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Transmutation and induced radioactivity of W in the armor and first wall of fusion reactors

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Abstract

The transmutation and induced activity of W in the armor and first wall of a fusion reactor were calculated for various blanket compositions, taking account of multiple step reactions. Neutron spectra calculated with ANISN showed that the flux of low energy neutrons at both armor and first wall using water coolant is fairly high compared to liquid Li, He gas and FliBe coolants. About 4% of W transmutes to Re for the W armor of all blankets after 10 MWy/m^2 irradiation and is not affected by the difference in blanket composition. On the other hand, W in the first wall substantially transmutes to Re followed by Os for the water cooled blanket. For the longer irradiation, W was predicted to transmute to Os base alloy. The induced activity of the W armor is hardly influenced by the neutron spectrum. The formation of ^{186m}Re and ^{186}Re controlling the induced activity of the armor for long cooling times is not significant from the viewpoint of the safety level.

1. Introduction

Interaction between materials and fusion neutrons causes compositional change of materials, helium and hydrogen gas production, and induced radioactivation as well as displacement damage. Tungsten is a promising armor material and main alloying element in reduced activation ferritic steels which are candidate blanket structural materials. However, W was reported to change to Re and Os in HFIR and FFTF [1] and has been predicted to heavily transmute under the fusion neutron irradiation [1–3]. The extent of the transmutation of W is much affected by neutron spectrum [1]. In order to simulate the compositional change of W in the armor and first wall in fusion reactors, it is necessary to know the spectrum which depends on the composition of the blanket materials. Furthermore, in addition to the availability of sufficient nuclear data, a simulation calculation treating multiple step reactions must predict the compositional change with a high accuracy [1]. In the present paper, the effect of various blanket compositions on the transmutation and induced radioactivity of W for the armor and first wall are examined.

2. Calculation procedures

2.1. Reactor designs and neutron spectra

The neutron spectrum calculation was made using ANISN for the ITER inboard structure design [3]. The main structures are composed of a W armor of 2 cm, first wall of 1.5 cm, blanket/shield of around 150 cm, SUS 316 vacuum vessel, super-conducting magnet, and liquid helium vessel. In the present study, only the composition of blanket/shield materials was changed maintaining configuration and dimensions of a fusion reactor.

Table 1 shows several combinations of blanket/shield materials examined in the present study. ITER originally adopted the blanket(SUS blanket) made with stainless steel, Li_2O enriched in ^{6}Li, Be and water, and the shield materials made with stainless steel and water. In RAF(reduced activation ferritic steel) blanket, SUS316 was replaced by 9Cr–2W steel. For FliBe blanket, 9Cr–2W steel, LiF–BeF_2, and B_4C are used as the blanket materials. V blanket was one option for ITER where

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Table 1
Material composition of several blamket and shield designs

