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Research Article

Tritium Breeding Performance Analysis of HCLL Blanket Fusion Reactor Employing Vanadium Alloy (V-5Cr-5Ti) as First Wall Material

Indah Rosidah Maemunah, Zaki Su'ud, Abdul Waris, and Dwi Irwanto

Nuclear Physics Department, Institut Teknologi Bandung, Bandung 40132, Indonesia

Correspondence should be addressed to Zaki Su'ud; szaki@itb.ac.id

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Neutronic analysis in the HCLL blanket module has been established, and the calculation was performed by the ITER team, including the first wall (FW). In this study, seven materials have been investigated for FW material by considering characteristics such as high neutron fluence capability, low degradation, under irradiation, and high compatibility for blanket material. A three-dimensional configuration simulated in MCNP5 program codes was performed to investigate the neutronic performance and radiation damage effect. Employing seven candidates are vanadium carbide (VC), titanium carbide (TiC), vanadium alloy (V-5Cr-5Ti), graphite (C), tungsten alloy (W-CuCrZr), ceramic alloy (SiC), and HT-9 to study optimization of FW materials configurated in the HCLL blanket module. This novelty study concludes that vanadium alloy (V-5Cr-5Ti) is becoming a promising material candidate. This alloy has the highest number of neutronic performing for 1.27 TBR and 1.26 in multiplication energy factor in all investigations. Meanwhile, the amount of atomic displacement, hydrogen, and helium production are around 22.31 appm, 765.55 appm, and 281.57 appm, respectively. Even though vanadium alloy has a reasonably high radiation damage effect, it is still tolerable compared to several thresholds of DPA. So, it is considered excellent material for FW. Nevertheless, this alloy can replace after 13.45 years for radiation damage.

1. Introduction

Currently, the most extensive fusion reactor program is a fusion demonstration power plant (DEMO) that would be built after the international thermonuclear experiment reactor (ITER) project in France [1]. This long and massive project involved many countries, such as the USA, Japan, China, Korea, India, and the EU [2]. The ITER is currently under construction and is predicted to complete in 2050 [3]. A blanket module is a crucial research project that contributed to the fusion reactor. European team developed the two tritium blanket modules (TBM). One strongly related to this study is helium-cooled and lithium–lead (HCLL) for a fusion demonstration reactor (DEMO) [4–6]. The primary purpose of TBM is tritium production, which requires a self-sufficiency condition [7]. It indicated to the tritium breeding ratio (TBR) parameter that tritium produced in a blanket is higher than tritium burnt needed in the chamber. In 2017, Jean and the team estimated the TBR value in the HCLL blanket is 1.08 [8], then the efficiency requires a minimum of 1.05 for DEMO [9, 10].

In this paper, the neutronic calculation is performed to determine the nuclear parameters for the fusion reactor in the first wall (FW). The primary objective of the neutronic analysis is to determine the optimum material used in each zone supported by high TBM performance, including the first wall (FW) zone [11, 12]. Using material candidates of FW variation, this study aims to determine an effective FW material for performing a high neutron capability and radiation damage effect in this HCLL module design.

Employing seven material candidates are vanadium carbide (VC), titanium carbide (TiC), vanadium alloy (V-5Cr-5Ti), graphite (C), tungsten alloy (W-CuCrZr), ceramic alloy (SiC), and HT-9. Tungsten is a well-known material leading in FW material candidates but facing high sputtering or critical issues. In a tokamak, the first observed huge sputtering effect in plasma originated from tungsten limiter [13], but it is still favorable material for a long operation [14].

On the other hand, iron, aluminum, and chromium are also recommended materials due to the positive effect of increasing of replacing time [15]. So, it is necessary to compare to other material candidates for investigating an optimization of the nuclear capability, and low radiation damage properties such as tritium production, energy multiplication, displacement per atom (DPA), gas production, and a lifetime of material. In this study, we found out if vanadium alloy has the highest performance in tritium breeding and long lifetime material from extreme radiation, such as in a fusion reactor.

Nevertheless, research with vanadium alloy based was carried out since the 1990s [16]. Due to its properties of vanadium alloy, it reduced critical issues such as low activation in high neutron energy, high-temperature strength, high thermal stress, and low activation leading in structural material [17]. Moreover, much research emphasizes that vanadium alloy has a high tritium breeding capability, high purity, easy fabricability, high heat load capability, and good resistance in high extreme irradiation [18, 19]. This alloy becomes a promising material for the first wall and breeding material. Besides that, the crucial issues faced by a low percentage of Cr and Ti in vanadium alloys are the nonmetallic element effect on high radiation [20], the hardness, and the heat conductivity of alloy material [21]. Adding Ti, Al, and Cr composition increases material hardness [22] while reducing of nonmetallic effect in vanadium alloy composition by minimizing C, N, and O percentages. Due to those issues, this novelty research employs V-5Cr-5Ti alloy for liquid Pb-15.7Li (eutectic) breeder material in the HCLL blanket fusion module. This vanadium alloy is a more efficient and highly recommended composition for first wall material.

2. Blanket Configuration and First Wall Design

2.1. Blanket Configuration. Based on ITER data [2], surrounding material in the blanket zone will be bombarded by high neutron energy, 14.1 MeV. The neutron is assumed to be isotropic. Moreover, the plasma density is around 0.67 gr/cm^3, and the volume concentration is assumed to be fully neutron. Magnetic coils confine a charged particle that moves in a limited radius in a torus-shaped. It consists of toroidal and poloidal coils with a total thickness of 40 cm containing Nb_3Sn and NbTi, respectively. The minor radius of the torus is 4 m. Meanwhile, the major radius is 8 m. This blanket frame is separated into six layers built up from the first wall (FW), helium coolant, LiPb breeding zone, reflector, and so forth. Detailed configuration of 6 layers of the blanket module in HCLL is simulated in the program, as shown in Figures 1 and 2.

