TRITIUM BREEDING CALCULATION IN A STELLARATOR BLANKET

S.V. Chernitskiy, V. E. Moiseenko

National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine

In current blanket projects, tritium breeding ratio (TBR), the ratio of tritium production rate to the neutron production rate, is low (1.1…1.2). The MCNPX Monte-Carlo code has been used to model the neutron kinetics and to look for a principal possibility of increase TBR within a stellarator blanket limited space.

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INTRODUCTION

Thermonuclear reactions are nuclear reactions between light atomic nuclei occurring at very high temperatures (~ 10^8 K and higher). Examples of thermonuclear reactions are:

$$D + D = {}^3He\ (0.82\ MeV) + n\ (2.45\ MeV);\quad Q=3.25\ MeV\ , \tag{1}$$

$$D + D = T\ (1.01\ MeV) + p\ (3.03\ MeV);\quad Q=4.04\ MeV\ , \tag{2}$$

$$D + T = {}^4He\ (3.52\ MeV) + n\ (14.06\ MeV);\quad Q=17.6\ MeV. \tag{3}$$

The cross sections of these reactions (and the probability of interaction of the reacting components) with an incident energy of less than 1 MeV are 0.09, 0.16, and 5 barn, respectively. The reaction of nuclear fusion of tritium and deuterium is the most promising for the implementation in the controlled thermonuclear fusion, since it requires lower energy of the reagents and its cross section even at low energies is large enough.

The disadvantages D-T fuel are as follows:

1) tritium is not found in nature and must be produced of lithium in a blanket of a fusion reactor in the following nuclear reactions: ${}^6Li(n,\alpha)T$+4.8 MeV, ${}^7Li(n,n'\alpha)T$-2.4 MeV [1];

2) tritium is radioactive [2] (half-life is12.3 years), system of D-T reactor contains from 10 to 100 kg of tritium;

3) 80 % of the energy in a D-T reaction is carried by 14 MeV neutrons, which induce artificial radioactivity in reactor components and produce radiation damage.

As a rule, the blanket should not build up the components of nuclear fuel. However, if tritium is one of the components of the fuel, then the blanket should produce it, i.e. besides energy production, to perform the function of a breeder reactor.

A thermonuclear reactor is usually surrounded by a shell (blanket) in which the transformation of the energy of nuclear fusion products into thermal energy is carried on. In addition to the "passive" blanket providing radiation protection, there is also an "active" blanket, in which tritium is produced. The function of the blanket is to take off energy, transform it into heat for further transfer it to the electrical generating systems, as well as protect humans and the environment from ionizing radiation generated by a fusion reactor. Behind the blanket in a thermonuclear reactor there is a layer of radiation protection, the functions of which are to further weaken the neutron flux and γ-radiation which is generated owing to the artificial radioactivity to reduce heat deposition to the cryogenic magnetic coils of the fusion reactor. Then the biological protection comes which can be made of concrete with a thickness of about 2 m. The thickness of the blanket and protection layer in the reactor should be as small as possible especially in case of stellarator-reactor. At the same time, it is necessary to provide the reproduction of tritium and the conversion of the energy of neutrons into heat. In addition, when using superconducting magnetic coils, it is necessary to ensure at an acceptable level of damage to the material of the superconductor, as well as nuclear heat release in the windings.

At the facility W-7X [3], it is planned to produce tritium in a blanket with thickness of 50 cm. The limit value of the tritium breeding ratio (TBR) is planned at the level of 1.2. However, taking into account technical issues (20…30 % of the external surface of the blanket will serve for input windows for different diagnostics) during operation this value may be lower.

Thus, the purpose of this work is to investigate possibilities of producing tritium in sufficient quantities in the blanket of a fusion reactor (especially of a stellarator).