	Region	Thickness (cm)	Outer radius (cm)	Composition (vol. fraction)
SUS	Armor	2.0	197	W
	First Wall	1.5	198.5	SS 0.7 + H_2O 0.3
	Blanket	19.5	218.0	SS 0.05 + Li_2O 0.1575 + Be 0.4725 + H_2O 0.05 + He 0.1
	Shield 1	15.0	235.0	SS 0.9 + H_2O 0.1
	Shield 2	13.0	248.0	SS 0.95 + H_2O 0.05
RAF	Armor	2.0	197	W
	First Wall	1.5	198.5	9Cr2W 0.7 + H_2O 0.3
	Blanket	19.5	218.0	9Cr2W 0.05 + Li_2O 0.1575 + Be 0.4725 + H_2O 0.05 + He 0.1
	Shield 1	15.0	235.0	9Cr2W 0.9 + H_2O 0.1
	Shield 2	13.0	248.0	9Cr2W 0.95 + H_2O 0.05
FLiBe	Armor	2.0	197	W
	First Wall	1.5	198.5	9Cr2W 0.7 + $LiFBeF_2$ 0.3
	Blanket	19.5	218.0	9Cr2W 0.2 + $LiFBeF_2$ 0.7 + Be 0.1
	Shield 1	15.0	235.0	9Cr2W 0.7 + B_4C 0.3
	Shield 2	13.0	248.0	9Cr2W 0.7 + B_4C 0.3
V	Armor	2.0	197	W
	First Wall	1.5	198.5	V5Cr5Ti 0.7 + Li 0.3
	Blanket	19.5	218.0	V5Cr5Ti 0.02 + Li 0.76 + Be 0.22
	Shield 1	15.0	235.0	V5Cr5Ti 0.13 + Li 0.87
	Shield 2	13.0	248.0	V5Cr5Ti 0.46 + Li 0.54
SiC	Armor	2.0	197	W
	First Wall	1.5	198.5	SiC 0.7 + He 0.3
	Blanket	19.5	218.0	SiC 0.25 + Li_2ZrO_3 0.14 + Be 0.56 + He 0.05
	Shield 1	15.0	235.0	SiC 0.56 + B_4C 0.24 + He 0.20
	Shield 2	13.0	248.0	SiC 0.665 + B_4C 0.285 + He 0.05

V–5Cr–5Ti was considered as the first wall and liquid lithium was used as breeder and coolant. SiC blanket is composed of SiC, Li_2ZrO_3, Be and He gas.

The nuclear data library used, with, respectively, 42 and 21 energy groups of neutron and gamma ray, was FUSION-40 [4] based on JENDL-3. The calculation was made with scattering order of P5 and angular quadrature order of S8.

2.2. Transmutation and induced activity calculation

Transmutation and radioactivity calculations were conducted using the IRAC-3 code on the basis of the neutron spectra obtained by ANISN. In the calculation, primary reactions with a cross section larger than 1 mbarn were treated. For the subsequent step reactions, reactions whose cross section is >10 mbarn and in addition the cross section for the primary transmutation is >10 mbarn, were considered. In case of pathways producing long half-lived radioactive nuclides such as ^{186m}Re, ^{192m}Ir and ^{193}Pt, reactions were examined independently of the cross section size.

In Fig. 1 reaction chains for ^{186}W calculated in the present study are shown as an example. Nuclear data with 42 energy groups used for the transmutation calculation were JENDL-3 [5] and FENDL-1.1 [6]. Relevant nuclear data on the formation of meta-stable radioactive nuclides and the reaction of radioactive nuclides are adopted from JENDL-3 and FENDL-1.1, respectively. The neutron wall loading was assumed to be 1 MW/m^2.

3. Results and discussion

3.1. Transmutation of W armor and W element in the first wall

Figs. 2 and 3 show the neutron spectra at the armor and first wall, respectively, for various blanket/shield compositions. As seen in these figures, the neutron flux at low energy regions is higher for SUS or RAF blankets than others. This is mainly caused by the water coolant. There is almost no difference in neutron spectrum between SUS and RAF blankets. In FliBe, SiC and V blankets, the sharp decrease of the neutron flux is observed with decreasing neutron energy. Furthermore, in all blanket systems the neutron flux at low energy regions is bigger in first wall than in armor.