According to the name of the blanket, helium-cooled lithium lead blanket (HCLL) is used as a fixed helium gas as a coolant and liquid lithium lead (Pb-15.7Li (eutectic)) as tritium breeder and multiplier. It is considered a suitable module, especially from the tritium production performance. Natural lithium leads to a higher TBR than lithium alloy [23]. The author's research shows that the TBR from pure lithium reaches around 1.09 [24, 25]. However, pure lithium cannot survive extreme conditions such as fusion reactors, while lithium alloy can survive more. Due to this reason, lithium alloy, such as lithium lead (LiPb), is still considered a promising tritium breeder [4]. Besides, it used to be a coolant and neutron multiplier simultaneously. Moreover, LiPb breeds tritium in a significant amount. The tritium breeder performances will generally improve when the neutron multiplier, such as beryllium or lead, is applied. Another reason, a lead-containing in breeding is contributed to high tritium production and energy multiplication [26]. A ^{6}Li is vital for tritium breeding due to a significant cross-section of ^{6}Li (n, T) He reaction so that for breeding optimization, it would enrich ^{6}Li until 90% [27].

The cross-section of LiPb is also perfect for neutron shielding. The high-energy neutron can be moderated by LiPb and finally trigger a reaction with lithium to produce tritium. This detail is shown in Figure 3. As seen in Figure 3, the highest cross-section in thermal and high energy are represented by ^{6}Li and Pb, respectively [28]. Therefore, the Li and Pb combination will be a good material for moderating high neutron energy from the fusion reaction.

As mentioned in the introduction, the main reason the material candidates chose was their lower average erosion rate in high neutron energy. Accordingly, the coating layer is paired with tungsten and beryllium to fit each other. Beryllium prospers to moderate neutron energy from the plasma chamber, multiplies neutrons, and improves neutron thermalization before entering the breeding zone. After beryllium coating, a tungsten barrier was used to prevent beryllium-steel interactions in a blanket for a few mm. The structure layer is used as a barrier in a 0.3 cm material thick zone, such as the breeder zone (BZ), FW, coolant zone, and reflector. The frame of the blanket, which surrounds the TBM, consists of a front frame, which protects the TBM in intensive neutron heating and bombardment environment. The front frame surrounding the TBM consists of the materials SS316 and Eurofer97 with consecutive percentages are 50% and 50% in 0.3 cm material thick.

As named HCLL blanket module, the cooling system employs helium gas which has a highly effective heat transport from the blanket. Significantly, helium gas production in FW would help carry out the gas from the system, reducing a gas trap possibility into the material.

In addition to the reflector after BZ, it is used to reflect neutrons that reduce neutron interaction in a magnetic coil. The number of neutrons in BZ is also rising due to direct back neutrons inside. Automatically, it increases tritium production and also the energy multiplication factor. Table 1 and Figure 3 show detailed nuclei density and thickness of a single zone that would be input in the program code.

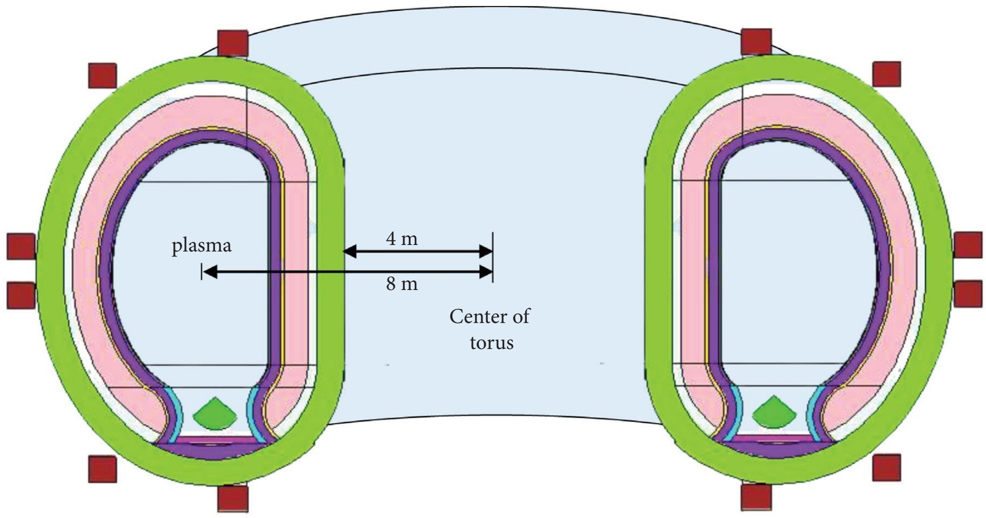


Figure 1: Blanket module with specification layer in the HCLL TBM reactor.

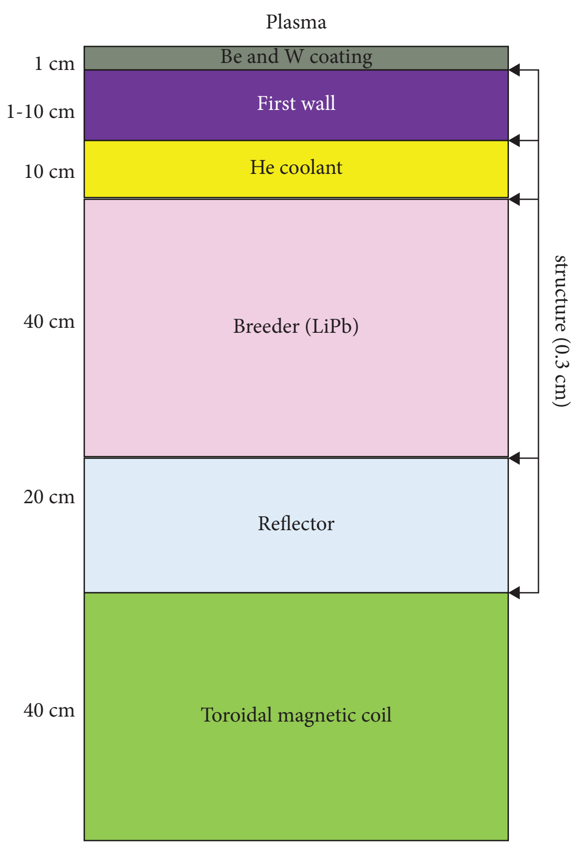


Figure 2: Blanket configuration from plasma to out-edge-blanket.

