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Multi-temperature neutron irradiation of pure beryllium and beryllides to 2.5–3 dpa in BR2 reactor☆

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A B S T R A C T

This paper reports the current status of neutron irradiation experiments designed to evaluate beryllide ($Be_{12}V$, $Be_{12}Ti$, $Be_{12}Ti$ + 1 wt%$Be_{12}V$) and pure beryllium under controlled neutron flux conditions in the BR2 reactor. The target fluence corresponds to 2.5–3 dpa in Fe, achieved over three to four cycles, at four distinct temperatures (400, 600, 750, and 900°C) with using dedicated stainless-steel capsules, designed according to the BAMI (Basket for Material Irradiation) concept, which allows fast deployment and high neutron flux without active temperature control or gas flushing. To determine irradiation condition, thermal and neutronic calculations (FEM and MCNP) were conducted. Gadolinium (Gd) is selected as the thermal neutron shield to reduce thermal flux, with its burn-up and reactivity effects assessed for reactor safety. Eight capsules will accommodate different sample geometries (pebbles, disks, and cylinders), filled with helium to ensure inert conditions.

1. Introduction

In a fusion reactor, 14.1 MeV neutrons play a central role in the blanket system by enabling tritium breeding and converting neutron energy into heat. Within this context, neutron multipliers are indispensable components that improve the overall neutron economy of the blanket.

The Water-Cooled Ceramic Breeder (WCCB) blanket concept is currently under evaluation for the Japanese DEMO reactor (JA-DEMO). Originally, the design was loading a mixed pebble in the blanket. Pure beryllium (Be) in pebble form was proposed as the primary neutron multiplier and still now in TBM-WCCB. On the other hands, beryllides (beryllium intermetallic compounds) have since been suggested as superior alternatives due to their favorable properties, such as reduced swelling [1,2] and improved tritium retention [3–6]. Recently, with the proposal of using beryllide in block form [7–9], $Be_{12}Ti$ is not only being considered a prominent candidate for this application. But $Be_{12}V$ or $Be_{12}Ti$ also has been considered a candidate for the blanket which loads pebble form for breeding functional materials.

Within these blanket designs, beryllide has been proposed as a neutron multiplier, while lithium titanate (Li_2TiO_3) is considered as the tritium breeder material. These functional materials are expected to experience changes in tritium retention behavior as well as mechanical and thermal properties under neutron irradiation. Therefore, understanding irradiation-induced effects is essential for ensuring reliable blanket performance.

To address these issues, the National Institutes for Quantum Science and Technology (QST) has been conducting research and development under the Broader Approach (BA) activities, which aim to accelerate the realization of fusion energy through collaboration between Japan and Europe in relation to ITER. These efforts include the development of fabrication technologies and characterization of advanced breeding functional materials.

As part of this program, neutron irradiation tests were planned and executed at the BR2 reactor of SCK·CEN to enable post–irradiation examination (PIE) of neutron multipliers. Irradiation capsules compatible with the required specimen geometries were designed, developed, and validated based on the BAMI concept. In parallel, safety assessments, including tritium generation estimates derived from neutronic (MCNP) analyses, were performed, and these predictions will be correlated with PIE tritium release measurements to refine tritium inventory assessments.

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This paper reports the current status of neutron irradiation at SCK·CEN for advanced neutron multiplier candidates, with emphasis on their post–irradiation behavior and implications for DEMO blanket design.

2. Neutron multiplication materials for neutron irradiation

In this study, two types of neutron multiplier materials were prepared for irradiation testing at the BR2 reactor.

2.1. Beryllium pebbles and beryllide pebbles

Beryllium (Be) pebbles with diameter of 1 mm produced via the rotating electrode method (REM) and subsequently sieved to isolate a uniform size of 1 mm for testing. For the Be12V pebbles, in previous study, the fabrication process was studied [10–12]. Firstly, beryllium powder (99.4 wt%, particle size <45 µm, Materion Brush, USA) and vanadium (V) powder (>99%, particle size <45 µm, Kojundo chemical laboratory, Japan) were mixed using an automatic mortar for 1 hr (Retsch, RM200) with stoichiometric ratio of Be-7.7at% V. The mixed powders were then consolidated into rods using spark plasma sintering (SPS) (KE-PASII, KAKEN, Japan)). The sintering temperature was monitored using an infrared (IR) method to ensure precise control. Plasma sintering was conducted at 800°C. Finally, Be-7.7at% V rods were mechanically polished from all sides to remove any surface contamination such as graphite film or from the graphite die and plungers. Then, these fabricated Be-V rods were processed into pebbles using the same REM process. Similar to the pure Be pebbles, the resulting Be12V pebbles were sieved to obtain a 1 mm diameter for use as the test material.