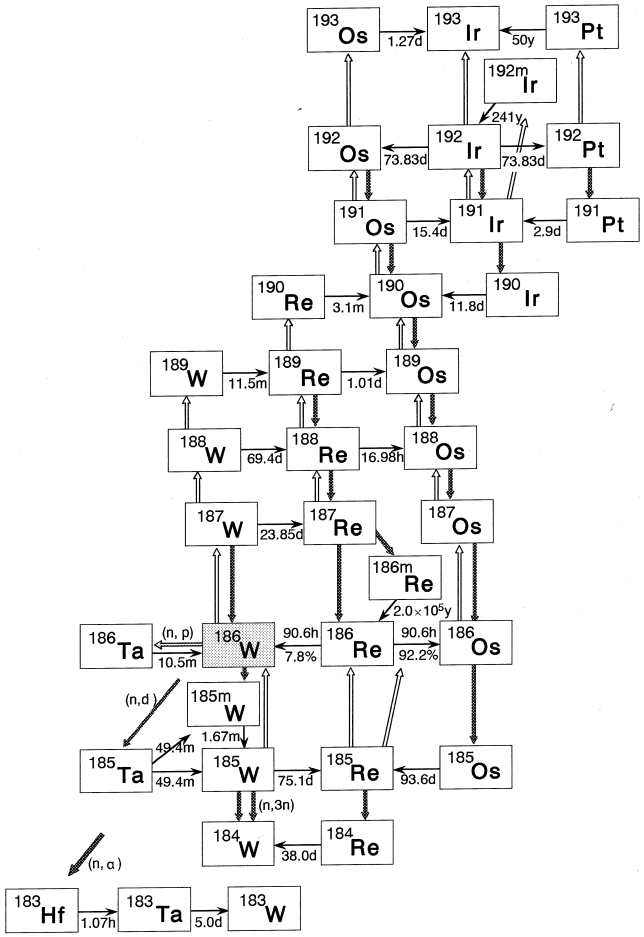

Fig. 1. Reaction chains of ^{186}W.

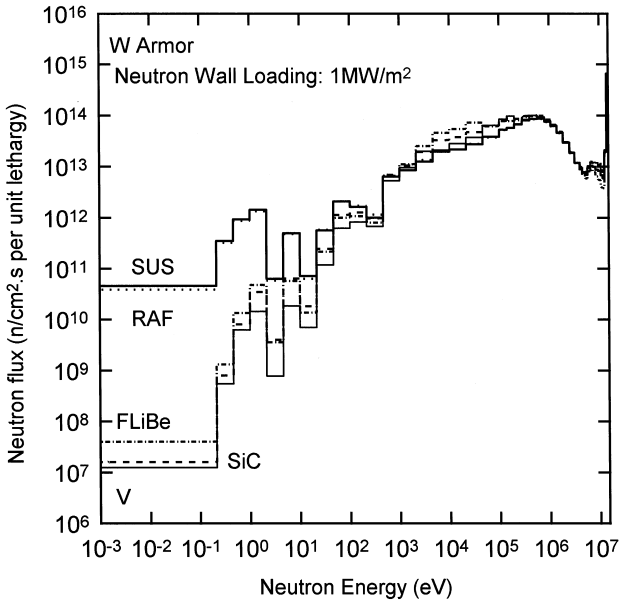

Fig. 2. Neutron spectra at the W armor for various blankets.

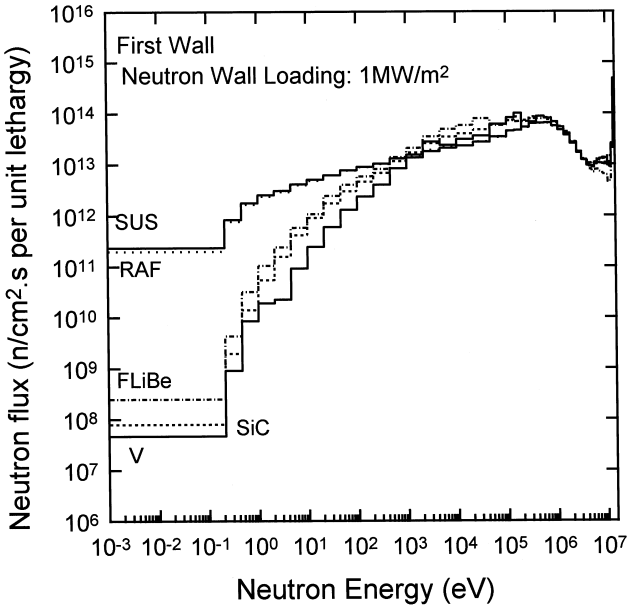

Fig. 3. Neutron spectra at the first wall for various blankets.