2.2. First Wall Design. High neutron energy passes through FW to increase the breeding capability. Due to the highly moderated and multiplying neutron with the material in FW, it makes up a neutron performance capability in a reactor. In principle, the tritium production from BZ must be more than that consumed in the fusion chamber due to the transport reduction by a necessary process such as heating friction and particle trap in the streaming system. So, a ratio of tritium production and tritium burnt in the chamber, named tritium breeding ratio (TBR), should be over one. On the other hand, the energy multiplication factor (M) is also an important parameter indicated by heat energy by multiple inelastic neutrons scattering reactions [27]. The FW experiences the highest exposure to neutron energy hence causing material damage. The neutron interaction in the FW material causes gas production and atomic displacement. Therefore, maintenance is required, and FW is replaced to fulfill the sustainable reactor system and long plant shutdown period.

Regarding that condition, material candidates on the FW should have easy fabrication, low cost, a low-level displacement per atom (DPA), and a reasonable limit of gas production. Meanwhile, it must fulfill the requirement of a safety system, environmental advantages, availability of plants, unlimited material supply, and material properties. The material candidates are chosen by their properties: high melting point, low sputtering, low conductivity, low induced radioactivity, low induced radioactivity, neutron fluence capability, mechanical properties at high temperatures, low degradation level under neutron irradiation, and low decay heat. However, the detailed data are given later.

This calculation is modified of FW materials such as vanadium carbide (VC), titanium carbide (TiC), vanadium alloy (V-5Cr-5Ti), graphite (C), tungsten alloy (W-CuCrZr), ceramic alloy, and HT-9 to investigate the best option for the material of FW to support the blanket system. In the previous description, the reason for the material selected is their properties among materials, as we can see in Table 2. These data are related to high-heat conductivity by their thermal conductivity and specific heat information. Moreover, a high melting point is advantageous for material under 14 MeV neutron energy bombardment.

In another case, the general requirement for FW material is low neutronic absorption of cross-section, so light materials tend to lead to a low neutron absorption in high incident energy by (n, γ) reaction cross-section, as seen in Figure 4.

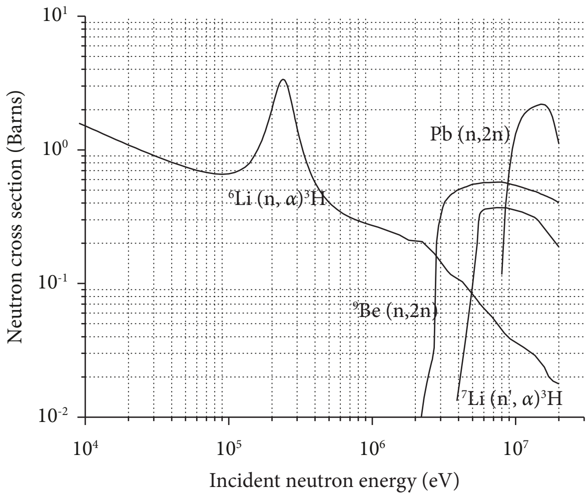


FIGURE 3: Cross-section for reactions ^{6}Li (n, α)^{3}H, ^{7}Li (n, $n\alpha$)^{3}H, ^{9}Be (n, $2n$), and Pb (n, $2n$) [29].

Hydrogen gas produced of (n, p) reaction [33] will be as high as (n, p) cross-section reaction in nuclides. It is similar to the α-particle that can produce helium gas bubbles [34]. However, the (n, p) and (n, α) reaction cross-sections also indicated high neutron reactions in heavy materials such as tungsten and vanadium, as seen in Figure 5. It helps maximize an interaction neutron in the material.

Besides enhancing tritium breeding by (n, p) and (n, α) reaction cross-sections, candidate materials selection for FW must be considered neutron multiplier capability. Regarding the coolant and BZ, it is necessary to create a massive amount of thermal neutron energy supported by the $(n, 2n)$ reaction. This essential calculation is shown in Figure 6.

The correlation of the criteria issue of the material chosen is related to the cross-section of multiplying reaction due to thermalize high neutron energy. It increases the breeding activity caused by having many thermalizing neutron enhancements interact with ^{6}Li in BZ. Hence, FW material is chosen to improve the reactor performance by using FW material candidates. This is the reason behind the candidate materials selected for the FW blanket, starting with light elements to heavy elements. Moreover, heavy materials are highly recommended for optimizing FW occupation in the module.

3. Calculation Methods

This study simulates a neutron transport calculation by using the MCNP5 program [35]. This code was performed in a three-dimensional geometry with a unique and complex design. Using ENDF/B-VII.1 [33] is built up the continuous energy nuclear and atomic data libraries available in regimes 10^{-11} MeV to 20 MeV. The calculation aims to measure neutronic performance and radiation damage, such as tritium breeding, energy multiplication factor, gas production, and displacement per atom for FW materials of the HCLL blanket module. It is employed two steps for calculating results. First, MCNP5 calculated an energy-dependent neutron flux and reaction rate using a tally card and then multiplied by the neutron DPA cross-section for each material. Second, a DPA cross-section data from ENDF/B-VII.1 by the IAEA Nuclear database [36] was processed in NJOY nuclear data processing system for neutrons with energy up to 20 MeV, as seen in Figure 7 [37]. It includes both NRT and MD-BCA cross-sections for gas production cross sections.

This study aims to make the result obtained as a reference for ITER or DEMO in further. As mentioned before, simulation in neutronic performance investigates neutron transport around the blanket region and determines the value of TBR. The simulations use several parameters such as blanket geometry (seen in Figure 2), material components (seen in Table 1), and thickness (seen in Figure 3). Hence, Table 3 shows the atomic densities of material candidates used in the FW structure that is written in input code.

4. Result and Discussion

Neutron fluxes have been measured in the whole reactor (from FWS to magnetic coils) in another paper, as we can see in Figure 8. Neutron source corresponds to a fusion power of P_{fus} = 500MW or equals to $n_{\text{fus}} = 1.77\, x\, 10^{20} n/s$. Neutron fluxes have the highest peaks of absorption reaction in BZ, and they become shallow in the reflector area. In Figure 2, a three-dimensional simulation includes neutron movement from plasma to the shielding. Neutron never comes to the magnetic coil, so there is no need to investigate neutronic analysis in a coil. The first fundamental in a fusion power plant is the possibility of neutron leakage outside the system. It is shown in Figure 8, where neutron flux distribution indicates how many neutrons trap in blanket material. A blanket module employs the HT-9 as FW material. Meanwhile, any other materials used are similar, as seen in Table 1.

