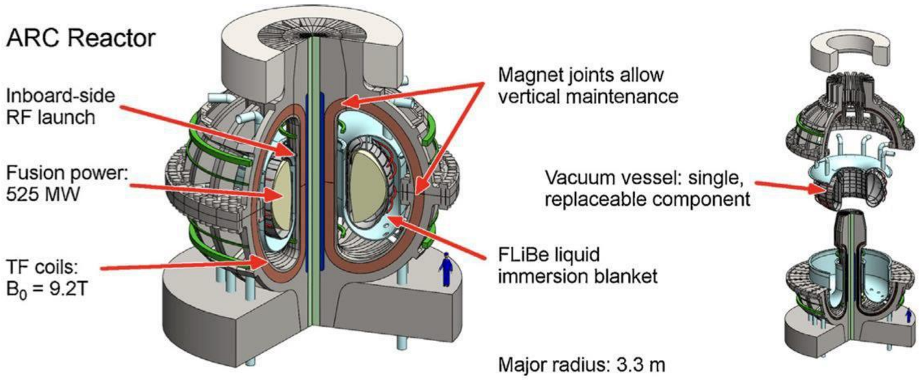

Figure 1. Inner structure of ARC reactor and vacuum vessel [4]

There is a first wall, double-walled vacuum vessel, tritium production layer and shield between the plasma and the magnet structure, where neutron and helium particles emerge with an energy of 17.6MeV because of the D-T reaction. Inside the double-walled vacuum vessel, there are cooling channels and a neutron multiplying layer. The vacuum vessel is located inside the tritium breeding layer where the liquid molten salt solutions are located. The vacuum vessel in the molten salt solution is shown in Figure-2 [5]. The ratio of the amount of tritium breeding in the reactor layers to the amount of tritium consumed in the plasma is expressed as the tritium production ratio (TBR). The TBR must be ≥1.05 to ensure the continuity of the fusion reactor self-production of lithium. Tritium production is obtained because of the neutron absorption of lithium isotopes in the liquid molten salt solution used in the cooler channel and tritium production layer, as specified in equation (1) and equation (2).

$$ {}^{7}_{3}Li + n\,(fast) \rightarrow {}^{3}_{1}H + {}^{4}_{2}He + \mathrm{n(thermal)} - 2.5\ \mathrm{MeV} \tag{1}$$

$$ {}^{6}_{3}Li + n\,(thermal) \rightarrow {}^{3}_{1}H + {}^{4}_{2}He + 4.8\ \mathrm{MeV} \tag{2}$$

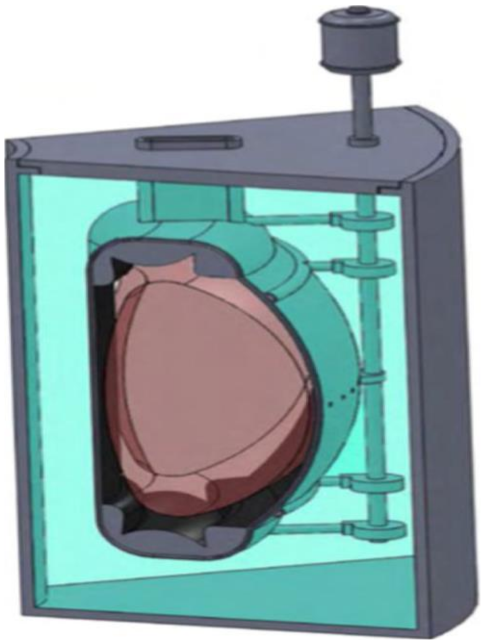

Figure 2. Structure of molten salt surrounding the vacuum vessel [5]