2.2. Beryllide blocks

The second type involved blocks manufactured from powders obtained after homogenization heat treatment of a mixture of Materion beryllium powder and high-purity titanium and vanadium powders. Following the approach reported in previous studies [13–16], Be-7.7at% Ti powder which is corresponding to the stoichiometric composition of $Be_{12}Ti$ was prepared by mixing beryllium (purity: 99.4 wt%, particle size < 45 µm, Materion Brush, USA) and titanium (>99.9 wt%, particle size < 45 µm, Kojundo Chemical Laboratory, Japan) using a mortar grinder for 1 h. Additionally, $Be_{12}Ti$ + 1wt.%$Be_{12}V$ powder was prepared using the same method to investigate the effect of vanadium addition on irradiation behavior. The mixed powders were then homogenized by heat treatment at 1200°C for 24 h under an argon flow of 200 mL/min in an atmosphere-controlled furnace (FT-1700–200B-VAC, Full-tech, Japan). This homogenization process promotes the formation of the desired $Be_{12}Ti$ intermetallic phase and ensures compositional uniformity throughout the powder. The homogenized powder was consolidated by plasma sintering at 1200°C for 20 min under a pressure of 17 kN. To prevent adhesion between the graphite die, punch, and powder during sintering, carbon films were applied at the contact interfaces. A predetermined amount of powder was loaded into the setup, and blocks were fabricated using a plasma-sintering device. The selected conditions were intended to achieve high densification while preserving the desired $Be_{12}Ti$ phase stability. After sintering, the blocks were machined into disk and cylindrical specimens using wire electrical discharge machining (EDM). To eliminate the surface layer affected by EDM and any regions that reacted with the carbon film, all specimens were polished prior to irradiation. This surface preparation is critical to ensure that the irradiation-induced changes observed during post-irradiation examination are representative of the bulk material behavior rather than artifacts from the fabrication process.

3. Status of neutron irradiation experiment

3.1. Irradiation campaign design and Implementation

The irradiation campaign for beryllide ($Be_{12}Ti$) and pure beryllium specimens was systematically designed and executed in the BR2 reactor between 2024 and 2025. Table 1 summarizes the specimen composition according to the target temperatures. The primary objective of this experiment was to irradiate beryllide and pure beryllium samples under controlled conditions as listed in Table 1.

3.1.1. Neutronics analysis and dpa Calculation

The anticipated irradiation conditions were determined through neutronics calculations using the licensed MCNP model of BR2 and thermal analysis employing both FEM and analytical approaches. To calculate dpa, the number of displacements per atom was computed using coupled neutron-photon transport, and activation calculations were performed using ALEPH2 [17]. The PHITS [18] Monte Carlo radiation transport code was employed to obtain neutron spectra from the timeline sequence in ALEPH2, which reflects the BR2 irradiation cycles.

The general-purpose nuclear data library JEFF-3.3 [19] was utilized for neutron transport in PHITS and for fuel depletion in ALEPH2. For obtaining the dpa response, the IAEA-dedicated displacement cross-section library [20], generated at KIT using cross-section data from JEFF-3.3, was employed. The displacement cross-sections were generated at KIT using the NRT standard [21],

$$\sigma_{displ}(E) = \frac{0.8}{2E_d}\int_{T_{min}}^{T_{max}} \frac{d\sigma(E,T)}{dT} T dT \quad (1)$$

where T is the recoil (PKA) kinetic energy transferred to the lattice atom during a collision, and E_d is the threshold energy, a minimum energy required to displace an atom, taken as 40 eV (i.e. for Fe).

3.1.2. Thermal analysis and capsule positioning optimization

Based on the neutronics calculations, thermal analysis was

Table 1
Desirable number of samples, target irradiation temperature, type and size of the samples.