Neutron fluxes in Figure 8 range of distance at 277.5 cm–400 cm from the center of the plasma chamber for the whole reactor (from FW to magnetic coils). It peaks at BZ in a blanket module. Neutron is moderated after the BZ area due to the eutectic LiPb that captured ^{6}Li. The neutrons become negligible in the magnetic coil, and neutrons mostly (~99%) are absorbed in a blanket, especially in BZ and reflectors.

The diverse material of FW aims to find an effective material for the high performance of the blanket, especially for tritium breeding capability and radiation damage. In that respect, the selection of the FW material must be conducted carefully.

4.1. Tritium Breeding Capability. As mentioned above, the first point of neutronic analysis of variation of FW material is to support the effectiveness of tritium breeding in BZ. A neutronic calculation measures the neutron interaction with a material compound in any zone that affected the breeding capability of tritium and the energy multiplier in the blanket module, including the FW zone.

In the 40 cm thickness of the blanket zone (BZ), as shown in Figures 2 and 3, it simultaneously has lithium lead (LiPb) as a breeder material and coolant. LiPb is eutectic material

Table 1: Atomic densities of blanket material in each zone.

Zona	Materials	Atomic weight (gr/cm^3)	Nuclide	Percentage of components (%)	Nuclei density (atom/barn.cm)
Coating layer	Be + W	10.565	Be	50	6.178984$E-02$
			W	50	3.157400$E-02$
Structure	Eurofer97	7.909	B	0.001	1.681813$E-06$
			C	0.105	1.589460$E-04$
			N	0.018	2.335812$E-05$
			O	0.01	1.136275$E-05$
			Al	0.008	5.390778$E-06$
			Si	0.006	3.883318$E-06$
			P	0.004	2.348130$E-06$
			S	0.003	1.700692$E-06$
			Ti	0.008	3.038295$E-06$
			V	0.2	7.137966$E-05$
			Cr	9	3.075477$E-03$
			Mn	0.42	1.389838$E-04$
			Fe	88.98	2.896494$E-02$
			Co	0.005	1.542542$E-06$
			Ni	0.005	1.548865$E-06$
			Cu	0.005	1.430401$E-06$
			Nb	0.001	1.956775$E-07$
			Mo	0.001	1.894787$E-07$
			Ta	0.07	7.062309$E-06$
			W	1.1	1.088054$E-04$
	SS316	8.00	C	0.03	1.202998$E-04$
			N	0.1	3.437545$E-04$
			Si	1	1.714489$E-03$
			P	0.045	6.997740$E-05$
			S	0.015	2.252572$E-05$
			Cr	17.5	1.620769$E-02$
			Mn	2	1.753185$E-03$
			Fe	64.81	5.588630$E-02$
			Ni	12	9.847091$E-03$
			Mo	2.5	1.254826$E-03$
FW	Seen in Table 2				
Coolant	Helium	0.125	He	100	1.879840$E-02$
Breeder	LiPb	10.52	Li-6		1.177322$E-02$
			Li-7	17	1.433417$E-01$
			Pb	83	2.536968$E-02$
Shielding/reflector	BeO 50% + graphite 50%	2.5215	Be-9	257	3.634600$E-02$
			O-16	25	3.634300$E-02$
			C	50	5.070100$E-02$
Magnetic coil	Nb_3Sn (toroidal)	8.69	Nb	15	8.445883$E-03$
			Sn	85	3.746144$E-02$
	NbTi (poloidal)	5.7	Nb	53	2.984212$E-02$
			Ti	47	5.136304$E-02$

Table 2: Material candidate properties of the first wall (FW) [30–33].

Material properties	VC	TiC	V-5Cr-5Ti	HT-9	C	SiC	W
Melting point (°C)	2810	3160	1890	1420	3600	2730	3400
Density (g cm^{-3})	5.77	4.93	6.1	7.8	2.266	3.21	19.25
Thermal expansion (10^{-6} K^{-1})	10.96	9.5	10.5	12.6	6.5	4.0	4.4
Thermal conductivity (Wm^{-1} K^{-1})	50	17.14	35.3	27.7	25	60	175
Specific heat (J kg^{-1} K^{-1})	690	840	575	800	707	510	130

used in many blanket designs with low lithium inventory and sufficient tritium breeding capability [16]. Either it becomes a breeder or moderator, lithium lead is supposed to be a coolant to be heat removed as helium or water delegation in BZ. A ^{7}Li and Pb could be a neutron multiplier that thermalizes the high energy of neutron with a reaction of

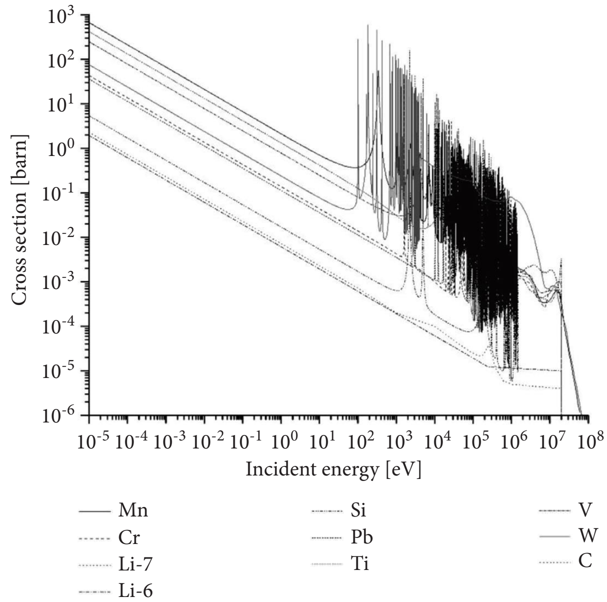
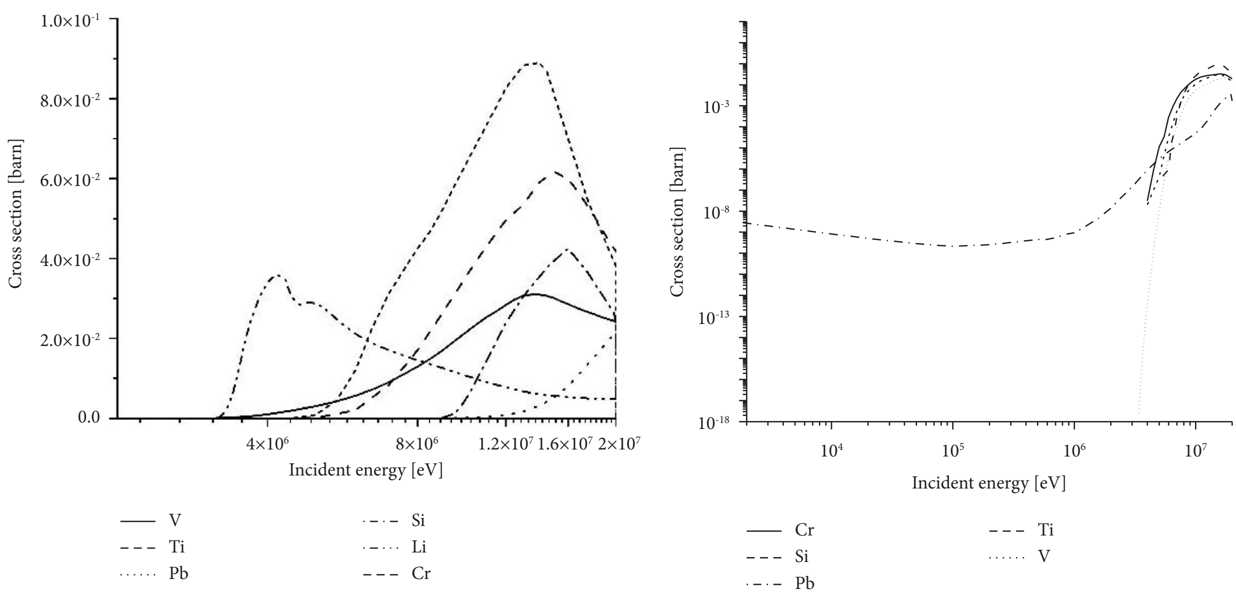