Lithium element found in nature consists of 7.5 % Li-6 and 92.5 % Li-7 isotopes. Since n(fast) resulting from the D-T reaction occurring in the plasma has a high energy level, it is primarily absorbed by the Li-7 specified in equation (1), and an energy of 2.5 MeV is needed for this reaction. This reaction is an endothermic reaction, resulting in 1 neutron particle and tritium. The resulting neutron has been moderated, that is, its energy level has decreased relative to the first neutron particle. As a result of the neutron absorbed by the isotope Li-6, which has less isotope abundance in equation (2), an energy of 4.8 MeV is released, and tritium emerges. The Li-6 isotope can react with neutrons in a wider energy range, while Li-7 can only react in the higher energy range. For this reason, it can be thought that it is easy for the TBR value to be greater than 1.05 due to the formation of neutrons as a result of fast neutron reacting with Li-7, but there are reflector and heater elements in the reactor structure that can cause neutron leakage. On the other hand, Li-6 helps to produce tritium by reacting with neutrons in a wide energy range. Since Li-6 can react in a wide energy range, Li-6 enrichment is desired to ensure tritium production and increase TBR values. Since Li-6 enrichment is a costly process, neutron multiplication layers that provide (n,2n) neutron multiplier reactions are used in the reactor to meet the TBR≥1.05 condition. Since beryllium used in the neutron multiplier layer contains traces of uranium and other heavy nuclides, studies on the use of different materials and the removal of this layer continue [16,17]. OpenMC [20] open source neutronic analysis program, which provides simulation of cross section interactions of neutrons with nuclei with Monte Carlo neutron and photon transport code, was used within the scope of the study. ENDF / B-VII nuclear data files were used for cross-section data of nuclear reactions [21]. The neutron source intensity of the reactor is 9×10^{18} n/s [6]. The neutron source emits 14.1 MeV isotropic neutrons, with height, width and depth set at 100 cm on the central axis of the cylinder. The selected code directory ran 100000 threads in 30 groups. The layers, thicknesses and materials used in the ARC reactor under consideration are shown in Table-1.

Table-1. Materials of ARC reactor [4,5,6]

Materials	**Layer Name**	**Layer Thickness**
Tungsten	First wall (FW)	0.1 cm
SiC composite / V4Cr4Ti alloy	Vacuum Vessel Inner Wall (STR1)	1 cm
FLiBe, FLiNaK, FLiNaBe, FLiNaRb molten salts	Cooling Channel (CHANNEL)	2 cm
Berilium	Neutron Multiplier (NMULT)	1 cm
SiC composite /V4Cr4Ti alloy	Vacuum Vessel Inner Wall (STR2)	3 cm
FLiBe, FLiNaK, FLiNaBe, FLiNaRb molten salts	Tritium Breeding Layer (BLANKET)	50 cm
WB_4	Shield	20 cm

In the simulations, a two-dimensional D-shaped ARC reactor was simulated so that the geometry can be created easily, and the simulation can be performed quickly. This selection does not affect TBR calculations [16]. Atomic weight percentages of V4-Cr4-Ti alloy are given in Table-2 and atomic weight percentages of SiC composite material are given in Table-3 [11,18].

Table-2. V4Cr4Ti composition, % in mass [3]

Material	Vanadium(V)	Chromium (Cr)	Titanium (Ti)	Nickel (Ni)	Iron (Fe)
V4-Cr4-Ti	91.988	4.02	3.98	0.007	0.0049

Table-3. SiC composite composition, % in mass [3]

Material	Silicon (Si)	Carbon (C)	Oxygen (O)
SiC composite	65.75	30.10	4.043

The properties of the molten salt solutions are given in Table-4, and the properties of the materials used in the first wall, neutron multiplication and shield in Table-5 are given.

Table-4. Properties of molten salts [19]

Material	Atomic weight (%)	Physical density [g/cm^3]	Melting point temperature (K)
FLiBe	%50 2LiF, %50 BeF_2	1.94	733
FLiNaK	% 46.5 LiF, %11.5 NaF, %42 KF	2.02	727
FLiNaBe	%31 LiF, %31 NaF, %38 BeF_2	2.03	588
FLiNaRb	%33 LiF, %33NaF, %33 RbF	2.69	708

Table-5. Physical properties of W184, Be and WB_4 materials [6, 8]

Material	Layer Name	Physical density [g/cm^3]	Melting point temperature (K)
W184	First wall (FW)	19.25	3695
Be	Neutron Multiplier	1.848	1551
WB_4	Shield	8.23	-

3. RESULTS AND DISCUSSION

To ensure the sustainability of the operation of the reactor without the need for an external tritium supply, each neutron from the D-T reaction must provide more than one tritium production. For this reason, TBR greater than or equal to 1.05 in the ARC reactor is one of the criteria for the efficiency of the fusion reactor. In the study, a total of 44 models, isotopes in molten salts (Li-6, Li-7, Be-9, F-19, Na-23, K-39, K-41, Rb-87 and Rb-85), layers that will contribute to tritium breeding (cooler channel layer, neutron multiplication layer and tritium breeding layer) and it was evaluated on the basis of the total tritium production rate (TBR) values depending on the Li-6 enrichment ratio. Of the 32 models that were calculated as having a neutron multiplication layer, the Be material was removed for 12 models that met the TBR $\geq$1.05 condition, and the tritium breeding ratio values were analyzed again by expanding the cooling channels.