Composition	Estimated mass (g) of samples for loading	Temperature (°C)	Dimension
Be	1.0	400,600	1 mm pebble
$Be_{12}V$	2.0 at 750 and 900℃ 1.0 at 400 and 600℃	400,600, 750, 900	1 mm pebble
Be	4 disks at each temp.	400, 600	Ø:7 mm T:1.4 mm
$Be_{12}Ti$ + 1 wt% $Be_{12}V$	8 disks at each temp.	400, 600, 750, 900	Ø:7 mm T:1.4 mm
$Be_{12}Ti$	8 disks for 400 and 600℃, 12 disks for 750 and 900°C	400, 600, 750, 900	Ø:7 mm T:1.4 mm
$Be_{12}Ti$ + 1 wt% $Be_{12}V$	13 cylinders at each temp.	400, 600, 750, 900	Ø:2.2 mm T:2.6 mm
$Be_{12}Ti$	26 cylinders at each temp.	400, 600, 750, 900	Ø:2.2 mm T:2.6 mm

conducted to predict the irradiation temperatures. The capsule positions within the channels were adjusted according to the optimal correspondence between the required irradiation temperature and the available neutron flux, which determines the nuclear heating rate. As shown in Fig. 1, the design accommodated four capsules per channel(B-180). Intra-cycle variations in nuclear heating are also illustrated in the corresponding figure. These fluctuations affect the variation in irradiation temperature, typically amounting to approximately 5–10% of the absolute irradiation temperature value. Table 2 presents the "List of irradiation capsules (including ID and target nuclear heating)" used in the calculations.

3.1.3. Capsule and fabrication

The irradiation device followed the BAMI (Basket for Material Irradiation) concept, consisting of sealed, un-instrumented capsules stacked in an aluminum basket inserted into a BR2 fuel channel. This configuration enabled flexible positioning along the axial flux profile, allowing irradiation across a wide range of temperatures and fluences. Fig. 2 shows cross-sectional and 3D views of the RH basket with capsules positioned inside a fuel element consisting of six plates.

A total of eight capsules were prepared to accommodate specimens at four temperatures (400, 600, 750, and 900°C), with two capsules per temperature (one for pebbles and one for disks/cylinders) as shown in Figs. 3 and 4. The capsules were fabricated from stainless steel (SS), necessary for high-temperature irradiation (>600°C). The capsules had an outer diameter of 15 mm, a wall thickness of 1.65 mm, and a length of 100 mm. Each capsule included the two holders. Holders inside the capsules were made of tungsten to maintain specimen position during irradiation.

The tungsten holders are distanced from the capsule wall and centered by three pins at both the bottom and upper end plugs in Fig. 2. The centering pins also guarantee the appropriate gap between the holder and capsule wall to achieve the target temperature profile throughout the entire irradiation period. Each capsule is equipped with a SiC passive sensor for post-irradiation temperature verification.

The capsules were joined by TIG welding and underwent non-destructive testing (radiography, pressure, and leak tests). Each capsule was filled with helium at 1 bar gauge pressure to maintain an inert atmosphere. Welding and assembly were performed in an inert helium atmosphere inside a glovebox.

3.1.4. Irradiation execution

The irradiation campaign was conducted from June 2024 to March 2025 according to the BR2 reactor operation schedule. The campaign was designed to achieve a target neutron fluence of 2.5–3 dpa (Fe reference) at four nominal temperatures: 400, 600, 750, and 900°C, for comparison with literature and previous BR2 campaigns. For reference, the neutron fluence corresponding to 1 dpa on an Fe basis at $E_n > 0.1$ MeV was set at $1.8 \times 10^{21} n/cm^2$.

Each BR2 irradiation cycle had an effective duration of 28–30 days. Depending on the axial (vertical) position of a specific capsule within the designated reactor channel, 4–6 cycles were required to reach the cumulative target of 2.5–3 dpa (Fe reference). This position dependency reflects the axial flux (and nuclear heating) profile of the channel and was reflected in the channel/level assignment of the eight capsules (see Table 3 for capsule IDs, channel/axial positions, and planned cycles).

3.2. Post-irradiation examination plan

Following neutron irradiation, comprehensive post-irradiation examination (PIE) will be conducted on the materials listed in Table 1 to evaluate the effects of neutron irradiation under the four temperature conditions. The PIE will be performed at KIT-IAM (Karlsruhe Institute of Technology – Institute for Applied Materials). The following examinations are planned to assess key performance parameters relevant to fusion blanket applications, although specific examination and detailed conditions are currently under negotiation between the collaborating institutions.

Tritium retention and release behavior will be investigated through thermal desorption experiments conducted at various heating rates. These heating-controlled measurements will assess the dynamics of tritium generated by neutron irradiation in beryllium and beryllide materials.

Dimensional stability will be evaluated through precision dimensional measurements and visual inspection to quantify irradiation-induced dimensional changes and swelling behavior. This assessment is critical for understanding the impact of neutron irradiation on the mechanical integrity of neutron multiplier materials.