Figure 4: (n, γ) reaction cross section as an absorption reaction in nuclides using ENDF/B-VII.1 [33].



(a)

(b)

Figure 5: (a) (n, p) reaction cross-section and (b) (n, α) reaction cross-section as absorption reaction in nuclides by using ENDF/B-VII.1 [33].

^{7}Li$(n, 2n)$, Pb$(n, 2n)$, and Pb$(n, 3n)$ [29]. One of the crucial problems is delivering tritium production into plasma. Lithium lead might lead to easy transportation caused of its low lithium inventory, so losing tritium might be unnoticeable. Low melting temperature and easy fabrication are considered to optimize blanket performance, so lithium lead represents a compromise material to be a tritium breeder.

The tritium breeding in the blanket depends not only on FW material but also on its thickness. Therefore, the calculation of FW thickness efficiency can be decided by measuring tritium breeding capability in each thickness. Figure 9 shows the variation of thickness of FW using seven candidate materials for finding the trend of FW thickness ideal.

The effect of FW thickness on the TBR value in each FW material is shown in Figure 9. For the thickness from 1–10 cm, the TBR values tend to be linear. It concludes that 1 cm is optimal for FW thickness, and a higher thickness does not significantly affect the TBR value. Nevertheless, the efficiency of FW thickness requires measuring further data that will be described later. Furthermore, the breeding capability used LiPb in BZ also depends on FW materials, which is proven by Figure 10.

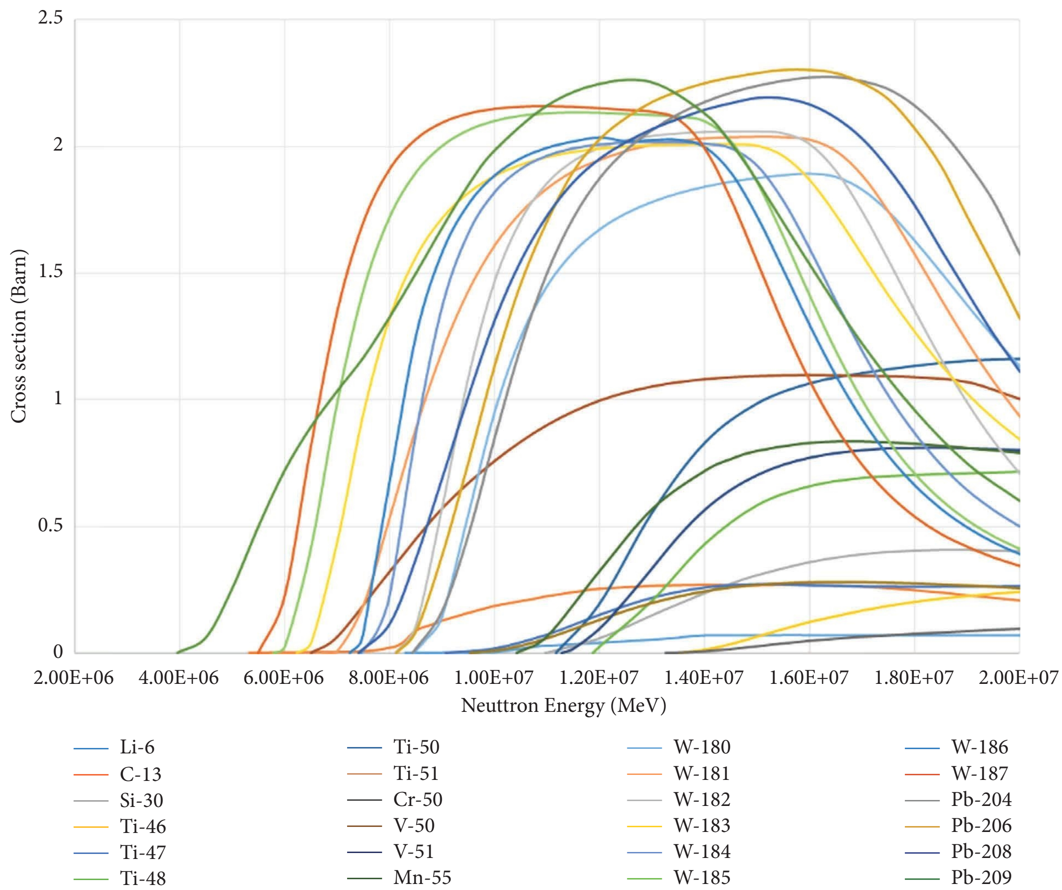


Figure 6: Cross-section of reaction $(n, 2n)$ in every element related to the material of FW by using ENDF/B-VII.1 [33].

