

<https://doi.org/10.52676/1729-7885-2026-3-63-70>
UDC 621.039.5:539.12:620.193

NEUTRON ACTIVATION AND GAS PRODUCTION IN TITANIUM AND CHROMIUM BERYLLIDES IN FISSION AND FUSION NEUTRON FIELDS

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Beryllium-based intermetallic compounds are considered promising functional and structural materials for advanced nuclear systems due to their favorable neutronic, thermal and activation characteristics. In this work, neutron-induced activation in titanium and chromium beryllides (Be_{12}Ti and Be_{12}Cr) containing technological impurities was investigated under fission and fusion neutron environments. Experimental gamma-spectrometric measurements and Monte Carlo calculations were performed for specimens irradiated in the WWR-K research reactor. Agreement between calculated and measured specific activities for the dominant activation products Sc-46, Mn-54, Fe-59 and Cr-51 confirms the applicability of the neutronics approach. Neutron-induced gas production (He -4, He -3, T and Li -6) was additionally evaluated for an ITER-relevant D-T spectrum under fixed-fluence conditions. The results demonstrate pronounced spectrum-dependent differences in activation and transmutation behaviour and provide a basis for extrapolating fission-irradiation data to fusion-relevant conditions.

Keywords: beryllides, WWR-K research reactor, gamma spectroscopy, fusion, fission, ITER, DEMO, activation, gas production.

1. INTRODUCTION

Structural and functional materials for fusion blankets and in-vessel components experience a neutron environment that is fundamentally different from that of fission reactors. In D-T fusion devices (ITER/DEMO-class), the neutron field is dominated by ~ 14.1 MeV neutrons from the D-T reaction, whereas fission systems (especially thermal research reactors) exhibit spectra with a prominent thermal component around 0.025 eV (often referenced at 0.0253 eV, $v_0 = 2200$ m/s) and a broad epithermal-to-fast tail extending to a few MeV. These spectral differences directly translate into different balances among displacement damage, transmutation, and gas production, and they limit the validity of direct extrapolation from fission irradiation campaigns to fusion service conditions [1-3].

A large body of fusion materials literature has emphasized that “fluence equivalence” alone is not sufficient to reproduce fusion-relevant damage metrics, because the energy dependence of reaction channels strongly biases the formation of helium, hydrogen/tritium, and other transmutation products (Figure 1). In particular, high-energy neutrons increase the probability of threshold reactions that are weak or absent under predominantly thermal spectra, thereby amplifying gas production and shifting activation pathways. Quantitative comparisons of fusion vs fission irradiation have repeatedly shown that, for the same accumulated fluence, fusion conditions can yield substantially higher gas generation and altered damage partitioning [11].

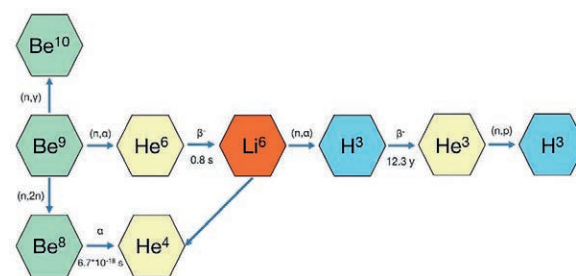


Figure 1. Schematic representation of neutron-induced transmutation reactions in beryllium

At the same time, the lack of high-fluence 14 MeV neutron sources means that fission reactors remain a primary experimental platform for irradiation and post-irradiation examination of candidate fusion materials. Consequently, the field has increasingly converged on “spectrum-aware” qualification strategies: experimental irradiation in available fission facilities combined with validated neutronics/activation/transmutation modelling to translate results into fusion-relevant metrics. This approach is consistent with DEMO-oriented roadmaps that explicitly call for model-anchored qualification frameworks until representative fusion neutron test capability becomes available [4-6].

Within this context, beryllium-based intermetallics (beryllides) have emerged as attractive functional materials for breeding blankets as advanced neutron multipliers, motivated by their thermomechanical stability and irradiation-relevant behaviour. Recent

work on titanium and chromium beryllides has highlighted progress in industrial-scale fabrication and characterization, including microstructural stability and high-temperature mechanical performance relevant for blanket service windows. In parallel, hydrogen isotope interaction (retention/release) remains a central functional constraint for beryllide deployment in fusion systems and has been actively investigated under fusion-relevant boundary conditions [7, 8, 9, 10].