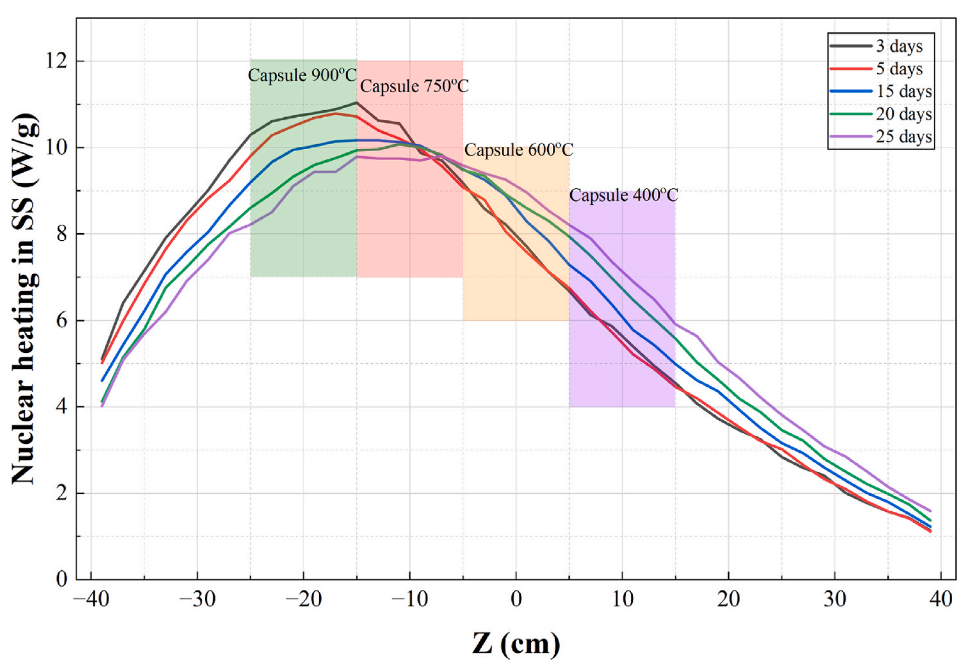

Fig. 1. Variation of the nuclear heating in SS during the irradiation cycle along the core length in B-180 channel.

Table 2
List of irradiation capsules wit IDs and target nuclear heat generation values.

Capsule ID	Holder ID	Samples Shapes	Target Temp.(℃)	Nuclear heating in SS(w/g)	Max Temp.(℃)	Min. Temp.(℃)	Ave. Temp.(℃)
JBe1	JP4	Disks, cylinder	400	6.5	406.9	405.7	406.3
	JC4		400	6.5	426.8	426.6	426.7
JBe2	JST4	pebbles	400	6.5	409.9	399.9	405
	JSB4		400	6.5	409.9	399.9	405
JBe3	JP6	Disks, cylinder	600	8.9	603.7	602.1	602.9
	JC6		600	8.9	605	604.9	604.95
JBe4	JST6	pebbles	600	8.9	607.65	594	600.8
	JSB6		600	8.9	607.65	594	600.8
JBe5	JP7	Disks, cylinder	750	10.5	767.3	765.4	766
	JC7		750	10.5	752	751.7	751.85
JBe6	JS7	pebbles	750	10.5	771.4	755.3	763.3
JBe7	JP9	Disks, cylinder	900	10.5	911	909.4	907.7
	JC9		900	10.5	881.4	881.25	881.3
JBe8	JS9	pebbles	900	10.5	913.1	897	905