3.1. SiC Composite First Wall Material

In Figure-3, the change in TBR values depending on the Li-6 enrichment ratio of the models consisting of 4 different types of molten salt (FLiBe, FLiNaBe, FliNaRb, FLiNaK) prepared at 4 different enrichment rates (% 7.59, 30%, 60% and 90%) using SiC composite material is seen.

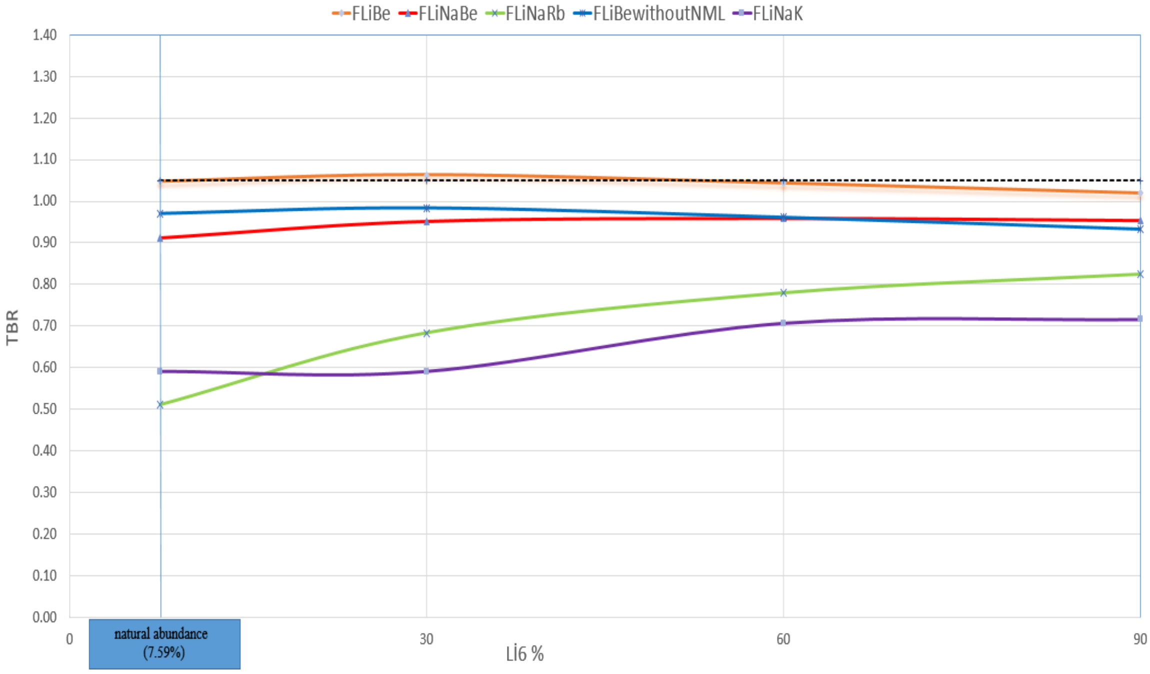

Figure 3. Variation of TBR distributions according to Li-6 enrichment ratios of molten salts prepared using SiC composite material.