CONCEPT OF STELLARATOR BLANKET

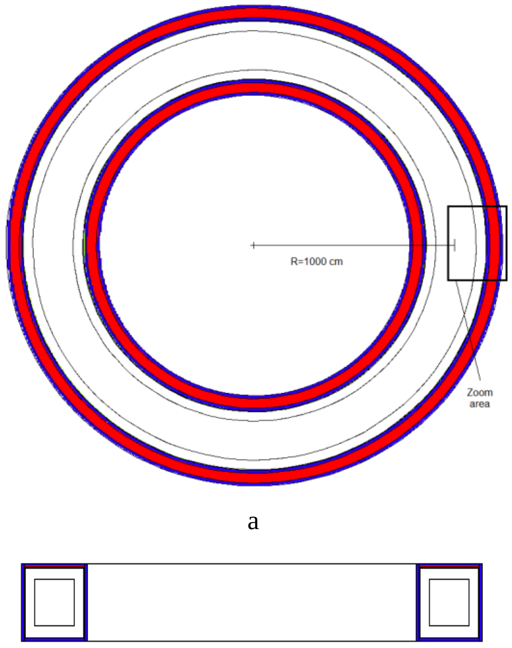
When using a deuterium-tritium fusion reactor, it is necessary to replenish the amount of fuel (D + T) in the reactor and remove ${}^4He$ from the plasma. As a result of reactions in plasma, tritium burns out, and the main part of the fusion energy is transferred to neutrons, for which the plasma is transparent. This leads to the necessity of placing a special zone (blanket) between the plasma and the magnetic system, in which tritium is reproduced and the main part of the neutron energy is absorbed. It reproduces plasma tritium substitutes burned out.

Tritium can be produced by irradiating lithium-6 with neutron fluxes from the same reactor that the fusion reaction is carried out:

$${}^6Li+n\rightarrow(4)He+3T+4.78\ MeV. \tag{4}$$

In this case, not only tritium is formed, but energy is also released. If the fusion chamber is surrounded by a layer of ${}^6Li$ (it constitutes 7% in the natural lithium), it is possible to reproduce the consumable tritium. And although in practice some neutrons are inevitably lost, their loss is easily replenished by introducing into the blanket neutron multipliers such as beryllium or lead, the nuclei of which, when a single fast neutron enters it, emits two.

Depending on the material of the blanket, a fusion reactor with D-T fuel can be "pure" or hybrid. The blanket of a "pure" thermonuclear reactor contains Li, in which, under the action of thermonuclear neutrons, tritium is obtained and the thermonuclear reaction is enhanced from 17.6 to 22.4 MeV. In the blanket of a hybrid ("active") thermonuclear reactor, not only tritium is produced, but also there are zones in which a depleted ^{238}U is placed to produce ^{239}Pu. The energy efficiency of a hybrid thermonuclear reactor is about ten times higher than in a pure thermonuclear reactor due to fission reactions. At the same time, better absorption of thermonuclear neutrons is achieved, which increases the safety of the installation. However, the presence of fissile radioactive substances creates a radiation environment close to that which exists in nuclear fission reactors.



a

b

Fig. 1. Model of the stellarator reactor:
a – toroidal cross-section; b – poloidal cross-section

With the computer code MCNPX [4], calculations were performed on the tritium production for different configurations of the blanket in the stellarator. The general view of the stellarator model is shown in Fig. 1. As can be seen from Fig. 1, the model is of the stellarator of an installation of industrial size.

MODEL 1

Fig. 2 shows the radial structure of the model of a fusion reactor blanket. It can be seen that a plasma D-T source of thermonuclear neutrons is located in a vacuum chamber with a diameter of 3 m. The diameter of the plasma – 2 m. For the first wall a thickness of 3 cm was chosen. The first wall in the model is made of HT-9 steel with a mass density of 7.7 g/cm^3 [5].

The thickness of the blanket was chosen 50 cm. This thickness is chosen for reasons of compactness of the stellarator installation (the total thickness of the blanket, reflector and protection should be at the level of 1 m). Blanket is filled with lithium [6]. Outside of the blanket is a layer of reflector of lead and bismuth eutectics, the thickness of which is selected 15 cm. The LBE was assumed to be a mixture of 44.5 wt.% lead and 55.5 wt.% bismuth with mass density 10.17 g/cm^3 [7].