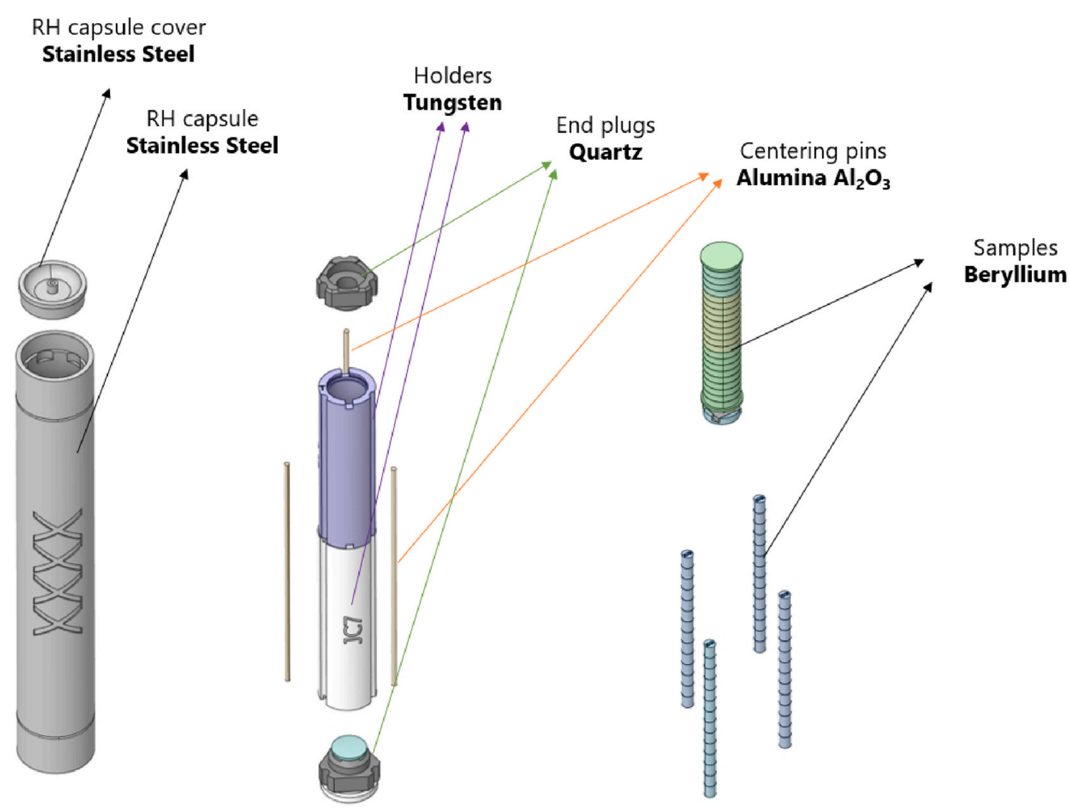

Fig. 2. Stainless steel BAMI RH capsule used for the irradiation of Be samples. The capsule has an outer diameter of 15 mm and is loaded in VIn element fuel element channel.

Microstructural characterization will be performed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to identify irradiation-induced defects, evaluate phase stability, and examine grain boundary modifications. These analyses will provide insights into microstructural behavior under different irradiation conditions.

Mechanical properties will be assessed through compressive strength tests on cylindrical specimens (φ 2.2 mm × 2.6 mm). These tests will be performed at both room temperature and at temperatures corresponding to the irradiation conditions to evaluate the temperature dependence of irradiation-induced mechanical property degradation.

Thermal properties will be evaluated by measuring specific heat and thermal diffusivity to determine changes in thermal conductivity after irradiation. These measurements will clarify the influence of irradiation

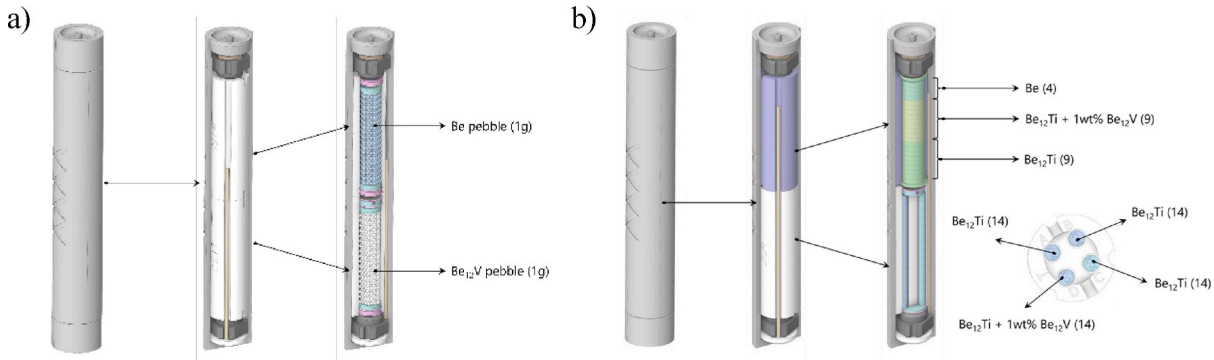

Fig. 3. Capsule design (a) at 400/600°C for pebbles. (b) 400/60000B0C for pellets/disks and cylinders.