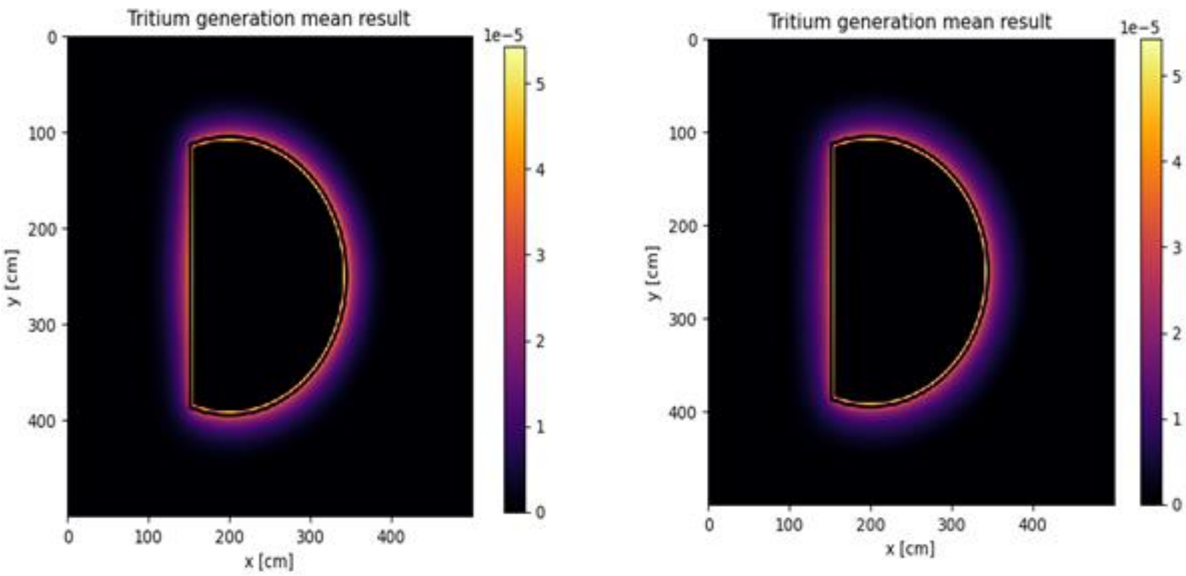

Figure 4. (a) the average tritium production of the models with the highest TBR value among the models using SiC material on the left and (b) the models with the lowest TBR value on the right

In Figure 4, among the models in which SiC material was used, Figure 4-a reveals the highest TBR value (1.063) that was obtained with 30 % Li-6 enriched FLiBe model with 1.063, and Figure 4-b reveals the lowest TBR value (0.51) that was obtained in the FLiNaRb model that contains natural Li.

In Figure 5, TBR contributions of layers responsible for tritium production in the Li6 enrichment of FLiBe molten salts using SiC material at different rates are indicated. Similarly, the TBR performances of the models (FLiBewithoutNML) prepared by removing the neutron multiplication layer (NML) are expressed in Figure 6.

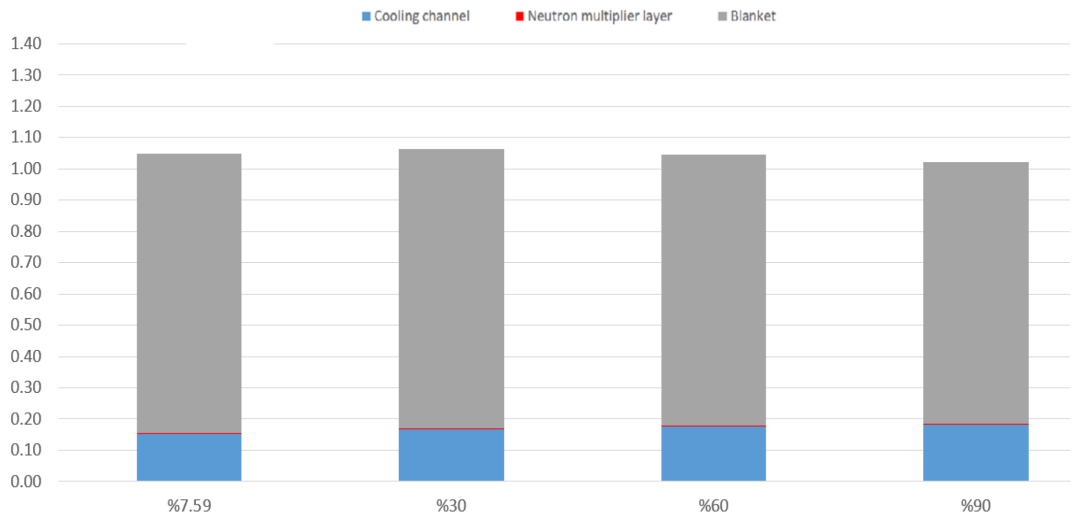

Figure 5. TBR variation depending on the layers responsible for tritium production in different Li-6 enrichment (7.59%, 30%, 60%, 90%) of FLiBe molten salts.