Using these neutron spectra, transmutation of W was calculated. In the case of first wall, RAF and FLiBe systems were examined where 9Cr–2W steel containing W is used as a blanket structural material.

Figs. 4 and 5, respectively, show transmutations of W in the armor and first wall as a function of neutron fluence. The concentration change of elements in first wall is represented relative to the initial W concentration in the 9Cr–2W steel. In these figures, the dpa are also indicated. The damage rates for W are 5.21 and 3.86 dpa per 1 MWy/m^2, respectively, at the armor and the first wall.

A slight decrease in W content is observed for the W armor with increasing neutron fluence. Re, Ta and Os increase with the fluence. On the other hand, there is substantial transmutation of W at the first wall position. Re exceeds W in concentration at around 30 MWy/m2 (115 dpa) as shown in Fig. 5. After further irradiation,

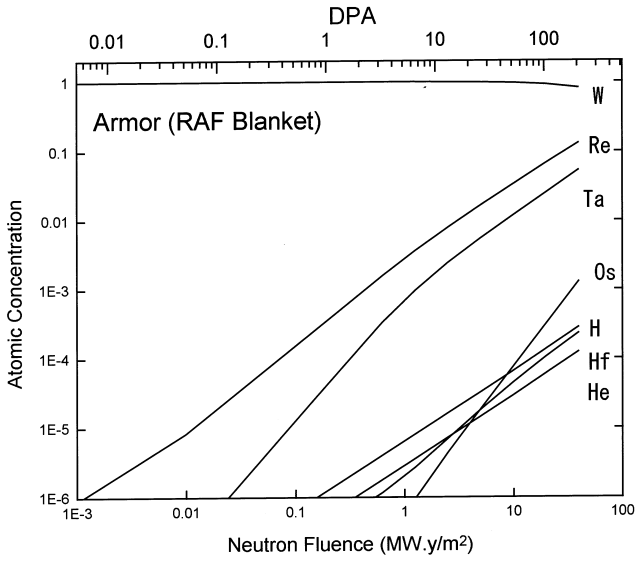

Fig. 4. RAF Blanket: W transmutation in the armor as a function of neutron fluence.

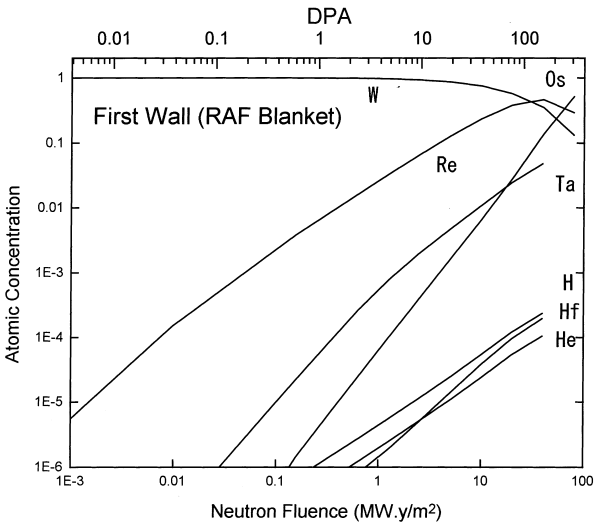

Fig. 5. RAF Blanket: W transmutation in first wall as a function of neutron fluence.

the Os content becomes so high that W is expected to change to Os alloy, from the trend of concentration change with the fluence shown in Fig. 5.

The effect of neutron spectrum on the compositional change of W was examined for various blanket/shield systems.

Table 2 shows the transmutation of W in the W armor and the first wall of 9Cr–2W steel for different blanket/shield systems after 10 MWy/m^2 irradiation. The fluences correspond to 52.1 and 38.6 dpa for W in armor and first wall, respectively. The calculation for W transmutation in the 9Cr–2W was only made for RAF and FLiBe blankets since other blanket first wall materials do not contain W.