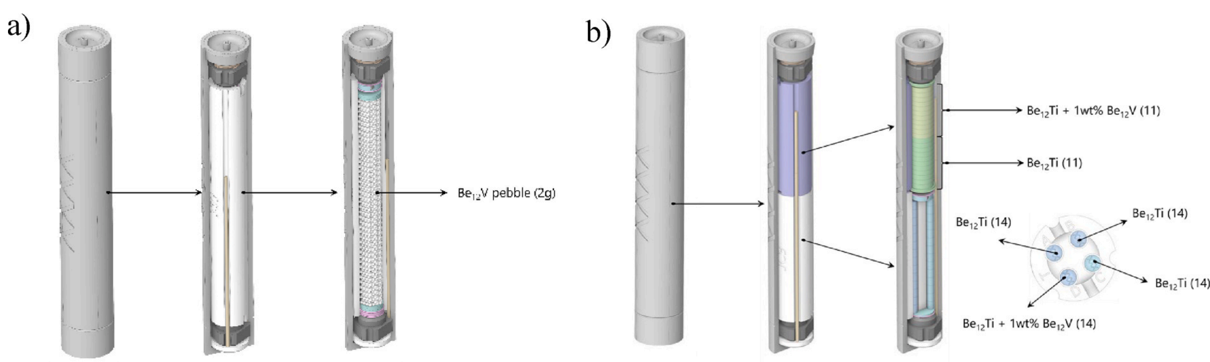

Fig. 4. Capsule design (a) at 750/900°C for pebbles. (b) 750/900°C for pellets/disks and cylinders.

Table 3
Information on the irradiation configuration used for irradiation.

Capsule ID	JBe1	JBe3	JBe5	JBe7	JBe2	JBe4	JBe6	JBe8
DPA(1st cycle)	0.3	0.45	0.56	0.54	0.5	0.66	0.75	0.75
Irradiation channel	C139 K301 (F)	C139 K301 (F)	C139 K301 (F)	C130 K301 (F)	C41 K301 (F)	C41 K301 (F)	C41 K301 (F)	C41 K301 (F)
Realized nuclear heat based on pre-cycle neutronic calculations, W/g in SS	6.5	8.9	10.5	10.5	6.5	8.9	10.5	10.5
DPA(2nd cycle)	0.55	0.73	0.86	0.89	0.5	0.66	0.78	0.78
Irradiation channel	B180 K304 (F)	B180 K304 (F)	B180 K304 (F)	B180 K304 (F)	C319 K337	C319 K337	C319 K337	C319 K337
Realized nuclear heat based on pre-cycle neutronic calculations, W/g in SS	7.43	9.81	11.5	11.94	6.61	8.83	10.5	10.44
DPA(3rd cycle)	0.42	0.6	0.75	0.8				
Irradiation channel	B180 K327 (F)	B180 K327 (F)	B180 K327 (F)	B180 K327 (F)				
Realized nuclear heat based on pre-cycle neutronic calculations, W/g in SS	5.7	8.08	9.98	10.67				
DPA(4th cycle)	0.46	0.65	0.8	0.83				
Irradiation channel	D300 K327 (F)	D300 K327 (F)	D300 K327 (F)	D300 K327 (F)				
Realized nuclear heat based on pre-cycle neutronic calculations, W/g in SS	6.25	8.69	10.79	11.09				
DPA(5th cycle)	0.48	0.66						
Irradiation channel	D300 K362	D300 K362						
Realized nuclear heat based on pre-cycle neutronic calculations, W/g in SS	6.5	8.9						
DPA(6th cycle)	0.52							
Irradiation channel	C259 K340 (F)							
Realized nuclear heat based on pre-cycle neutronic calculations, W/g in SS	7							

conditions and defect formation on thermal transport properties.

Detailed examination matrices, testing parameters, and quality assurance procedures are being finalized through ongoing coordination. These PIE activities will provide critical data for validating the performance of beryllium, beryllide-based neutron multipliers and support the design of advanced blanket systems for DEMO.

4. Summary and future work

Neutron irradiation tests on beryllide and pure beryllium specimens have been successfully completed in the BR2 reactor under four distinct temperature conditions (400, 600, 750, and 900°C) to a target fluence of approximately 2.5–3 dpa (Fe reference). The irradiation campaign employed stainless–steel capsules based on the BAMI concept, which enabled rapid deployment and exposure to high neutron flux without active temperature control. Thermal and neutronic analyses were performed to design the irradiation conditions and to estimate the irradiation environment for each capsule.

A total of eight capsules were fabricated to accommodate different specimen geometries required for post–irradiation testing.

Post-irradiation examination (PIE) is planned to focus on key performance metrics for fusion blanket applications, including tritium retention and release behavior, microstructural evolution, dimensional stability and swelling, compressive strength at both room temperature and irradiation temperature, and thermal property changes. These comprehensive investigations will provide data for design validation of beryllide-based neutron multipliers and be one of the data for life-assessment.

