Tritium Retention in Plasma Facing Materials

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In the next step D/T fusion device, the accurate predictions of tritium retention in Plasma Facing Component is important both from the point of view of the safety and the physics performance.

However, for reliable prediction of T-retention, a detailed knowledge and understanding on the mechanisms, which are responsible for T-retention is essential. The mechanisms are quite complex, for example, in fusion devices; the PFC is in contact with plasma and PFC surface exposed to large flux of ion and neutral particles. The large flux of ions may be retained in the PFC materials by implantation in the depth of ion range, the particles will diffuse to the bulk of materials and eventually, the particles are trapped. In addition, the ion and neutral particles cause the sputtering of surface. The sputtered particles are ionized in plasma and redeposited somewhere on the surface within the fusion devices. The sputtering and deposition lead to T-retention via co-deposition.

After a decade experimental investigation and theoretical study on D/T plasma wall interaction, D/T transport in materials as well as neutron effects, the progress on understanding of the complex of T-retention is significant, so that the prediction of T-retention can be performed more accurate.

In this paper, a detailed analysis on the mechanisms of tritium retention has been performed, based on:

1. Tritium retention via implantation,
2. Tritium retention via bulk diffusion,
3. Tritium retention via neutron transmutation,
4. Tritium retention via co-deposition,
5. Tritium retention via neutron damage induced trapping sites
6. Tritium retention in dust and flakes,

Keywords: tritium, plasma facing materials, implantation, co-deposition, neutron effects

I. Introduction

The characteristics of tritium retention and release of plasma facing materials are extremely important from an environmental, safety, economical and plasma density control point of view.

As next step fusion devices, i.e. the International Thermonuclear Experimental Reactor (ITER), unlike present tokamaks devices, will be long pulse, high heat flux, higher PFC temperature and they will produce intensive neutron fluxes. Substantial R & D is still needed to elucidate the influences of long pulse, high heat flux, high target temperature and intense neutron on PFC tritium retention and eventually on the total tritium in the devices.

The present fusion devices with short pulse (< 20 second), and low target temperature, the tritium retention will be dominated by implantation, whilst the bulk diffusion will be the major mechanism of tritium inventory for next step devices with long pulse ~1000 seconds and higher target temperature >350 ˚C. The bulk retention will contribute significant to total tritium inventory. Erosion and redeposition of PFC during normal and off-normal operation caused tritium retention via co-deposition of tritium in plasma and redeposited particles, which based on present knowledge, will play also dominant role.

Intense neutron will induce damage on the microstructure and critical properties of PFC materials[1,2] e.g. thermal conductivity, swelling and consequently the behavior of tritium trapping will be changed. Depending on neutron damage, they could limit the utilization of PFC materials in the next step fusion devices. The another issue is tritium production by neutron reaction (transmutation) with PFC materials, which, depending on PFC materials, may be significant.

The other important mechanism is tritium retention in dust or flakes. During the normal operation, the PFC will be sputtered by plasma and re-deposition occurred and dust is formed at PFC surface. Flakes are formed during the off-normal events; e.g. disruption, ELMs or run-away electrons by peel-off of layers over saturated with hydrogen isotope.

In this paper, a detailed analysis on the possible mechanisms of tritium retention has been performed and relevance of results is discussed.

II. Results of analysis

II.A. Implantation

The tritium retention via implantation is special relevant to present tokamak device, because it is short pulse machine and low PFC temperature. The most of particles are stopped at the depth of ion range, which is dependent on impinging particle energy. After the implantation there is almost no further diffusion to the bulk. At the relevant energy for next step PFC ($\leq$ 200 eV), the ion range D into beryllium or carbon is around 5-10 nm. The saturation level of retention is a function of energy and target temperature. Database is very well established. Fig. 1 and Fig. 2 show the ion range of D into Be and carbon as a function of ion energy[3]. It is seen that the two low Z materials behave very similar. The total amount of retention via implantation is proportional to the fluency and impinging particle energy.

II.B. Retention via bulk diffusion

In the next step fusion devices, the operation conditions will be significantly different from the present tokamaks: long pulse ~500-1000s, or steady state operation, higher target temperature (because of higher heat loading $\geq$ 10 MW/m^2). Therefore, the role of bulk diffusion will make an important contribution to total tritium retention. The diffusivity D (cm^2/s) is expressed as : $D = D_0 \exp(-E_d/RT)$, where D_0 is pre-exponential factors and E_d is the activation energy. The total amount of retention via bulk diffusion is correlated to the solubility of materials which is expressed as $S = K_s P^{1/2}$ where K_s is Sieverts constant and $K_s = K_{s0} \exp(-E_s/RT)$. K_{s0} (at. fr. Pa$^{-1/2}$) is a pre-exponential factor, Es is

