INVESTIGATIONS OF LITHIUM CARBIDE AS TRITIUM BREEDING MATERIAL FOR BLANKET OF THE FUSION REACTOR

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Comparison of tritium formation values in the course of irradiation by neutrons of fusion reactor of lithium carbide and Li-based ceramics (Li4SiO4 and Li2TiO3) has been done. The influence of neutron thermalization effect by lithium carbide matrix for tritium yield has been estimated. The yield of tritium during neutron lithium carbide irradiation is 1.5-2 times higher than in the case of Li-based ceramics. The estimated tritium breeding ratio for lithium carbide is about 1.5.

INTRODUCTION

The long lasting campaign of a thermonuclear reactor assumes continuous tritium replenishment in the active zone of the reactor. All projects of the fusion reactor imply presence of tritium breeding zone which is component of blanket. Selection of the effective breeding material which should response different requirements is a serious problem. Breeding material should provide both high yield of tritium through the relevant nuclear reactions and easy tritium release for the fuel preparation system. Analysis of the reports submitted for the International Conference on Fusion Reactor Materials [1], shows that the most frequently used breeder materials are different types of lithium ceramic, such as Li4SiO4 and Li2TiO3. Lithium metatitanate (Li2TiO3) attracts attention due to its chemical stability and high rate of tritium release at relatively low temperatures (200 to 400°C). Lithium orthosilicate (Li2SiO3) distinguishes by its low activation, resistance to hydration, and increased yield of tritium due to the relatively high content of lithium.

We have investigated lithium carbide (Li2C2) as tritium breeding material for the fusion reactor blanket. The aim of this work is compare the tritium breeding ratio (TBR) with lithium carbide and lithium ceramics (Li4SiO4 and Li2TiO3). Lithium carbide is 1.5-2.6 times higher in comparison with lithium ceramics (Li4SiO4 and Li2TiO3) ones. It has been estimated that neutron moderation by lithium carbide results in noticeable increasing of tritium yield while irradiation.

PROPERTIES OF LITHIUM CARBIDE

Lithium carbide is colourless, fragile crystal material. Its density at room temperature is 1.65 g/cm³. Lithium carbide can be received at direct interaction of lithium and carbon (2Li+C→Li2C2) in vacuum at 650-700°C or while heating of lithium in the current of acetylene or ethylene [2-4]. Industrial production of lithium carbide in the former USSR has been started since 80th years of last century. For synthesis of lithium carbide one can use components of high purity. Implying the simplicity of the synthesis the product of high purity is potentially achievable.

According to the data received on the studying the system lithium — carbon [3], the compound Li2C2 can exist in several polymorphic modifications with temperature of transition at 410, 440 and 550°C. Interaction of Li2C2 with water causes explosion due to release of hydrogen, the other product of the reaction is elemental carbon [2]. At high temperature lithium carbide intensively dissociates into lithium and graphite. The pressure while dissociation at 925°C is 0.35 kgs/cm² [4].

As concerns the service or disposal of the components of fusion reactor at the end of its life cycle it is important to estimate the induced activity of the breeding materials. The investigations carried out earlier [5] have shown that the total radioactivity of the radionuclides induced while irradiation lithium carbide and lithium ceramics (Li4SiO4 and Li2TiO3) by fusion neutrons (fluence 2·10²³ cm⁻²) of is quite similar. After 3 years of material cooling there is no other radionuclides excepting tritium. The equivalent dose rate of the irradiated hypothetically pure lithium carbide reaches the safe level (23 μSv/h) for one minute after the irradiation end and this simplifies maintenance the installation. The mass of tritium forming in the lithium carbide is 1.5-2.6 times higher in comparison with lithium ceramics (Li4SiO4 and Li2TiO3). The rate of tritium recovery is about 1·10⁻⁶ g/s while irradiation of 100 kg of lithium carbide. This value is in a good agreement with data given in work [6].

RESULTS AND DISCUSSION

TRITIUM BREEDING RATIO (TBR)

For sustainable fuel cycle of the fusion reactor the quantity of tritium atoms formed by single thermonuclear neutron (Tritium Breeding Ratio - TBR) has to be more than 1,05 [6]. The structural model of lithium blanket suggested in the work [6] assumes the minimum quantity of lithium about 100 kg. TBR value for such model of blanket is about 1.28. TBR value for the lithium blanket [9] of 2 m thickness (without neutron reflector) is about 2. Such a difference for TBR values for the same material, possibly, can be explained by both different blanket designs and different neutron spectrum. This may be result of missing in the computations the neutrons absorption and leakage.

Let us consider an infinite medium of lithium carbide for the calculation of the TBR value for Li2C2.
Lithium carbide is assumed to be irradiated by monoenergetic 14 MeV neutrons. We suppose that leakage of neutrons does not present, and isotope composition of lithium and carbon corresponds to their natural abundances (7.42% Li6 and 92.58% Li7, 98.9% C12 and 1.1% C13). It has been previously shown [7] that the main amount of tritium (99.985% of the total concentration of tritium) while irradiation of lithium carbide forms on the nuclei of lithium. The rest amount of tritium (0.015%) is formed on the C13 isotope. Nuclear reactions of formation of tritium in the material are given below.