CRediT authorship contribution statement

Taehyun Hwang: Writing – review & editing, Writing – original draft. **Jae-Hwan Kim:** Writing – review & editing, Supervision, Project administration. **Yutaka Sugimoto:** Writing – review & editing. **Hiroyasu Tanigawa:** Supervision, Project administration. **Dmitry Terentyev:** Supervision, Data curation. **Stefano Fontanelli:** Investigation, Data curation. **Ramil Gaisin:** Conceptualization. **Vladimir Chakin:** Methodology, Conceptualization. **Pavel Vladimirov:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] K. Tsuchiya, H. Kawamura, T. Ishida, Compatibility between Be-Ti alloys and F82H steel, J. Nucl. Mater. 367–370 B (2007) 1018–1022, https://doi.org/10.1016/j.jnucmat.2007.03.186.

[2] K. Tsuchiya, Y. Namekawa, T. Ishida, Compatibility between Be-V Alloy and F82H steel, J. Nucl. Mater. 386–388 (2009) 1056–1059, https://doi.org/10.1016/j.jnucmat.2008.12.273.

[3] H. Kawamura, E. Ishitsuka, K. Tsuchiya, M. Nakamichi, M. Uchida, H. Yamada, K. Nakamura, H. Ito, T. Nakazawa, H. Takahashi, S. Tanaka, N. Yoshida, S. Kato, Y. Ito, Development of advanced blanket materials for a solid breeder blanket of a fusion reactor, Nucl. Fusion 43 (2003) 675–680, https://doi.org/10.1088/0029-5515/43/8/306.

[4] Y. Fujii, M. Miyamoto, J.H. Kim, M. Nakamichi, N. Murayoshi, H. Iwakiri, Hydrogen retention behavior of beryllides as advanced neutron multipliers, Nucl. Mater. Energy 9 (2016) 233–236, https://doi.org/10.1016/j.nme.2016.03.001.

[5] M. Miyamoto, Y. Sugimoto, D. Nishijima, M.J. Baldwin, R.P. Doerner, A. Zaloznik, J.H. Kim, M. Nakamichi, Comparative study of surface modification and D retention between beryllium and beryllides under high flux plasma exposure, Nucl. Mater. Energy 27 (2021) 101014, https://doi.org/10.1016/j.nme.2021.101014.

[6] V. Chakin, R. Rolli, R. Gaisin, U. Hoeppener-Kramar, M. Nakamichi, M. Zmitko, Tritium release and retention in beryllium and titanium beryllide after neutron irradiation up to damage doses of 23-38 dpa, Fusion Eng. Des. 161 (2020) 111938, https://doi.org/10.1016/j.fusengdes.2020.111938.

[7] R. Gaisin, R. Rolli, V. Chakin, P. Vladimirov, Beryllides as advanced materials for neutron multiplication Neutron multiplier materials for breeding blanket, in: Proc. 15th Int. Work. Beryllium Technol., Karlsruher Institut für Technologie (KIT), Karlsruher, 2022: pp. 141–164. doi:10.5445/IR/1000160103.

[8] L.V. Boccaccini, F. Arbeiter, P. Arena, J. Aubert, L. Bühler, I. Cristescu, A. Del Nevo, M. Eboli, L. Forest, C. Harrington, F. Hernandez, R. Knitter, H. Neuberger, D. Rapisarda, P. Sardain, G.A. Spagnuolo, M. Utili, L. Vala, A. Venturini, P. Vladimirov, G. Zhou, Status of maturation of critical technologies and systems design: Breeding blanket, Fusion Eng. Des. 179 (2022) 113116, https://doi.org/10.1016/j.fusengdes.2022.113116.

[9] S. Youji, T. Hiroyasu, S. Yoshiteru, Development of water-cooled cylindrical blanket in JA DEMO, Nucl. Fusion 64 (2024), https://doi.org/10.1088/1741-4326/ad2950.

[10] P. Kurinskiy, J.H. Kim, M. Nakamichi, Fabrication and characterization of Be12V pebbles with different diameters, Fusion Eng. Des. 146 (2019) 656–659, https://doi.org/10.1016/j.fusengdes.2019.01.048.

[11] M. Nakamichi, J.H. Kim, M.M. Nakamura, T. Shibayama, C.K. Dorn, C. Vladimir, D. V. Bachurin, C. Stihl, P.V. Vladimirov, Beryllium and its alloys as neutron multiplying materials, Compr. Nucl. Mater. Second Ed. (2020) 203–250, https://doi.org/10.1016/B978-0-12-803581-8.11673-X.