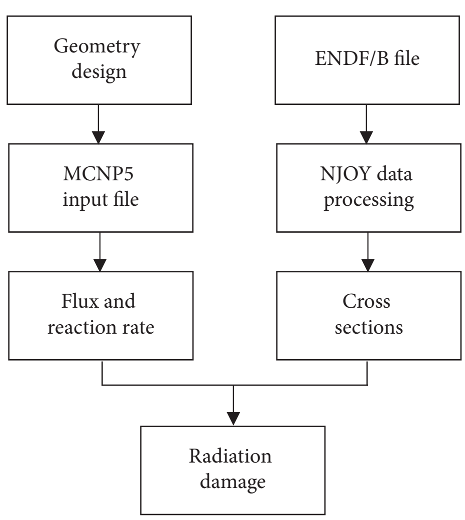


Figure 7: Two steps of radiation damage calculation in MCNP5 program using ENDF/B-VII.1.

FW material properties influence neutron flux distribution in FW to the BZ. The highest TBR comes from vanadium alloy and tungsten, while the lowest TBR value is given to graphite. The capability to scatter and moderate high neutron energy plays an essential role in this case caused by the cross-section of the neutron capture, which is worse than vanadium and others.

Next, Figure 11 shows the energy multiplication factor (M) in the blanket and FW material through the neutron interaction. It is an important parameter for the fusion reactor performance. The kinetic energy, 14.1 MeV, is converted to heat energy by an elastic, and inelastic collision between neutron and particle. Furthermore, tritium breeding is caused by exothermic energy from a neutron-absorbed reaction of ^{6}Li in a breeding zone (BZ). Next, there is an additional emission of gamma energy from neutron gamma production in structure and coolant that contributes to total heat energy. Energy multiplication factor (M) is the ratio of total energy deposited in the blanket divided by perfusion neutron or neutron initial energy per fusion, as follows:

$$M = \frac{E_{\text{totalinblanket}}}{E_{\text{neutroninitialenergyinafusion}}}. \tag{1}$$

The value of M exceeds one, indicating that the neutron energy is blanket beyond that of the neutron initial energy created in a fusion reaction. The two most promising FW materials are tungsten and vanadium alloy. These materials have undergone a short life of beta decay and relatively high thermal neutron capture cross-section [38].

Tritium breeding rate (TBR) and energy multiplication (M) have the same rate on steel, tungsten, titanium, and vanadium [3]. For heavy atoms, threshold energy in inelastic neutron collision $(n, n'\gamma)$ decreases to low energy. It

Table 3: Atomic densities of candidate materials used in the first wall to increase the neutronic performances in blanket HCLL module.

Nucleus	Nuclei density (atom/barn.cm)						
	VC	TiC	V-5Cr-5Ti	HT-9	C	SiC	W-CuCrZr
V	$5.518E-02$		$6.573E-02$	$2.309E-04$			
C	$5.518E-02$	$4.956E-02$	$3.581E-03$	$7.835E-04$	$1.128E-01$	$1.609E-01$	
Ti		$4.956E-02$	$3.890E-03$				
Cr			$5.272E-05$	$1.086E-02$			$6.182E-04$
N			$1.382E-04$				
O			$5.354E-05$				
Ni				$4.914E-04$			
Mn				$5.138E-04$			
Fe				$7.122E-02$			
Mo				$4.903E-04$			
W				$6.700E-04$			$3.154E-02$
Si				$6.700E-04$		$6.879E-02$	
Cu							$4.156E-02$
Zr							$5.888E-05$
Total	$1.104E-01$	$9.913E-02$	7.345-02	$8.593E-02$	$1.128E-01$	$2.297E-01$	$6.315E-02$

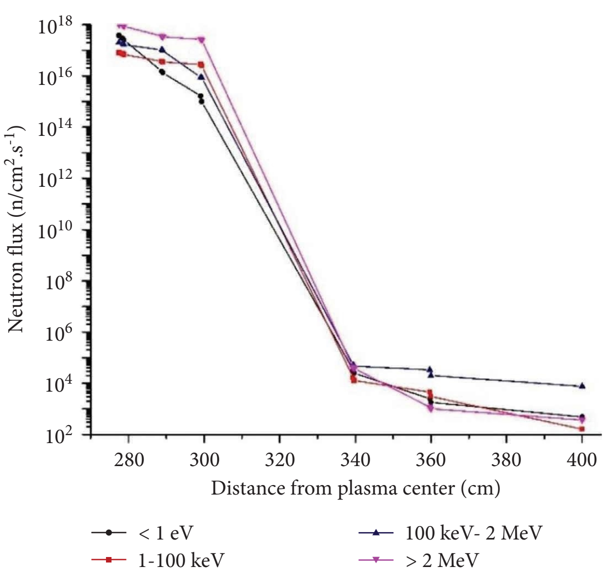


Figure 8: Neutron distribution in depth of HCLL blanket.

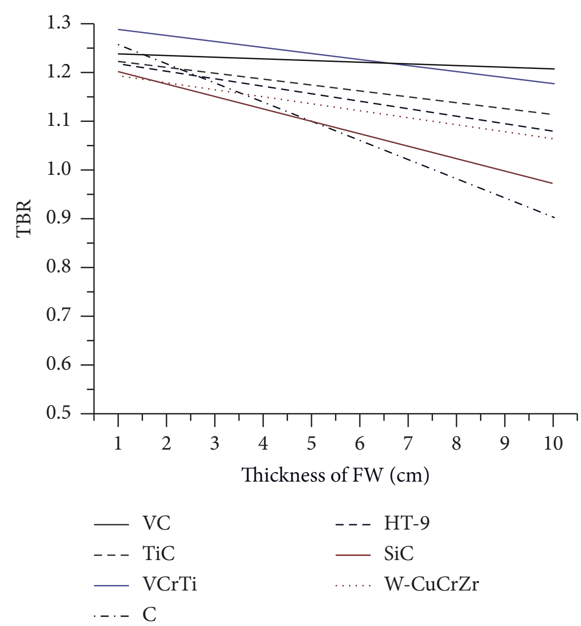


Figure 9: Different thicknesses of FW calculation affected in tritium breeding ratio (TBR) for variation of candidate FW materials.

corresponds to the cross-section of the reaction, increasing in heavier atoms generally [38].