Each neutron which is absorbed by the reaction \( \text{Li}^7(n,n'+T)\text{He}^4 \) leads to the formation of tritium and another neutron. This neutron in its turn can react with another isotope of lithium and as a result one may get extra nucleus of tritium. However, the reaction \( \text{Li}^7(n,n'+T)\text{He}^4 \) is run in a relatively narrow neutrons energy range: from 3.2 to 20 MeV (Fig. 1, line 2). But for neutrons with energy about 14 MeV, this reaction has a cross-section maximum which is 10 times higher than cross-section of the reaction \( \text{Li}^6(n,T)\text{He}^4 \). The TBR value for isotope of \( \text{Li}^7 \) is 1.13. For comparison, TBR value for lithium orthosilicate (Li4SiO4), depending on values of breeder enrichment by lithium-6, varies from 1.069 [10] to 1.147 [11] and for lithium metatitanate (Li2TiO3) it is equaled to 1.185 [11]. Thus, the calculated TBR value for lithium carbide exceeds 1.45 times the required minimum value (1.05) for the fuel cycle of reactor. The TBR value for Li2C2 is higher than for proposed recently lithium ceramics. Experimental data to determine \( k \) value for lithium carbide is absent so far. The paper [12] presents the TBR values in lithium sphere that is 50 cm thick and covered with a layer of 20 cm thick graphite calculated using various programs (see Table 1) and obtained experimentally [13]. Despite the difference of the calculated and experimental data values (from 9% to 23%), the value of the TBR (1.13) obtained in practice in the combined spherical system Li(50 cm)+C(20 cm) exceeds the threshold equal to 1.05 and is in magnitude comparable with the considered lithium ceramics.

### Table 1

<table>
<thead>
<tr>
<th>Reference</th>
<th>TBR</th>
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<td>Experimental data</td>
<td>1.13</td>
</tr>
<tr>
<td>Calculated data</td>
<td>1.03</td>
</tr>
<tr>
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<tr>
<td>BROND-2.1</td>
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<tr>
<td>FENDL-2.0</td>
<td>1.288</td>
</tr>
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</table>

Total TBR value for lithium carbide equals \( k = k_{\text{Li-6}} + k_{\text{Li-7}} + k_{\text{C-13}} \). Calculated value of TBR for lithium carbide irradiated by neutrons with 14 MeV energy (without consideration neutrons leakage) is 1.52. For comparison, TBR value for lithium orthosilicate (Li4SiO4), depending on values of breeder enrichment by lithium-6, varies from 1.069 [10] to 1.147 [11] and for lithium metatitanate (Li2TiO3) it is equaled to 1.185 [11]. Thus, the calculated TBR value for lithium carbide exceeds 1.45 times the required minimum value (1.05) for the fuel cycle of reactor. The TBR value for Li2C2 is higher than for proposed recently lithium ceramics. Experimental data to determine \( k \) value for lithium carbide is absent so far. The paper [12] presents the TBR values in lithium sphere that is 50 cm thick and covered with a layer of 20 cm thick graphite calculated using various programs (see Table 1) and obtained experimentally [13]. Despite the difference of the calculated and experimental data values (from 9% to 23%), the value of the TBR (1.13) obtained in practice in the combined spherical system Li(50 cm)+C(20 cm) exceeds the threshold equal to 1.05 and is in magnitude comparable with the considered lithium ceramics.

### Fig. 1. Dependence of the nuclear reaction cross section for tritium formation from the neutron energy:

1. \( \text{Li}^7(n,T)\text{He}^4 \)
2. \( \text{Li}^7(n,n'+T)\text{He}^4 \) [9]

\[
k_{\text{Li-6}} = 1 - \exp \left( -\int_0^{\infty} \frac{\xi \Sigma_s(u)}{E_s} du \right)
\]

where \( \Sigma_s \) — macroscopic cross-section of reaction (n,T); \( \xi \Sigma_s \) — moderating efficiency of lithium carbide.

The reaction \( \text{Li}^{13}(n,T)\text{He}^4 \) takes place only for high-energy neutrons (13.5-20 MeV). The TBR value for isotope of \( \text{Li}^{13} \) \((k_{\text{Li-13}})\) may be calculated by the formula (5).

\[
\frac{k_{\text{Li-13}}}{k_{\text{Li-6}}} = 1 - \exp \left( -\int_0^{\infty} \frac{\xi \Sigma_s(u)}{E_s} du \right)
\]
THE ESTIMATION OF INFLUENCE OF EFFECT OF NEUTRON THERMALIZATION BY LITHIUM CARBIDE MATRIX FOR TRITIUM FORMATION