In this study, we combine (i) experimental gamma-spectrometric validation of neutron activation products in Be_{12}Ti and Be_{12}Cr irradiated in the WWR-K research reactor with (ii) Monte Carlo-based activation/transmutation calculations performed for both the WWR-K spectrum and an ITER-relevant D-T fusion spectrum [2], [5]. Importantly, only the impurity-driven activation products measurable by gamma spectrometry (Sc-46, Mn-54, Fe-59, Cr-51) are treated as experimentally validated, while gas production species (He-4, He-3, T, Li-6) are reported strictly as calculation-based comparative indicators to quantify fusion–fission spectral effects under fixed fluence [11]. This approach directly targets the key qualification gap identified in the literature: separating what can be validated today in fission reactors from what must still be inferred for fusion via physics-based modelling [4-6].

2. METHODS

2.1 Materials

The investigated materials were titanium and chromium beryllides (Be_{12}Ti and Be_{12}Cr), considered advanced neutron multiplier candidates for fusion breeding blankets due to their favorable nuclear characteristics and improved thermomechanical stability compared with metallic beryllium. Recent progress in industrial-scale fabrication has demonstrated that dense beryllide blocks can be produced reproducibly by vacuum hot pressing (VHP), including full-size Be_{12}Ti and Be_{12}Cr blocks manufactured at the Ulba Metallurgical Plant (UMP), which supports the technological readiness of these compounds for blanket-relevant component forms.

For the present irradiation campaign, specimens were prepared as plates with the following dimensions: Be_{12}Ti : $8.5 \times 8 \times 1.5$ mm, and Be_{12}Cr : $5 \times 5 \times 1.5$ mm. The densities of Be_{12}Ti and Be_{12}Cr are 2.25 g/cm^3 and 2.401 g/cm^3 , respectively. The beryllide samples contained trace technological impurities (including Sc, Mn, Fe, and Cr), which are critical for neutron activation under fission-spectrum irradiation and therefore dominate the experimentally observable gamma-emitting radionuclide inventory in post-irradiation measurements.

The impurity inventories were accounted for in the activation calculations so that the computed radionuclide inventory reflected the real trace-element content (Table 1) rather than an ideal stoichiometric composition [10].

2.2 Fission Neutron Irradiation (WWR-K Reactor)

Neutron irradiation experiments were carried out at the core of the WWR-K research reactor under steady-state operating conditions. The reactor provides a mixed neutron spectrum dominated by thermal and epithermal neutrons, which is typical of research reactors used for materials testing. The standard neutron energy spectrum of the WWR-K reactor is shown in Figure 2.

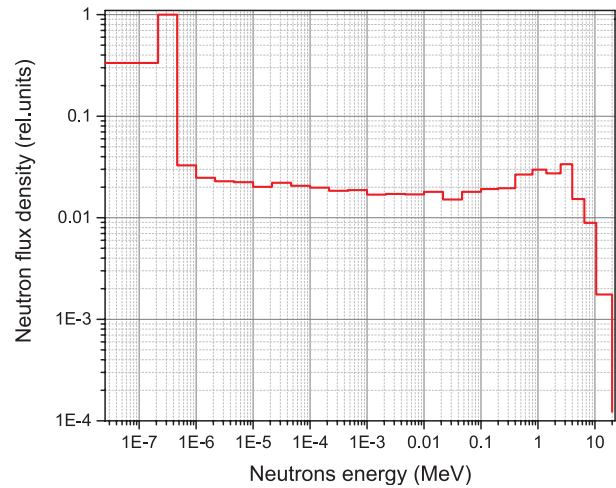


Figure 2. Representative neutron energy spectrum of the WWR-K reactor core

The WWR-K is a 6-MWth, light-water, tank-type research reactor characterized by a predominantly thermal neutron spectrum [12]. It is the Republic of Kazakhstan's only multipurpose research reactor [13]. The facility is equipped with ten neutron beam ports (nine radial and one tangential) to support external experiments and typically offers three central and seven peripheral irradiation positions, with the exact number of peripheral locations adjustable depending on ongoing experimental requirements.

Be_{12}Ti samples were irradiated at low temperature ($< 80^\circ\text{C}$) in an inert atmosphere to two neutron fluence levels over 168 and 252 effective full-power days (EFPD). Detailed irradiation conditions are provided in [14].