Indeed, fusion neutron passes through inelastic collision and energy loss in FW due to interaction between the neutron and the heavy atom. Consequently, a significant effect on the tritium production capability for the energy multiplication factor (M), and TBR is related to the atomic number of materials used in the FW. However, its capability to withstand high temperatures and fast neutrons is vital to be considered, as shown in Figure 11. The highest multiplication energy factor (M) is tungsten and, thus, vanadium alloy.

From the above discussion, vanadium ($Z_v = 27$) in vanadium alloy and W ($Z_W = 73$) with LiPb breeder material and coolant gives a good reactor performance in M and TBR values. Using graphite, silicon carbide, and HT-9 for FW gives a lower performance in M and TBR.

On the other hand, for sputtering consideration, vanadium alloy is not more suitable than tungsten alloy, so tungsten alloy might be better than vanadium alloy for minimizing diffusion of plasma. The sputtering phenomenon should be avoided because it can decrease plasma temperatures and become a problem for the sustainability of the fusion reaction. For HT-9, there is a nickel in low concentration, which helps overcome the sputtering effect. Therefore, HT-9 as martensitic material might be matched with tungsten combination as structure and material of FW.

4.2. Radiation Damage. In addition to M and TBR values resulting from the selection of FW materials, another crucial measurement that must be calculated for neutronic analysis is radiation damage. The high irradiation of the material causes high neutron energy from fusion production. In this study, the radiation damage effect on the material is

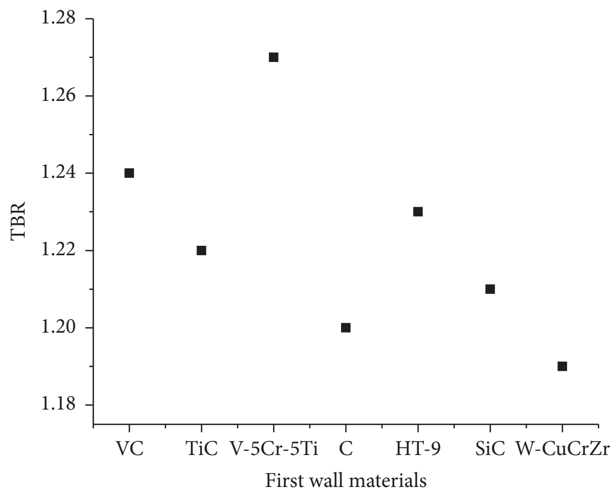


Figure 10: The first wall (FW) materially affected tritium breeding capability in the blanket zone.

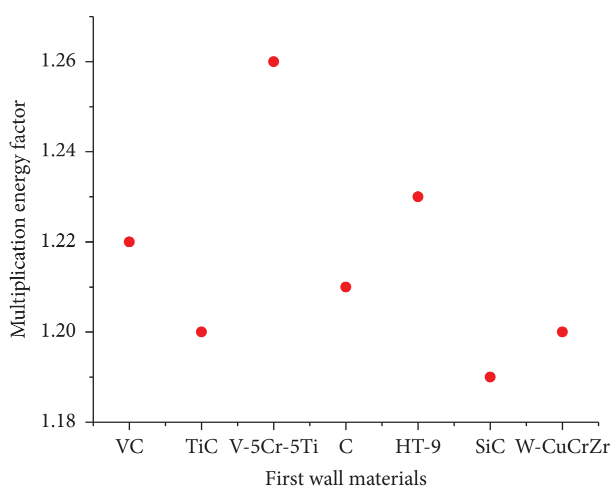


Figure 11: A multiplication energy factor (M) on the first wall (FW) zone.

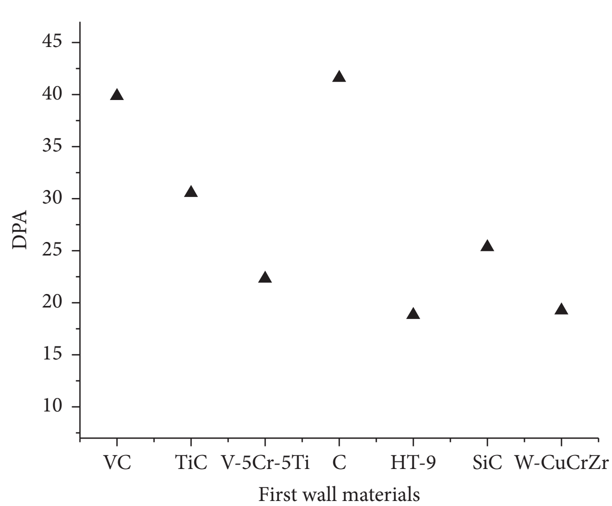


Figure 12: Radiation damage affects the material in FW.

represented by atomic displacement and gas production. By using NJOY nuclear data processing, displacement cross section ($\sigma_{\text{disp}}(E)$) given by ENDF/B-VII.1 file extracts to calculate radiation damage by multiplying neutron flux ($\varnothing(E)$), as we can see in equation (2).

Hence, Figure 12 shows the results of radiation damage in DPA on the FW material calculations in this study.

Because the FW faces intense neutron irradiation, it must evaluate FW displacement per atom (DPA). In 1 cm thickness of FW, Figure 12 presents the DPA in each FW material every year. Figure 12 also shows that vanadium alloy has a low atomic displacement material than any other carbide alloy materials, but not so low, considering high neutron interaction activity. This study also shows that the DPA/FPY value for tungsten is the smallest among others. This can be tough due to the hard material of tungsten which is among hard metals.

$$\text{DPA} = \int \sigma_{\text{disp}}(E)\frac{d\varnothing(E)}{\mathrm{d}E}\mathrm{d}E. \quad (2)$$

It is caused by two categories: the high activity of neutron interaction and material hardness. It can be interpreted that vanadium alloy is an accessible material to fabricate. It is evidenced by the DPA value of tungsten, which is the smallest due to its rigid material.

Rather than that, even though vanadium alloy has a high enough DPA, it could be ruled out with a coolant beyond the FW zone. The material in FW is used to be a tritium breeder catalyzer, so the high-risk density of neutron interaction in the material is represented in a high DPA value. Therefore, this analysis determines the coolant that accompanies the vanadium alloy, either neutral moderation or neutron multiplying. For example, lithium might be a coolant for not having a significant effect on DPA. Furthermore, it needed research to obtain the precise result in joining vanadium alloy with lithium coolant concept, either in the form of alloy or in self-zone customized.