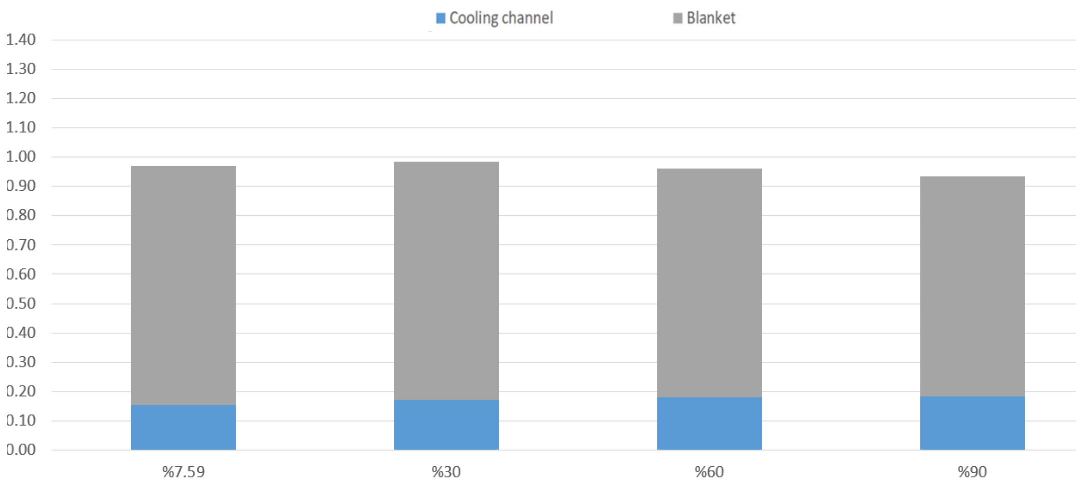

Figure 6. TBR variation depending on the layers responsible for tritium production in different Li-6 enrichment (7.59%,, 30%, 60%, 90%) of FLiBe without neutron multiplication layer.

3.2. V4Cr4Ti Alloy First Wall Material

The TBR value was greater than 1 in the models in which vanadium alloy was used with FLiBe and FLiNaBe molten salts. Also, the TBR value was greater than 1 in the versions of these molten salts that did not use neutron multiplication layer. TBR=1.05 value, which is necessary to ensure sustainability in the tritium production of the ARC reactor, was obtained in the FLiBe and Li-6 enriched FLiNaBe models. In Figure 7, among the options in which the vanadium alloy is used, the highest TBR value is 1.25 (a) in the FLiBe model with 60% Li-6 enrichment on the left, and the lowest TBR value is 0.56 (b) on the right with 7.59% Li-6 enrichment FLiNaRb obtained in the model.

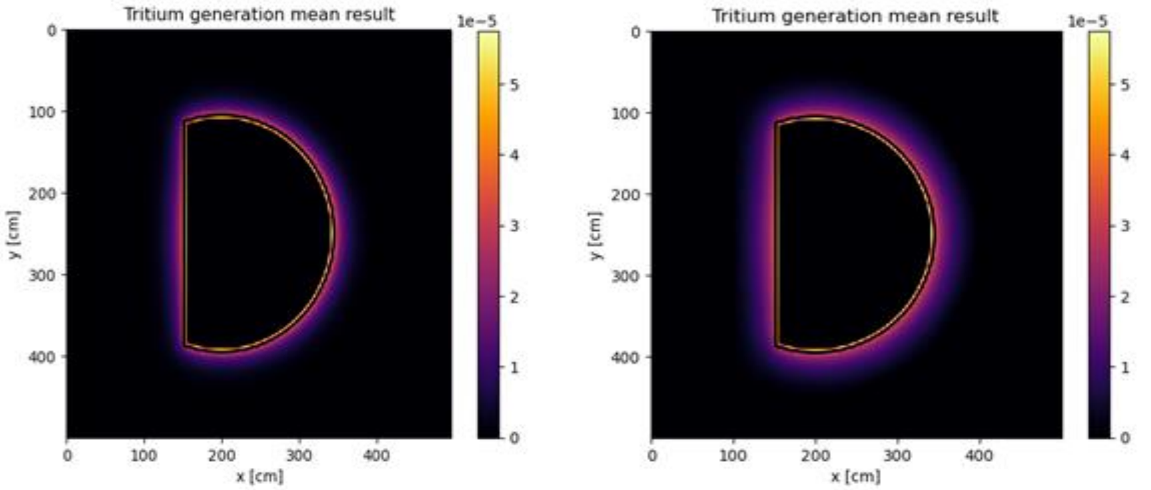

Figure 7. (a) the average tritium production of the models with the highest TBR value on the left and (b) the lowest TBR value among the models using the vanadium alloy on the right

In Figure 8, TBR change of molten salts can be seen at different Li-6 enrichment ratios. It is seen that the amount of change in TBR values of molten salts that provide TBR ≥1.05 value, especially after 30% enrichment rate, gradually decreases and starts to take a constant value.