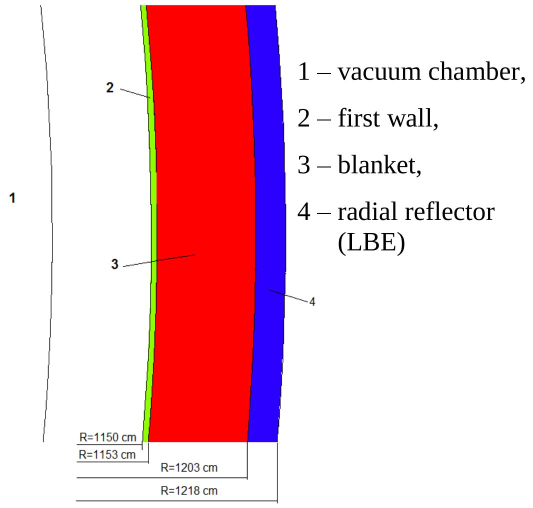


Fig. 2. Radial structure of the model 1

CALCULATION RESULTS FOR MODEL 1

In the first model, the blanket was filled with lithium. Concentration of lithium-6 is varied in calculations. The main result of the calculations is the tritium breeding ratio (TBR) – the ratio of the number of produced tritons to the number of spent (lost) neutrons. The results of calculations for the production of tritium are presented in Fig. 3.

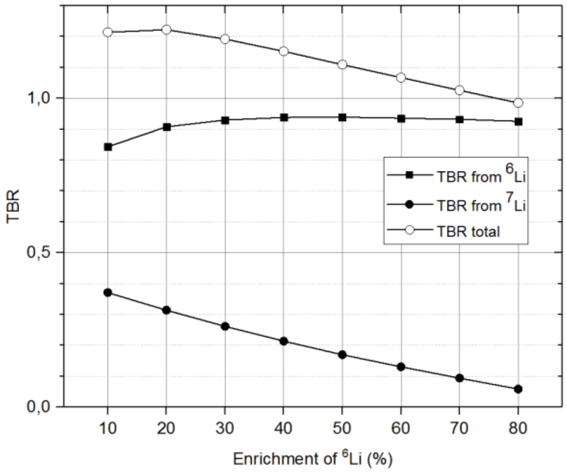


Fig. 3. Tritium breeding ratio as function of lithium enrichment

It can be seen that the main contribution to the production of tritium is made by the lithium-6 reaction. This is explained by the fact that lithium is a light element and the neutron spectrum in the blanket is low-energy. This increases the possibility of a neutron capture reaction with lithium-6 with the formation of tritium. The maximum TBR for this case is 1.22 and is observed if the blanket is filled with lithium with enrichment in lithium-6 to 20 %.

MODEL 2

Fig. 4 shows another arrangement of a fusion reactor blanket.

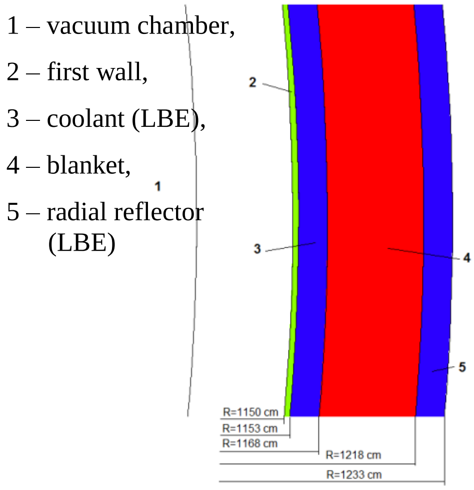


Fig. 4. Radial structure of the model 2.
1 – vacuum chamber; 2 – first wall; 3 – LBE coolant; 4 – lithium; 5 – radial reflector (LBE)

Unlike the first model, here between the first wall and the blanket is a layer of lead and bismuth eutectic (LBE). Lead acts as an amplifier of a stream of fast neutrons due to the threshold reaction of neutron multiplication, such as $^{208}Pb\ (n,\ 2n)\ ^{207}Pb$. The thickness of this zone was chosen 15 cm because the mean-free-path of a fast neutron in LBE is equal to this magnitude.