Be_{12}Cr specimens were irradiated at high temperature (390°C) in an inert environment to target neutron fluences of 2.8×10^{20} and $4.5 \times 10^{20} \text{ n/cm}^2$, corresponding to 68 effective full-power days (EFPD). Further details are provided in [15].

Table 1 Chemical composition of beryllide blocks in wt%. The uranium content is presented in ppm.

Material	Ti	Cr	C	N	O	Mg	Al	Si	Ca	Fe	U, ppm	Be
Be12Ti	27.8	–	0.034	0.106	0.686	< 0.00005	0.020	0.0162	0.015	0.118	0.395	Bal.
Be12Cr	–	30.8	0.0346	0.0177	0.555	< 0.0002	0.0156	0.0237	0.0088	0.114	0.54	Bal.

These irradiation positions represent typical central and peripheral locations in a light-water research reactor, providing predominantly thermal neutron fields with position-dependent flux magnitude and spectral hardness.

2.3 Computational methodology

Monte Carlo neutron-transport and activation calculations were performed using MCNP6 [16] with the ENDF/B-VII.1 evaluated nuclear data library [17]. The computational framework accounted for material composition, technological impurity content and neutron spectral characteristics. For the fission activation calculations, 500 cycles were used, including 50 inactive and 450 active cycles with 200,000 histories per cycle. For the fusion calculations, 10,000,000 histories were used. The cross-section temperature was 293.6 K for all isotopes included in the calculations.

To enable a physically meaningful comparison between fission and fusion environments, the total neutron fluence was fixed to the same value for both cases. As a result, the irradiation time differs between fission and fusion scenarios, reflecting spectrum-dependent reaction rates. This approach follows established practices in fusion materials research aimed at isolating spectral effects from fluence-driven phenomena.

Fusion neutron calculations were performed using an ITER-relevant D-T spectrum, characterized by a dominant neutron energy near 14 MeV (Figure 3). For the fusion case, a D-T plasma in the main tokamak operating mode was modeled as the neutron source. Following the reference conditions reported in [18], the total neutron source strength was set to 2×10^{19} n/s and used as the normalization parameter for the ITER-like neutron spectrum in the activation/transmutation calculations. This source strength was applied to scale the flux level consistently with the reference scenario, while fusion-fission comparisons in the present work were performed under a fixed target fluence (i.e., irradiation time was adjusted to achieve the prescribed fluence in each spectrum).

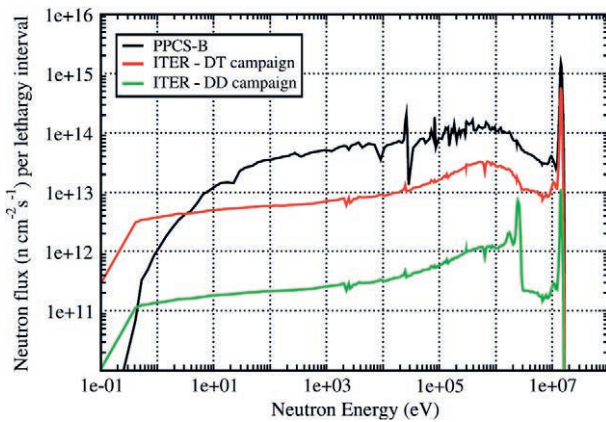


Figure 3. Neutron spectra for the first wall of the model B conceptual power-plant design – PPCS-B[19], as well as the spectra for the two neutron-producing campaigns of ITER.

Although direct experimental validation of fusion gas production was not available, the adopted calculation procedure is consistent with approaches commonly used in DEMO-oriented materials studies.

3. RESULTS AND DISCUSSION

Table 2 summarizes the atomic densities of the main gas-producing isotopes (Li-6, T, He-3, He-4) in the beryllium sublattice of Be_{12}Ti , calculated for two identical integral neutron fluences (1.04×10^{21} and 1.46×10^{21} n/cm²) under WWR-K reactor conditions and an ITER-relevant D-T neutron spectrum.

At a fixed fluence, the most pronounced feature of the fusion spectrum is the substantial increase in He-4 production. At 1.04×10^{21} n/cm², the He-4 concentration increases from 4.26×10^{-6} (WWR-K) to 1.07×10^{-4} (ITER), corresponding to an approximately 25-fold increase. A similar trend is observed at 1.46×10^{21} n/cm², where He-4 increases from 5.95×10^{-6} to 1.50×10^{-4} , again by a factor of ~ 25 . This behavior is directly associated with the increased contribution of threshold and high-energy transmutation reactions in the D-T neutron field.