Carbon and lithium are effective neutron moderators, providing thermalization of the neutron spectrum. For example, the authors [12] believe that the TBR value in spherical system Li(50 cm)+C(20 cm) is over two times than the TBR value in the lithium sphere that is 50 cm thick due to the reflected with the graphite layer flux of thermalized neutrons returned to the lithium sphere. The distribution of the moderated neutrons among the energies in the non-absorbing environment (i.e., the environment where the moderated neutrons are not absorbed) can be expressed as the following equation [14]:

$$n(E) = \frac{m_n}{2} \frac{q}{\xi \Sigma_s} \cdot E^\frac{3}{2}, \quad (8)$$

where $m_n$ – the mass of the neutron ($m_n=1$ amu), $q$ - the rate of neutrons generation (or neutron flux density before the moderation), $E$ – neutron energy, $\xi \Sigma_s$ - moderating ability of the environment is calculated using the formula (5). The number of lithium (or carbon) atoms (36.8 wt.% Li and 63.2 wt.% C) in 1 kg of the lithium carbide is defined as the following formula:

$$N = \frac{1000 \cdot 6.02 \cdot 10^{23} \cdot n}{M_{Li_2C_2}} \quad (9)$$

In formula (9) $n$ - number of Li (or C) atoms in Li$_2$C$_2$ molecule, $M_{Li_2C_2}$ - molecular mass of Li$_2$C$_2$.

For the construction of the projected spectrum of moderated neutrons in the lithium carbide we will use the neutron spectrum of the fusion reactor [15] designated as DEMO (Fig. 2, continuous part of the line 1). This spectrum does not contain any data on distribution of thermal neutrons. However, in the field of thermal neutrons (1-10$^{-5}$-1 eV) the cross section of reaction of the tritium from lithium-6 formation differs with the exceptionally high values, making $\sim 10^4-10^2$ barn. In this connection, the function describing DEMO neutron spectrum was extrapolated to 0.1 eV energy neutrons value (Fig. 2, dotted part of the line 1). Then, for a number of points of the obtained neutron spectrum, the moderating ability value of lithium carbide was calculated by the formula (3) and the data received was inserted into the formula (8). As a result, the predicted neutron spectrum was obtained in Li$_2$C$_2$ taking into account the moderation effect (Fig. 2, line 2). This illustration shows an increase in the proportion of moderated neutrons with the energy less than 1 MeV, which should contribute to the increase of the tritium recovery from Li$^6$(n,T)He$^4$ reaction. For the numerical determination of the neutron moderation effect on tritium formation using ACTIVA program [16], the integral cross sections of nuclear reactions taking place in the lithium were calculated for the following energy distributions of neutrons: DEMO spectrum and the spectrum of neutrons in lithium carbide based on their moderation (Fig. 2, line 2). The calculated value of the integral cross section of the reaction (n, T) on lithium-6 for the spectrum of the neutrons moderated by lithium carbide is next larger than the integrated cross section of the same reaction for DEMO spectrum. Given that the mass of the resulting radioactive isotope in the material is directly proportional to the cross section of the reaction of this isotope formation, the tritium formation from Li$^6$(n, T)He$^4$ reaction will be 10 times greater taking into account neutrons moderation in lithium carbide.

CONCLUSION

The use of lithium carbide as tritium breeding material for fusion reactor is perspective:

- calculated tritium breeding ratio from of lithium carbide (1.52) with a "margin" exceeds the required (1.05),
- it is an effective moderator, which 10 times increases the yield of tritium on Li-6 isotope.

![Fig. 2. Spectrum of neutrons: 1 – the neutron spectrum of the fusion reactor (continuous line), 2 – projected spectrum of neutrons in lithium carbide based on their moderation. (Intensities of the spectrum are normalized to 1).](image-url)
REFERENCES


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ИССЛЕДОВАНИЕ КАРБИДА ЛИТИЯ В КАЧЕСТВЕ ТРИТИЙВОСПРОИЗВОДЯЩЕГО МАТЕРИАЛА ДЛЯ БЛАНКЕТА ТЕРМОЯДЕРНОГО РЕАКТОРА

М.В. Аленина, В.П. Колотов, Ю.М. Платов

Проведен расчёт коэффициента воспроизводства трития (КВТ) для карбида лития (Li2C2). Расчётное значение КВТ для Li2C2 приблизительно на 33...42 % больше, чем для ортосиликата лия (Li2SiO4), и на 28 % больше, чем для метатитаната лия (Li2TiO3). Образование трития в карбиде лития по реакции Li+(n,T)He4 увеличивается на один порядок, если в расчётах учесть замедление нейтронов карбиодом лития.

ДОСЛІДЖЕННЯ КАРБІДУ ЛІТИЮ В ЯКОСТІ ТРИТИЙВОСПРОИЗВОДЯЧОГО МАТЕРІАЛУ ДЛЯ БЛАНКЕТА ТЕРМОЯДЕРНОГО РЕАКТОРА

М.В. Аленіна, В.П. Колотов, Ю.М. Платов

Проведено розрахунок коэфіцієнта відтворення тритію (КВТ) для карбіду літію (Li2C2). Розрахункове значення КВТ для Li2C2 приблизно на 33...42 % більше, ніж для ортосиликата літію (Li2SiO4) і на 28 % більше, ніж для метатитаната літію (Li2TiO3). Утворення тритію в карбіді літію за реакцією Li+(n,T)He4 збільшується на один порядок, якщо в розрахунках врахувати уповільнення нейтронів карбідом літію.