The W armor was not heavily transmuted for 52.1 dpa and about 5% of W changed to Re and Ta. As seen in this table, there is no clear difference in transmutation of the armor between different blankets. On the other hand, W in first wall presents a remarkable transmutation to Re, Os and Ta in spite of lower dpa than that of the armor. In the case of RAF blanket where water is used as a coolant, about 24% of W transmutes to Re while the concentration of Re is about 9.5% for the FLiBe blanket where neutron fluxes with energies below 1 keV are lower than in the RAF system.

Natural W is composed of ^{180}W (0.135%), ^{182}W (26.4%), ^{183}W (14.4%), ^{184}W (30.6%), and ^{186}W (28.4%). In all W isotopes, main reactions with a large cross section are the (n, γ) and (n, 2n) for secondary and further step reactions shown in Fig. 1. In particular, the cross section of (n, γ) is larger than several barns below 100 keV of neutron energy. That is, transmutation due to neutron capture is accelerated if the flux of low energy neutrons is high. On the other hand, (n, 2n) becomes dominant above around 1 MeV neutron energy. Since the integrated cross section of (n, γ) is higher than that of (n, 2n), W tends to transmute to Re followed by Os.

Furthermore, W is predicted to transmute to Os for the heavy neutron irradiation since Os has many stable isotopes. In the present irradiation conditions, it is found that the amounts of Ir and Pt formation for both armor and blanket first wall can be neglected up to about 500 dpa.

Table 2
Compositions of W in the armor and first wall for various blankets after 10 MWy/m^2 irradiation (at.%)

W armor									
	W	Re	Os	Ta	Hf	Ir	Pt	He	H
RAF	95.4	3.38	7.69×10^{-3}	1.19	4.51×10^{-3}	2.77×10^{-12}	4.05×10^{-15}	2.94×10^{-3}	6.62×10^{-3}
FLiBe	95.3	3.51	1.38×10^{-2}	1.17	4.48×10^{-3}	2.27×10^{-11}	5.75×10^{-14}	2.94×10^{-3}	6.60×10^{-3}
V	95.8	2.98	7.47×10^{-3}	1.18	4.51×10^{-3}	3.83×10^{-12}	7.21×10^{-15}	2.91×10^{-5}	6.55×10^{-3}
SiC	95.5	3.30	1.05×10^{-2}	1.15	4.36×10^{-3}	5.74×10^{-12}	1.07×10^{-14}	2.80×10^{-3}	6.30×10^{-3}
W in 9Cr–2W first wall									
RAF	74.6	23.5	0.66	1.09	3.81×10^{-3}	3.57×10^{-9}	2.62×10^{-11}	2.40×10^{-3}	5.41×10^{-3}
FLiBe	89.5	9.52	9.19×10^{-2}	0.85	3.18×10^{-3}	3.57×10^{-10}	1.69×10^{-12}	2.05×10^{-3}	4.61×10^{-3}

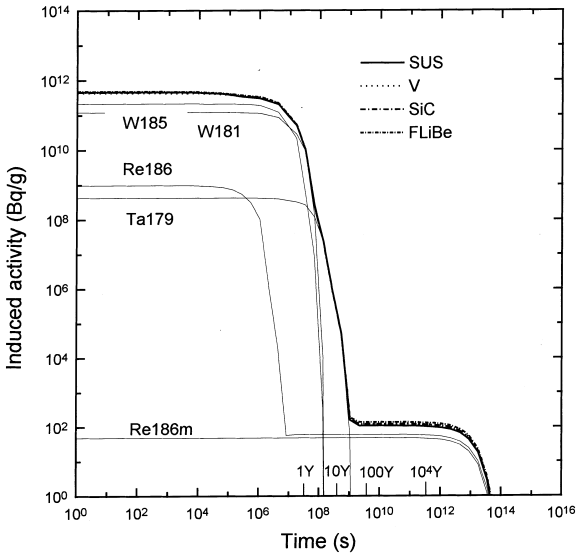

Fig. 6. Decay behavior of the induced radioactivity of W armor after 10 MWy/m^2 irradiation. The contribution of main nuclides to the radioactivity of W for the RAF blanket is indicated in the figure.