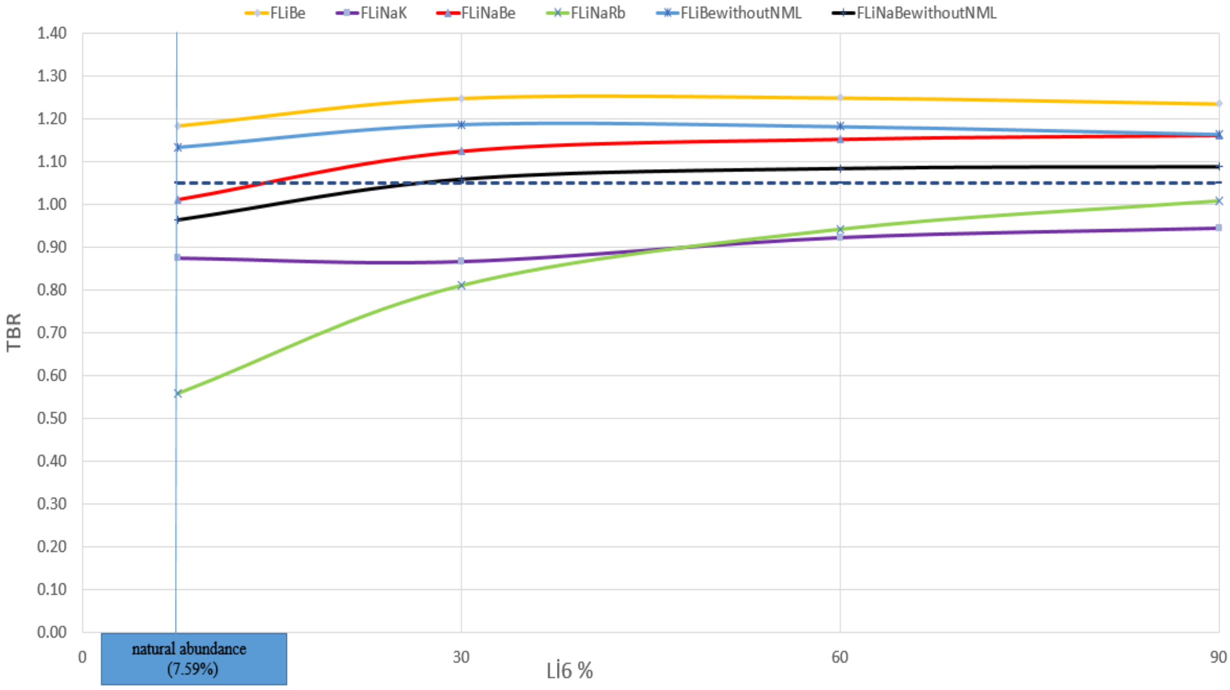

Figure 8. Variation of TBR distributions of molten salts prepared by using vanadium alloy material according to Li-6 enrichment ratios

In Figures 9, 10 and 11, respectively, TBR changes are expressed depending on the layers responsible for tritium production at different Li-6 enrichments (7.59%, 30%, 60%, 90%) of FLiBe, FLiNaBe and FLiBewithoutNML.