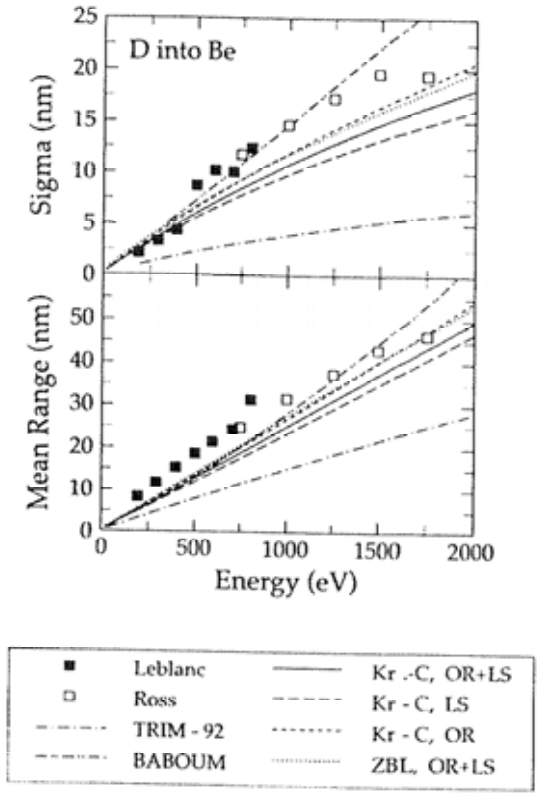

Fig.1 Mean ion ranges of deuterium in beryllium

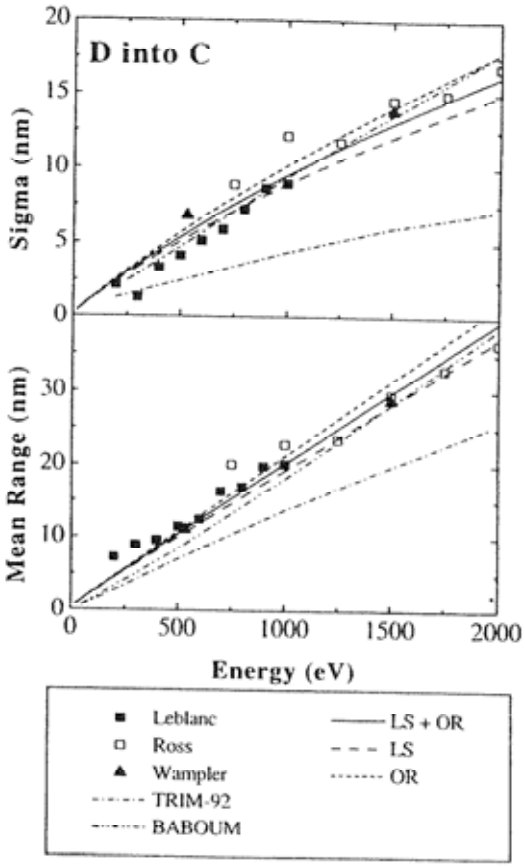

Fig.2 Mean ion ranges of deuterium in carbon

heat of solution. In general, the lower the temperature, the higher the retention via solution. However, at low temperature, the expected diffusivity is low, the time needed to reach the saturated values is longer. At a target temperature lower than 1600 K, the bulk saturation has not been reached even the exposure time as long as 10^8 seconds, because the low diffusivity of H-isotope in carbon based materials. Whilst the saturation value of retention in beryllium has been reached even after only 10^3 seconds, because of the high diffusivity.

II.C. Tritium retention via neutron transmutation

In the next generation fusion devices, i.e. the International Thermonuclear Experimental Reactor (ITER) will produce intense neutron fluxes via D-T reaction, which react with wall materials and may produce tritium, depending on concentration and target temperature, tritium will retain in the bulk of wall materials. For example, at present design of ITER, Be will be the first wall material. Several nuclear reactions contribute the tritium production, and depending on reaction time, the role of each reaction is significant different. In the first 24 hours, the $^9Be(n,t)^7Li$ reaction contributes more than 99.85% of total tritium production, the reaction $^9Be(n\alpha)^6He(\beta)^6Li(n,\alpha)t$ is dominant after 3 years. The contributions of all reactions as a function of reaction time are given in Table 1. The total tritium production via transmutation in ITER Be first wall as a function of reaction time is given in Table 2. It is seen, that the tritium production in Be first wall via transmutation can be as much as 1.5 kg (for the case: Be first wall: 1000 m^2 area, 1 cm thick)

II.D. Tritium retention via co-deposition

During the normal operation in fusion devices, the surface of wall materials will be sputtered constantly by bombarding with plasma (mainly D, T ions). During the deposition of the sputtered particles of C, Be will be co-implanted with plasma, which leads to tritium retention. Depending on target temperature or oxygen concentration in plasma (particular for beryllium) [4,5,6]. The retention can be as high as D/C= 0.4 and D/Be = 0.37 at 300 K. Fig. 3 show the D/T retention via co-deposition as a function of target temperature and oxygen concentration. Most recent result shows, that there is no deposition (co-deposition) by sputtering of carbon by plasma, at target temperature $\geq$ 100 C.