In contrast, tritium production under ITER conditions is several orders of magnitude lower than in the WWR-K spectrum. At 1.04×10^{21} n/cm², the tritium concentration decreases from 1.13×10^{-7} (WWR-K) to 2.75×10^{-11} (ITER), and at 1.46×10^{21} n/cm² from 2.12×10^{-7} to 5.16×10^{-11} . This trend is consistent with the greater relative contribution of neutron capture and (n,α)-type reactions in thermal spectra, including reactions on impurities and minor isotopes of beryllium and lithium, whereas under a 14 MeV-dominated fusion spectrum gas production is shifted toward helium generation, particularly He-4.

Table 2. Atomic density of main gas-producing isotopes in the Be sublattice of Be_{12}Ti specimens

Integral neutron fluence [n/cm ²]	Neutron-induced isotopes in Be [at/barn-cm]			
	Li-6	T	He-3	He-4
WWR-K reactor				
1.04×10 ²¹	4.86×10 ⁻⁰⁷	1.13×10 ⁻⁰⁷	5.96×10 ⁻¹⁰	4.26×10 ⁻⁰⁶
1.46×10 ²¹	6.41×10 ⁻⁰⁷	2.12×10 ⁻⁰⁷	1.44×10 ⁻⁰⁹	5.95×10 ⁻⁰⁶
ITER				
1.04×10 ²¹	1.29×10 ⁻⁰⁶	2.75×10 ⁻¹¹	2.36×10 ⁻¹⁶	1.07×10 ⁻⁰⁴
1.46×10 ²¹	1.80×10 ⁻⁰⁶	5.16×10 ⁻¹¹	6.49×10 ⁻¹⁶	1.50×10 ⁻⁰⁴

Table 3 presents the calculated atomic densities of Sc-46, Mn-54, and Fe-59 in the titanium matrix of Be_{12}Ti and associated impurities at the same neutron fluence levels as those in Table 1.

A pronounced spectral selectivity is observed. Upon transitioning from the WWR-K spectrum to the ITER-

relevant D–T spectrum, the production of Sc-46 increases by several orders of magnitude (e.g., at 1.04×10^{21} n/cm²: from 5.46×10^{-10} to 1.95×10^{-7}), indicating a strong enhancement of high-energy reaction channels responsible for Sc-46 formation under fusion conditions. A similar, though less pronounced, trend is observed for Mn-54, with an increase of approximately one to two orders of magnitude (from 1.62×10^{-11} to 6.01×10^{-10} at 1.04×10^{21} n/cm²).

In contrast, the production of Fe-59 is significantly reduced under fusion conditions (from 1.83×10^{-11} to 1.06×10^{-13} at the same fluence), which is consistent with the dominance of neutron capture reactions in thermal spectra that favor Fe-59 formation, and the reduced contribution of these channels in a 14 MeV-dominated neutron field.

Table 3. Atomic density of main activation products in Ti and impurities of Be₁₂Ti specimens

Integral neutron fluence [n/cm ²]	Neutron-induced isotopes in titanium and impurities [at/barn-cm]		
	Sc-46	Mn-54	Fe-59
WWR-K reactor			
1.04×10 ²¹	5.46×10 ⁻¹⁰	1.62×10 ⁻¹¹	1.83×10 ⁻¹¹
1.46×10 ²¹	6.01×10 ⁻¹⁰	2.07×10 ⁻¹¹	1.79×10 ⁻¹¹
ITER			
1.04×10 ²¹	1.95×10 ⁻⁰⁷	6.01×10 ⁻¹⁰	1.06×10 ⁻¹³
1.46×10 ²¹	2.74×10 ⁻⁰⁷	8.42×10 ⁻¹⁰	1.47×10 ⁻¹³

Figure 4 illustrates the accumulation kinetics of T, He-3, and He-4 in Be₁₂Ti over a single irradiation cycle. For the WWR-K reactor, a cycle duration of 21 days was adopted, corresponding to a standard operational fuel cycle, whereas for the ITER-relevant case the irradiation time was set to 11 days.