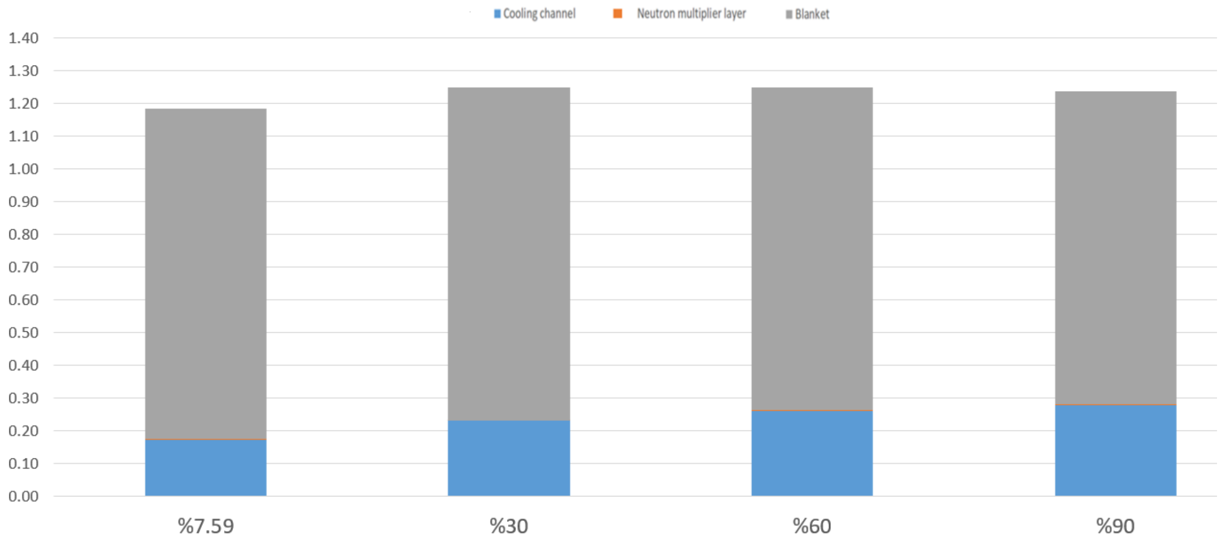

Figure 9. TBR variation depending on the layers responsible for tritium production in different Li-6 enrichment (7.59%, 30%, 60%, 90%) of FLiBe molten salts.

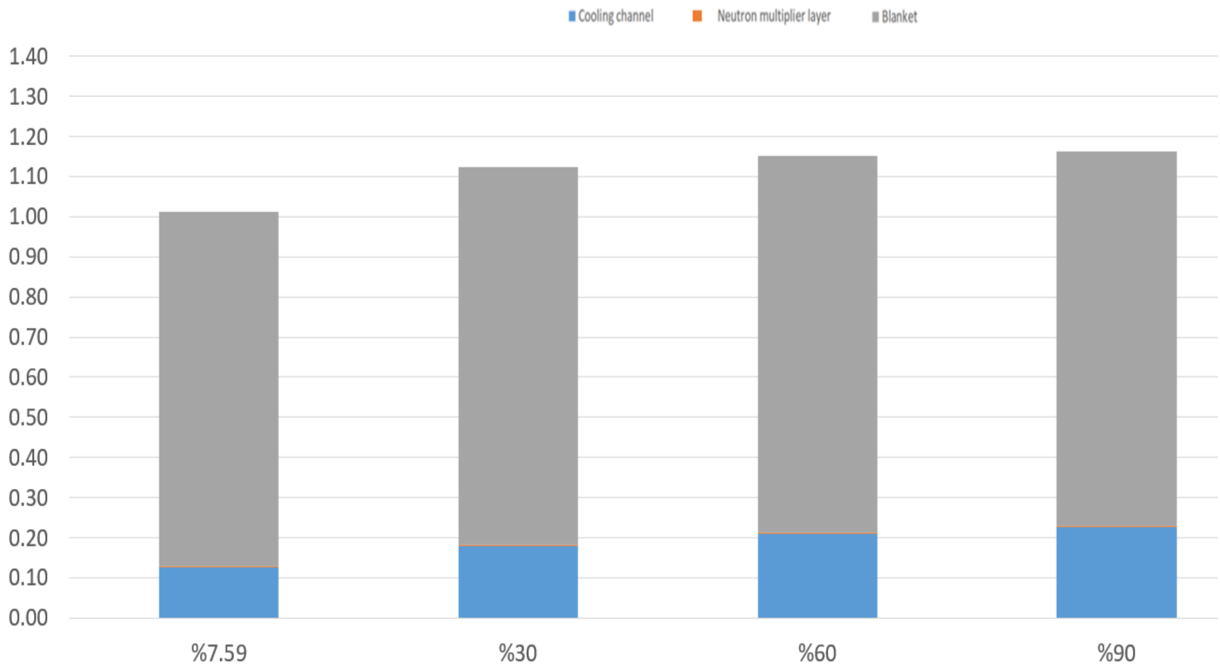

Figure 10. TBR variation depending on the layers responsible for tritium production in different Li-6 enrichment (7.59%, 30%, 60%, 90%) of FLiNaBe molten salts.