[12] M. Nakamichi, J.H. Kim, Fabrication of beryllide pebble as advanced neutron multiplier, Fusion Eng. Des. 89 (2014) 1304–1308, https://doi.org/10.1016/j.fusengdes.2014.02.081.

[13] T. Hwang, J.H. Kim, Y. Sugimoto, R. Gaisin, R. Rolli, P. Vladimirov, Y. Akatsu, S. Yokohama, S. Nakano, M. Nakamichi, Effect of temperature on mechanical properties of beryllium intermetallic compounds fabricated by plasma sintering, Nucl. Mater. Energy 40 (2024) 101686, https://doi.org/10.1016/j.nme.2024.101686.

[14] T. Hwang, J.H. Kim, Y. Sugimoto, Y. Akatsu, S. Nakano, M. Nakamichi, Development of advanced ternary beryllium intermetallic compounds, Fusion Eng. Des. 200 (2024) 114221, https://doi.org/10.1016/j.fusengdes.2024.114221.

[15] M. Nakamichi, J.H. Kim, Homogenization treatment to stabilize the compositional structure of beryllide pebbles, J. Nucl. Mater. 440 (2013) 530–533, https://doi.org/10.1016/j.jnucmat.2013.02.070.

[16] J.H. Kim, H. Iwakiri, T. Furugen, M. Nakamichi, Synthesis and reactivity of single-phase Be17Ti2 intermetallic compounds, Fusion Eng. Des. 102 (2016) 44–49, https://doi.org/10.1016/j.fusengdes.2015.10.034.

[17] A. Stankovskiy, G. Van den Eynde, Advanced method for calculations of core burn-up, activation of structural materials, and spallation products accumulation in accelerator-driven systems, Sci. Technol.Nucl. Install. 2012 (2012) 545103, https://doi.org/10.1155/2012/545103.

[18] T. Sato, Y. Iwamoto, S. Hashimoto, T. Ogawa, T. Furuta, S. Abe, T. Kai, P.-E. Tsai, N. Matsuda, H. Iwase, N. Shigyo, L. Sihver, K. Niita, Features of particle and heavy ion transport code system (PHITS) version 3.02, J. Nucl. Sci. Technol. 55 (2018) 684–690, https://doi.org/10.1080/00223131.2017.1419890.

[19] A.J.M. Plompen, O. Cabellos, C. De Saint Jean, M. Fleming, A. Algora, M. Angelone, P. Archier, E. Bauge, O. Bersillon, A. Blokhin, F. Cantargi, A. Chebboubi, C. Diez, H. Duarte, E. Dupont, J. Dyrda, B. Erasmus, L. Fiorito, U. Fischer, D. Flammini, D. Foligno, M.R. Gilbert, J.R. Granada, W. Haeck, F.-J. Hambsch, P. Helgesson, S. Hilaire, I. Hill, M. Hursin, R. Ichou, R. Jacqmin, B. Jansky, C. Jouanne, M.A. Kellett, D.H. Kim, H.I. Kim, I. Kodeli, A.J. Koning, A. Y. Konobeyev, S. Kopecky, B. Kos, A. Krása, L.C. Leal, N. Leclaire, P. Leconte, Y. O. Lee, H. Leeb, O. Litaize, M. Majerle, J.I. Márquez Damián, F. Michel-Sendis, R. W. Mills, B. Morillon, G. Noguère, M. Pecchia, S. Pelloni, P. Pereslavtsev, R. J. Perry, D. Rochman, A. Röhrmoser, P. Romain, P. Romojaro, D. Roubtsov, P. Sauvan, P. Schillebeeckx, K.H. Schmidt, O. Serot, S. Simakov, I. Sirakov, H. Sjöstrand, A. Stankovskiy, J.C. Sublet, P. Tamagno, A. Trkov, S. van der Marck, F. Álvarez-Velarde, R. Villari, T.C. Ware, K. Yokoyama, G. Žerovnik, The joint evaluated fission and fusion nuclear data library, JEFF-3.3, Eur. Phys. J. A 56 (2020) 181, https://doi.org/10.1140/epja/s10050-020-00141-9.

[20] A.Y. Konobeyev, U. Fischer, S.P. Simakov, Atomic displacement cross-sections for neutron irradiation of materials from Be to Bi calculated using the arc-dpa model, Nucl. Eng. Technol. 51 (2019) 170–175, https://doi.org/10.1016/J.NET.2018.09.001.

[21] M.J. Norgett, M.T. Robinson, I.M. Torrens, A proposed method of calculating displacement dose rates, Nucl. Eng. Des. 33 (1975) 50–54, https://doi.org/10.1016/0029-5493(75)90035-7.