This difference arises from the fact that the comparison is performed at a fixed integral neutron fluence rather than at an equal irradiation time. In the WWR-K reactor, 21 days represent one typical operating cycle and therefore reflect realistic irradiation conditions. In contrast, under the ITER-relevant D–T neutron spectrum, the higher neutron energy (~14 MeV) and flux intensity result in significantly increased reaction rates and radiation damage accumulation, such that the same fluence is achieved over a shorter time (~11 days).

This fluence-normalized approach is widely adopted in fusion materials studies, as it enables a physically meaningful comparison between fission and fusion conditions by isolating spectral effects from irradiation time dependencies [20].

Despite the difference in time scales, the key physical trend remains unchanged: under fusion conditions, He-4 is the dominant product and accumulates significantly faster on a fluence-normalized basis, whereas under fission conditions the relative contribution of tritium becomes more pronounced.

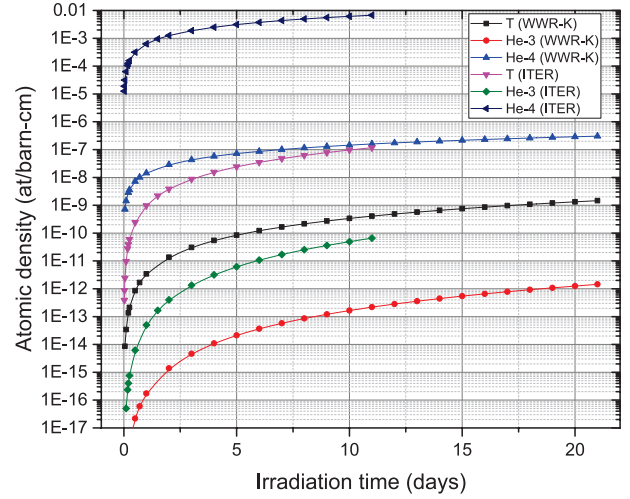


Figure 4. Time-dependent accumulation of T, He-3, and He-4 in Be₁₂Ti during a single irradiation cycle under WWR-K (21 days) and ITER (11 days) conditions

These curves should be interpreted as a time-resolved representation of the same spectral trends: under fusion conditions, products associated with high-energy reaction channels (such as Sc-46 and Mn-54) are formed significantly more rapidly, whereas the contribution of Fe-59 is markedly reduced on a fluence-normalized basis.

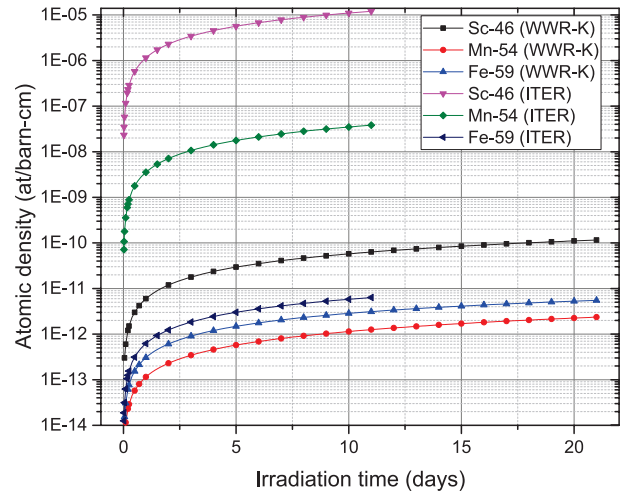


Figure 5. Time-dependent accumulation of Sc-46, Mn-54, and Fe-59 in Be₁₂Ti during a single irradiation cycle under WWR-K (21 days) and ITER (11 days) conditions

Table 4 presents the calculated atomic densities of Li-6, T, He-3, and He-4 in the beryllium sublattice of Be₁₂Cr for two neutron fluence levels (4.53×10^{20} and 2.77×10^{20} n/cm²), with values reported for multiple samples/positions. The small variation between replicated values (e.g., He-4 in WWR-K at 4.53×10^{20} n/cm²: 9.37×10^{-7} and 9.06×10^{-7}) indicates good internal consistency of the calculations under comparable conditions.

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As observed for Be_{12}Ti , a transition to the ITER-relevant spectrum results in a substantial increase in He-4 production. At $4.53 \times 10^{20} \text{ n/cm}^2$, He-4 increases from approximately $\sim 9 \times 10^{-7}$ (WWR-K) to 4.83×10^{-5} (ITER), corresponding to an enhancement of about a factor of 50. In contrast, tritium production decreases by several orders of magnitude (e.g., from 1.30×10^{-8} to 4.62×10^{-12}).