3.2. Induced radioactivity of W armor

The induced activation calculation was made for the W armor with various blanket systems.

Fig. 6 shows the decay behaviors of the induced activity of W armors after 10 MWy/m^2 (52 dpa) irradiation. Main nuclides contributing to the decay behavior for the RAF blanket are also indicated. At early stage of the cooling, ^{185}W and ^{181}W are main nuclides. For the longer cooling, ^{186m}Re (2.0×10^5y) and ^{186}Re (90.6h) which is produced by decay of ^{186m}Re, are controlling nuclides of the induced activity. The contributions of ^{192m}Ir (241y) and ^{193}Pt (50y) are not obvious under the present irradiation conditions. As seen in Fig. 6, the difference in blanket composition does not affect the induced activity in the same way for the first wall materials [7]. The activity level sharply decreases after cooling at around several years and reaches 100 Bq/g within 100 years. In general, the activity level defined as a natural radioactive nuclide is 370 Bq/g [8]. The activity of the W armor is therefore considered to be sufficiently reduced if it is cooled for 100 years. The activity level of 100 Bq/g mainly due to ^{186m}Re and ^{186}Re corresponds to the dose rate of about 0.04 μSv/h considering the wall size of 1 cm × 1 m^2. This level is low enough to satisfy 10 μSv/h for hands-on maintenance [3]. That is, the activity due to ^{186m}Re and ^{186}Re produced in the W armor is not so significant. Since W is considered to be used as an alloying element for the first wall, the induced activity of W itself at the first wall was not examined in the present study.

4. Conclusion

The effect of the difference in composition of blanket and shield materials on the transmutation and induced activity of W in the armor and first wall of a fusion reactor was examined. The armor and the first wall were assumed to be, respectively, pure W and 9Cr–2W steel in RAF and FLiBe blankets. The following conclusions are drawn:

1. The neutron spectrum at both armor and first wall is affected by the blanket composition. The flux of low energy neutrons increases when water is used as a coolant.
2. The transmutation of the W armor does not depend on the blanket composition. About 4% of W transmutes to Re after irradiation of 10 MWy/m^2 (52.1 dpa for W).
3. Substantial transmutation of W in the 9Cr–2W steel at the first wall with water coolant occurs. W is predicted to transmute to Os base alloy for the longer irradiation.
4. Induced activity decay behavior of the W armor is hardly affected by the difference in blanket composition.
5. The formations of ^{186m}Re and ^{186}Re controlling the long term induced activity of the armor are not significant from the viewpoints of safety activity level.

References

[1] L. R. Greenwood, F.A. Garner, J. Nucl. Mater. 212–215 (1994) 634.
[2] C.B.A. Forty, G.J. Butterworth, J.-Ch. Sublet, J. Nucl. Mater. 212–215 (1994) 640.
[3] T. Noda, M. Fujita, J. Nucl. Mater. 233–237 (1996) 1491.
[4] K. Maki, K. Kosako, Y. Seki, H. Kawasaki, Nuclear group constant set FUSION-J3 for fusion reactor nuclear calculations based on JENDL-3, JAERI-M 91-072, 1991.
[5] Y. Seki, H. Iida, H. Kawasaki, Graphical representation of transmutation and decay chain data, Transmutation Cross Section and Delayed Gamma Ray Emission Data, JAERI-1280, 1982.
[6] A. Pashchenko, P. Maclauglin, IAEA-NDS-148 Rev. 1, 1993.
[7] T. Noda, J. Nucl. Mater. 233–237 (1996) 1475.
[8] The low concerning prevention from radiation hazard due to radioisotopes, Japanese Low No. 167, 1957.