Apart from lithium, there are candidates for neutron multiplication and coolant, such as molten salt (FLiBe). In FLiBe through Be$(n, 2n)$, it pushes away the higher DPA value that caused the reaction of beryllium is stronger than Lead in LiPb with Pb$(n, 2n)$, and Pb$(n, 3n)$ reaction. On steel (HT-9), it represents the atomic displacement is less than vanadium carbide (VC) and higher than tungsten (W). However, the number of DPA is shown in Figure 12 is still below the upper limit of the permission DPA number. Duderstadt mentions the considered threshold number DPA is around 300–1000 appm [39].

Regarding the threshold number DPA for DEMO, these seven materials are enduring for 7–16 years, with 13.45 years for V-5Cr-5Ti, as seen in Table 4. This calculation could reference FW material age, which will last more than 13.45 years. However, further investigation is necessary to determine the fusion blanket's material resistance against neutron radiation.

4.3. Gas Production. The gas created in material interaction in a fusion reactor is mostly hydrogen and helium gas. Helium gas is produced from a fusion and transported into

Table 4: Neutronic performance and radiation damage effect in seven material candidates of the first wall.

Material candidates for first wall	TBR	M	DPA	H prod. (appm)	He prod. (appm)	Lifetime (years)*	
						DPA	He prod
VC	1.24	1.22	39.86	768.93	296.53	7.53	1.69
TiC	1.22	1.2	30.56	752.64	272.54	9.82	1.83
V-5Cr-5Ti	1.27	1.26	22.31	765.55	281.57	13.45	1.78
Graphite (C)	1.2	1.21	41.62	740.25	246.18	7.21	2.03
HT-9	1.23	1.23	18.84	735.13	236.24	15.92	2.12
SiC	1.21	1.19	25.35	741.56	251.24	11.83	1.99
W-CuCrZr	1.19	1.2	19.27	740.54	246.35	15.57	2.03

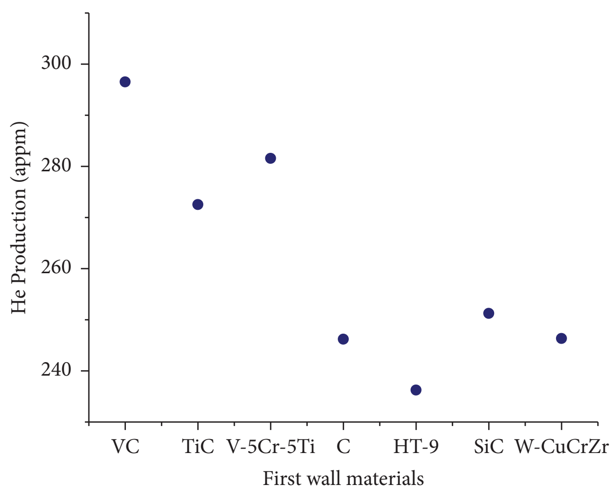


Figure 13: Helium production in each candidate FW materials.

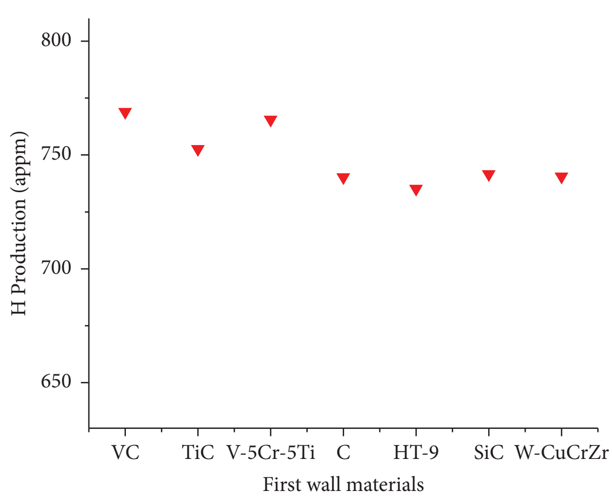


Figure 14: Hydrogen production in each candidate FW materials.

the material surrounding the fusion chamber. Both gases are also produced through reactions, including neutrons. In general, hydrogen production is higher in fusion structures than helium production. Due to the cross-section of (n, p), being low, the threshold energy (n, p) is lower than the threshold energy of alpha (n, α).

Helium production in FW, from Figure 13, indicates material damage due to the incoming neutron flux. The most significant gas production in this investigation occurs in graphite which will cause gas bubbles to occur in its structure. It will have an impact on reducing material resistance. According to the reference, the acceptable helium gas production in the material is around 6000–20000 appm (Duderstadt, 1982) [39]. So that even the highest helium production in vanadium alloy is still acceptable.

Another gas production that should be considered is hydrogen, and the calculation results for hydrogen gas production in FW are shown in Figure 14. It is clear that the amount of H production is much more significant than that of helium. This is due to the higher cross section for the H-production reaction than for helium. Most of the H-production in all of the investigations is almost similar. Due to the diffuse out of H-production transportation through metal, it can be avoided in material lifetime calculation.

5. Conclusion

In this research, neutronic analysis on FW of the blanket fusion reactor employs a neutron source with 14.1 MeV energy to investigate tritium breeding capability in the blanket reactor. In this simulation, the blanket utilizes helium as a coolant in the breeding zone and Eurofer97 as a structural material. Some materials have been investigated for application as FW by considering characteristics such as high neutron fluence capability, low degradation under irradiation, and high compatibility for blanket material. A three-dimensional simulation by MCNP5 has been conducted to investigate the neutronic performance and radiation damage effect. The novelty of this study invented the vanadium alloy (V-5Cr-5Ti), a promising material candidate in the FW material of the HCLL blanket. V-5Cr-5Ti has the highest number of 1.27 in TBR and 1.26 in multiplication energy factor in all investigations. Meanwhile, the amount of atomic displacement, hydrogen production, and helium production are around 22.31 appm, 765.55 appm, and 281.57 appm, respectively. It is still below any threshold number for material damage. So, it is considered suitable material for FW. Nevertheless, this alloy can replace after 13.45 years for radiation damage.

Data Availability

The data that support the findings of this study are available from the corresponding author, Prof. Zaki Su'ud, upon request The data are not publicly available due to their containing information that could compromise the privacy of research participants.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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