For He-3, the calculated values under fusion conditions decrease markedly, reaching 1.21×10^{-17} and 1.09×10^{-17} at/barn-cm at $2.77 \times 10^{20} \text{ n/cm}^2$ (Table 4); these values fall below the adopted calculation-significance threshold defined in the table footnote and should accordingly be interpreted with caution.

Table 4. Atomic density of main gas-producing isotopes in the Be sublattice of Be_{12}Cr specimens

Integral neutron fluence [n/cm^2]	Neutron-induced isotopes in Be [at/barn-cm]			
	Li-6	T	He-3	He-4
WWR-K reactor				
4.53×1020	1.20×10-07	1.30×10-08	3.30×10-11	9.37×10-07
4.53×1020	1.22×10-07	1.33×10-08	3.37×10-11	9.06×10-07
2.77×1020	7.85×10-08	5.08×10-09	1.42×10-11	5.42×10-07
2.77×1020	7.79×10-08	5.04×10-09	1.41×10-11	5.19×10-07
ITER				
4.53×1020	5.65×10-07	4.62×10-12	3.82×10-17	4.83×10-05
4.53×1020	5.64×10-07	4.57×10-12	3.47×10-17	4.83×10-05
2.77×1020	3.45×10-07	1.75×10-12	1.21×10-17 ¹	2.96×10-05
2.77×1020	3.45×10-07	1.72×10-12	1.09×10-17 ^a	2.96×10-05

Table 5. Atomic density of main activation products in Cr and impurities of Be_{12}Cr specimens

Integral neutron fluence [n/cm^2]	Neutron-induced isotopes in chromium and impurities [at/barn-cm]		
	Cr-51	Mn-54	Fe-59
WWR-K reactor			
4.53×1020	6.63×10-07	4.25×10-12	1.64×10-11
4.53×1020	6.69×10-07	3.95×10-12	1.64×10-11
2.77×1020	4.02×10-07	2.34×10-12	9.86×10-12
2.77×1020	4.01×10-07	2.30×10-12	9.87×10-12
ITER			
4.53×1020	2.04×10-10	2.73×10-10	4.74×10-14
4.53×1020	2.02×10-10	2.73×10-10	4.68×10-14
2.77×1020	1.26×10-10	1.67×10-10	2.87×10-14
2.77×1020	1.29×10-10	1.68×10-10	2.90×10-14

¹ Values below the adopted calculation-significance threshold (relative statistical uncertainty exceeding 50% in the MCNP6 activation run); reported for completeness rather than as a statistically significant result.

Figure 6 presents the accumulation kinetics of gas-producing species in Be_{12}Cr during a single irradiation cycle under WWR-K and ITER-relevant conditions. The interpretation should focus not on the absolute cycle duration but on the fluence-normalized comparison, which shows that the fusion spectrum intrinsically shifts gas generation toward He-4. This effect has direct consequences for swelling, embrittlement, and gas inventory in blanket materials and constitutes one of the primary drivers for the transition from metallic beryllium to beryllide compounds.

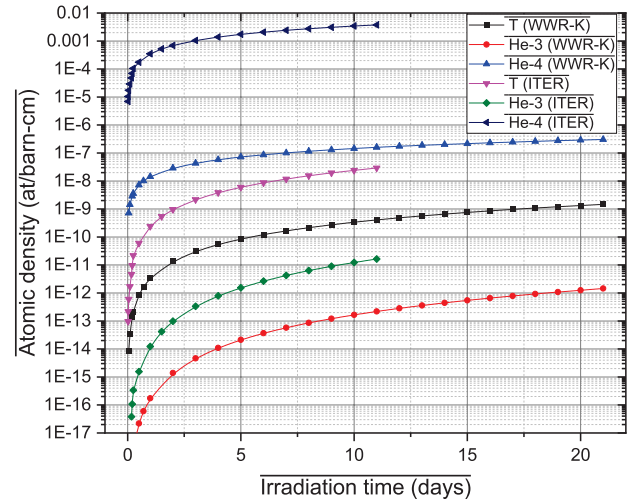


Figure 6. Time-dependent accumulation of T, He-3, and He-4 in Be_{12}Cr during a single irradiation cycle under WWR-K (21 days) and ITER (11 days) conditions

Table 5 presents the calculated atomic densities of Cr-51, Mn-54, and Fe-59 in the chromium-containing matrix of Be_{12}Cr and associated impurities. In contrast to Sc-46 behavior in titanium beryllide, the primary matrix product Cr-51 exhibits the opposite trend: under WWR-K conditions at a fluence of $4.53 \times 10^{20} \text{ n/cm}^2$, Cr-51 reaches $\sim 6.63 \times 10^{-7}$, whereas under ITER conditions it decreases to $\sim 2.04 \times 10^{-10}$, corresponding to a reduction by approximately three orders of magnitude ($\sim 3.3 \times 10^3$).