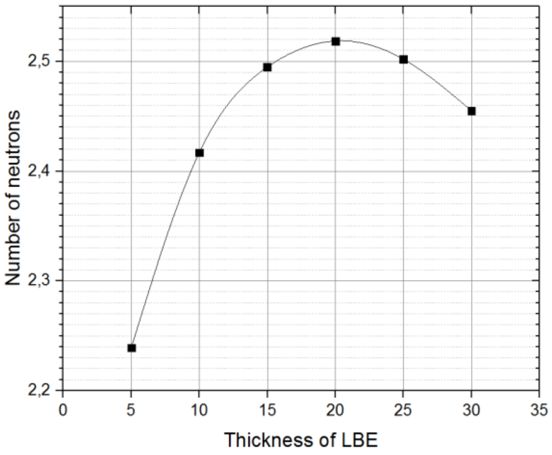


Fig. 5. Number of neutrons from LBE as function of radial width of LBE layer

Moreover, as shown by the calculation results (Fig. 5), the maximum neutron multiplication from 2.5 to 2.7 is obtained when the LBE thickness is in the range of 15…25 cm. However, taking into account that the model should be compact, the thickness of this zone is chosen minimal (15 cm).

CALCULATION RESULTS FOR MODEL 2

In this model, as in the previous case, the blanket was filled with lithium with different concentrations of lithium-6. The results of calculations for the tritium production are presented on Fig. 6. It can be seen that the tritium production is due to the neutron capture reaction on lithium-6, while lithium-7 does not make a noticeable contribution. This is because the neutron spectrum in the blanket becomes even more low-energy then in the model 1. The maximum amount of TBR is 1.34 and is observed if the blanket is filled with lithium with enrichment in lithium – 6…30 %.

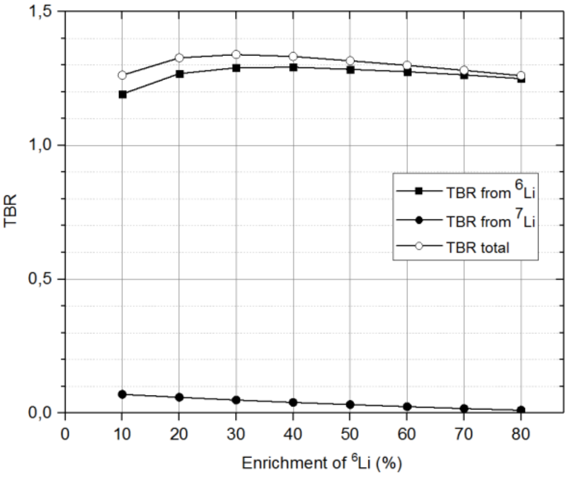


Fig. 6. Tritium breeding ratio as function of lithium enrichment

MODEL 3

Fig. 7 shows another model of a hybrid thermonuclear reactor blanket.