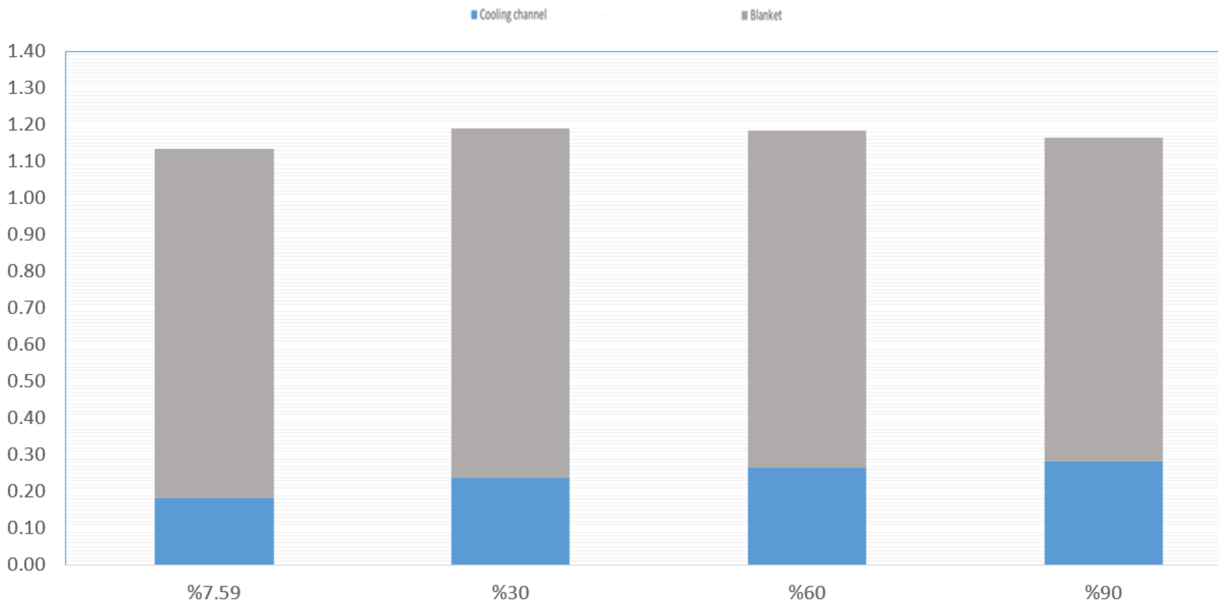

Figure 11. TBR variation depending on the layers responsible for tritium production in different Li-6 enrichment (7.59%, 30%, 60%, 90%) of FLiBe_noBe molten salts.

4. CONCLUSION

This study explained the effect of some molten salts on the tritium breeding ratio in the ARC fusion reactor. The obtaining results could be summarized as below:

It is seen that no model using SiC material on a vacuum vessel wall could provide the TBR=1.05 value, which is critical for ensuring the tritium production that provides the continuity of fusion reaction in the ARC reactor.

As the neutron multiplier layer was removed the tritium breeding ratio decreased in the models created using different vacuum vessel wall materials.

Only FLiBe and FLiNaBe molten salts could provide the sustainability condition (TBR≥1.05) of the D-T reaction when the neutron multiplication layer was removed and the reactor has a V4Cr4Ti vacuum vessel wall.

While TBR≥1.05 could be achieved in the models formed from FLiBe molten salt containing SiC composite material and neutron multiplication layer but it could not be achieved when the neutron multiplication layer was removed.

It was observed that the increase in the Li-6 enrichment ratio did not significantly change the TBR value after 30% Li-6 enrichment in models that provided TBR≥1.05.

TBR≥1.05 value could not be obtained in any of the models using FLiNaRb molten salt.

FLiBe coolant and vanadium alloy vacuum vessel wall material showed the best tritium breeding performance with respect to other used materials.

The results also revealed that FLiNaRb molten salt and SiC composite vacuum vessel wall material may not be a good choice for an ARC fusion reactor.

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Güven TUNÇ: Bringing the idea, planning the method, numerical calculations, evaluation and interpretation of the results, final check of the paper template, and proofreading.

Uğur ATALAY: Conducting the literature review, numerical calculations, evaluation and interpretation of the results, preparation of the manuscript, proofreading.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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