This behavior indicates the dominance of reaction pathways in the thermal neutron spectrum that efficiently produce Cr-51, primarily via neutron capture, and their significantly reduced relative contribution in a 14 MeV-dominated fusion neutron field.

At the same time, Mn-54 exhibits an increase under fusion conditions (e.g., from 4.25×10^{-12} to 2.73×10^{-10} at $4.53 \times 10^{20} \text{ n/cm}^2$), whereas Fe-59 decreases (from 1.64×10^{-11} to 4.74×10^{-14}).

Thus, considering the combined results for both Be_{12}Ti and Be_{12}Cr , it is evident that the neutron spectrum affects not only the magnitude of activation but also the profile of dominant radionuclides: some products are enhanced under fusion conditions, while others are suppressed.

Figure 7 shows the time-dependent accumulation of the corresponding activation products over one irradiation cycle under WWR-K and ITER conditions. For the discussion, it is sufficient to emphasize that the differences in curve shapes and saturation levels reflect the combined influence of spectral dependence, radioactive decay (half-lives), and effective production and burn-up rates. This is particularly important for the design of reactor-based irradiation experiments as surrogates for fusion conditions, where the selection of indicator nuclides must be spectrum-sensitive.

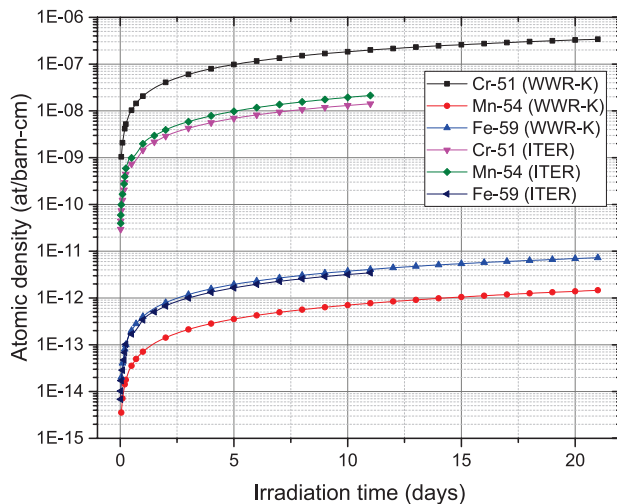


Figure 7. Time-dependent accumulation of Sc-46, Mn-54, and Fe-59 in Be_{12}Cr during a single irradiation cycle under WWR-K (21 days) and ITER (11 days) conditions

4. CONCLUSIONS

A comparative analysis of neutron-induced activation and gas production in titanium and chromium beryllides (Be_{12}Ti and Be_{12}Cr) was performed for the thermal neutron spectrum of the WWR-K research reactor and an ITER-relevant D–T fusion spectrum under identical integral neutron fluence conditions. This approach enabled the separation of spectral effects from those associated solely with irradiation level, thereby providing a physically consistent basis for comparing fission and fusion environments.

The calculations demonstrate that, at a fixed fluence, gas production in the beryllium sublattice is strongly dependent on the neutron spectrum. For both materials, a pronounced increase in He-4 accumulation is observed under the ITER-relevant spectrum: approximately a factor of ~25 for Be_{12}Ti and ~50 for Be_{12}Cr relative to those under WWR-K conditions at comparable fluence levels. In contrast, tritium production under fusion conditions is several orders of magnitude lower than in the thermal spectrum. These results indicate that direct extrapolation of gas production data from fission experiments to fusion conditions, without accounting for spectral differences, may lead to systematic errors, particularly in the assess-

ment of helium-induced swelling/embrittlement and hydrogen isotope inventories.