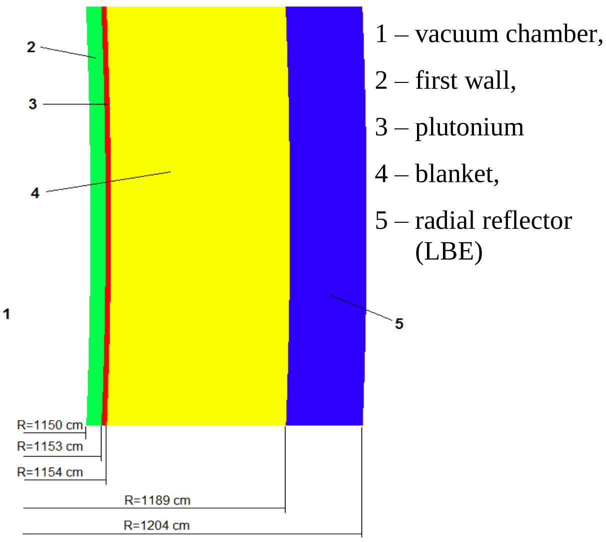


Fig. 7. Radial structure of the model 3

In this calculation model, behind the first wall thin layer (1 cm) of a homogenized mixture of plutonium with iron is put (Pu 239 – 46.8778 %, Pu 240 – 19.1079 %, Pu 241 – 3.483 %, Pu 242 – 4.2093 %, O 16 – 10 % and Fe – 16.322 %). The isotopical content reflects the concentration of plutonium isotopes in spent nuclear fuel of the power plant nuclear reactors. The thickness of the blanket has decreased and becomes 35 cm.

CALCULATION RESULTS FOR MODEL 3

The results of calculations for the production of tritium are presented on Fig. 8. The maximum amount of TBR is 2.9 and is observed when the blanket is filled with lithium with enrichment in lithium – 6…10 %.

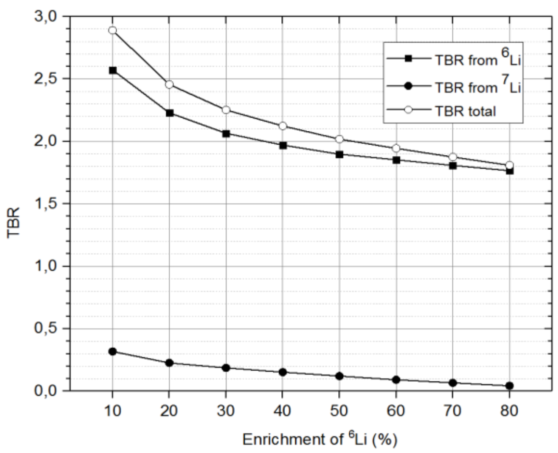


Fig. 8. Tritium breeding ratio as function of lithium enrichment

This increase of tritium production can be explained by the fact that neutron multiplication in the plutonium layer is more intense than in lead. In addition, the number of produced secondary neutrons during fission is 3.1, which is extracted from the calculation results.

CONCLUSIONS

Basing on the calculations it can be concluded that for first model TBR=1.22. In this case, lithium is located directly behind the first wall and serves as a coolant, and for tritium production. For second model TBR=1.34. Here, behind the first wall lead-bismuth eutectic is located whose main function is the multiplication of neutrons. For third model TBR=2.9. In this calculation model, behind the first wall thin layer of a homogenized mixture of plutonium with iron is located. Calculations have shown that the effective neutron multiplication factor will be at the level of 0.7 (deep subcriticality) and the energy released in a thin layer will be 258 MeV per neutron source which is more than one order of magnitude higher than in pure fusion. To reduce this energy by 5 times, it is necessary to reduce the amount of plutonium by 2 times. In this case TBR=1.47. In this instance, we can say that with this arrangement, the power plant can produce tritium in sufficient quantities for its own needs.

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НАРАБОТКА ТРИТИЯ В СТЕЛЛАРАТОРНОМ БЛАНКЕТЕ

С.В. Черницкий, В.Е. Моисеенко

В текущих проектах коэффициент размножения трития – отношение скорости образования трития к скорости производства нейтронов, низок, и составляет величину 1,1…1,2. Монте-карловский код MCNPX использовался для моделирования нейтронной кинетики и демонстрации принципиальной возможности увеличения наработки трития в пределах ограниченного пространства бланкета стелларатора.

НАПРАЦЮВАННЯ ТРИТІЮ В СТЕЛАРАТОРНОМУ БЛАНКЕТІ

С.В. Черніцький, В.Є. Моісеєнко

У поточних проектах коефіцієнт розмноження тритію – відношення швидкості утворення тритію до швидкості виробництва нейтронів, низький, і становить величину 1,1…1,2. Монте-карлівський код MCNPX використовувався для моделювання нейтронної кінетики і демонстрації принципової можливості збільшення напрацювання тритію в межах обмеженого простору бланкету стеларатора.