A strong spectral selectivity is also observed for activation products in both the matrix and impurities, affecting not only their absolute concentrations but also the composition of dominant radionuclides. In Be_{12}Ti , the ITER-relevant spectrum enhances the production of Sc-46 and Mn-54 while suppressing Fe-59, consistent with the energy dependence of the corresponding reaction channels. In Be_{12}Cr , the primary matrix product Cr-51 exhibits the opposite behavior: it dominates under WWR-K conditions but is strongly suppressed in the fusion spectrum, while Mn-54 increases and Fe-59 decreases. The time-dependent results (Figures 4-7) further confirm that the transition from fission to fusion conditions leads to a fundamentally different profile of dominant products and their accumulation kinetics over an irradiation cycle.

These findings highlight the importance of accounting for neutron spectrum effects in the qualification of beryllides for fusion applications. Both gas production behavior and activation product inventories must be interpreted with explicit consideration of neutron energy distribution, as it governs the underlying reaction pathways and, consequently, the key indicators of material degradation and radiological performance. The use of fluence-normalized comparison provides a robust and physically justified framework for such analyses and supports the development of reliable strategies for extrapolating fission-based experimental data to fusion-relevant conditions.

This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR24993119).

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БӨЛІНУ ЖӘНЕ ТЕРМОЯДРОЛЫҚ СИНТЕЗ НЕЙТРОНДЫҚ ӨРІСТЕРІНДЕ ТИТАН ЖӘНЕ ХРОМ БЕРИЛЛИДТЕРІНІҢ НЕЙТРОНДЫҚ АКТИВАЦИЯСЫ МЕН ГАЗ ТҮЗІЛУІ

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Бериллий негізіндегі интерметаллидті қосылыстар жаңа буын ядролық жүйелері үшін перспективалы функционалдық және құрылымдық материалдар ретінде қарастырылады. Бұл жұмыста технологиялық қоспалары бар Be₁₂Ti және Be₁₂Cr бериллидтеріндегі нейтрон әсерінен болатын активация және газ өнімдерінің түзілуі зерттелді. ВВР-К реакторында сәулелендірілген үлгілер бойынша гамма-спектрометриялық өлшеулер Монте-Карло әдісімен орындалған есептеулермен салыстырылды. Sc-46, Mn-54, Fe-59 және Cr-51 негізгі активация өнімдері үшін есептеу мен эксперимент арасында қанағаттанарлық сәйкестік алынды. Сонымен қатар бірдей интегралдық флюенс жағдайында ITER-ге тән D-T нейтрондар спектрі үшін He-4, He-3, T және Li-6 түзілуі есептік түрде бағаланды. Нәтижелер нейтрон спектрі активация және газ түзілу бейінін айтарлықтай өзгертетінін көрсетті. Сондықтан реакторлық сынақ деректерін термоядролық қондырғылар жағдайына көшіру кезінде спектрлік әсерлерді ескеру қажет.

Түйін сөздер: бериллидтер, ВВР-К реакторы, гамма-спектрометрия, бөліну, термоядролық синтез, ITER, DEMO, активация, газ түзілу.

НЕЙТРОННАЯ АКТИВАЦИЯ И ГАЗООБРАЗОВАНИЕ В БЕРИЛЛИДАХ ТИТАНА И ХРОМА
В НЕЙТРОННЫХ ПОЛЯХ РЕАКТОРОВ ДЕЛЕНИЯ И ТЕРМОЯДЕРНОГО СИНТЕЗА

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Интерметаллидные соединения на основе бериллия рассматриваются как перспективные функциональные и конструкционные материалы для ядерных систем нового поколения. В работе исследованы нейтронно-индуцированная активация и образование газовых продуктов в титановых и хромовых бериллидах Be12Ti и Be12Cr с учетом технологических примесей. Экспериментальные гамма-спектрометрические измерения образцов, облученных в реакторе ВВР-К, сопоставлены с расчетами методом Монте-Карло. Для основных продуктов активации Sc-46, Mn-54, Fe-59 и Cr-51 получено удовлетворительное согласие расчета и эксперимента. Дополнительно выполнена расчетная оценка образования He-4, He-3, T и Li-6 в спектре D-T-нейтронов, характерном для ITER, при одинаковом интегральном флюенсе. Показано, что нейтронный спектр существенно изменяет профиль активации и газообразования, что необходимо учитывать при переносе данных реакторных испытаний на условия термоядерных установок.

Ключевые слова: бериллиды, реактор ВВР-К, гамма-спектрометрия, деление, термоядерный синтез, ITER, DEMO, активация, газообразование.