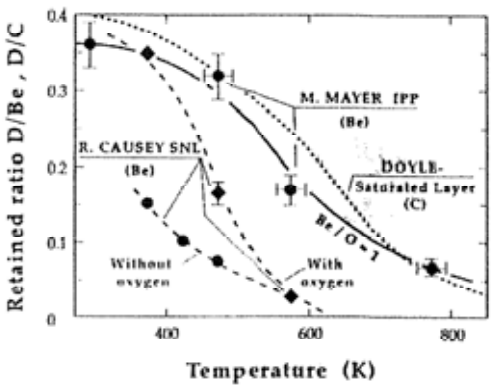

Fig. 3 D/T retention via co-deposition

Reaction	Reaction Time				
	24 h	1a	2a	3a	5a
$^9Be(n,t)^7$ Li	99,85	66,87	52,57	44,60	35,92
$^9Be(n,\propto)^6He(ß)^6Li(n,\propto)t$	-	31,95	44,88	50,30	54,77
$^9Be(n,X)t(ß)^3He(n,p)t$	-	0,88	1,96	2,8	4,38

Table 1 Tritium Production via Neutron Transmutation (%)

	Reaction Time			
	24 h	115.74 d (1.10^7 Sec)	1a	3a
Tritium (g)	0.675	90.624	360.838	1544.440

Table 2 Tritium Production in The ITER Be First Wall (1000m^2, 1 cm thick)

Material	Loading atmosphere		Loaded Tritium	
			Not irradiated	irradiated
Be	H_2 + 5 ppm T_2, 2 bar, 850 ºC, 6-7 h	(Bq/g) (T/Be)	~ 1 x 10^6 ~ 0.8 x 10^{-8}	~ 3 x 10^7 ~ 2.5 x 10^{-7}
	T_2, 2 bar, 850 ºC, 6-7 h	(T/Be)	~ 1.6 x 10^{-3}	~ 5 x 10^{-2} (~ 10000 appm)
Graphite	T_2, 0.8 bar, 850 ºC, 10 h	(T/C)	~ 1 x 10^{-4} (100 appm)	~ 1 x 10^{-3} (~ 1000 appm)

Table 3 Neutron induced tritium trap sites in carbon and beryllium

II.E. Tritium retention via neutron damage induced trapping sites

In several studies on the effects of neutron induced damage on the tritium retention have shown, that the neutron damage on wall materials (C, Be) will increase the tritium trapping sites. The tritium retention increases with increasing of neutron damages. Fig. 4 shows the tritium retention as a function of neutron damage and irradiation temperature. It is seen, almost independent on irradiation temperature, at a damage of 0.5 dpa, a saturation value of 1000 appm has been reached for carbon, whilst a saturation value of beryllium is 10000 appm. The comparison on the neutron damage induced tritium trapping sites in C and Be is given in Table 3. It is clear, under same neutron irradiation conditions, the neutron damage induced tritium trapping sites in Be is almost one order of magnitude higher than that of in carbon [7,8].

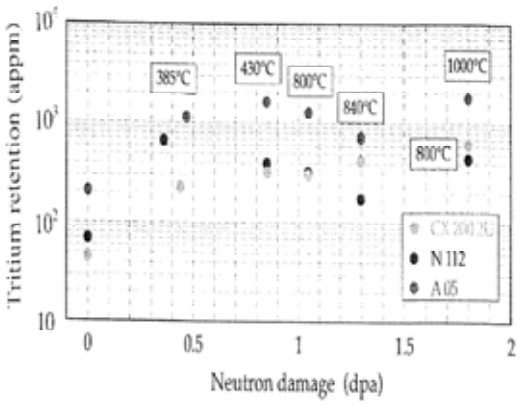

Fig. 4 T-retention as a function of neutron damage

II.F. Tritium retention in dust and flakes

Dust and flakes are formed either by sputtering at normal operation or at off-normal operation, i. g. disruption, run-away electron events. The results of a systematic study show, that the tritium retention in dust decreases with increasing particle size, and also decreases with increasing temperature. The tritium retention in dust as a function of particle size and temperature is given in Table 4. The results of detailed study on dust formation in JET showed, that average particle size of dust is about 27 μm [9,10].

Tritium pressure ≈ 3.5 x 10^{-3} Pa
Exposure time ≈ 1.0 x 10^5 s

Size (μm)	BET (m^2g^{-1})	25 °C	600 °C	800 °C
4.5	36.7	1.54	6.11	3.22
20	15.9	0.45	1.7	0.83
80	11.1	0.35	1.6	1.1

Table 4 Experimental investigation of T-retention in dust as a function of particle size (BET) and temperature (Tritium retention in carbon dust mg/kgC)

III. Conclusions

In this paper, a detailed analysis on the mechanisms of tritium retention in plasma facing materials has been performed.

The tritium retention via implantation is a dominant mechanism for present tokamak device, because the low wall temperature and short pulse operation. In addition, the D/T retention in flakes may be important, depending on plasma condition. However, as next generation devices, i.e., the International Thermonuclear Experimental Reactor (ITER) will produce intense neutron fluxes, the temperature of plasma facing components is high, long pulse or steady state operation, the mechanisms of retention fusion devices are a complex. The bulk diffusion, neutron damage induced trapping sites, co-depositions will play dominant role and contribute major fraction to total tritium inventory.

Acknowledgements

The author would like to thank A. T. Peacock, W. Eckstein, J. Roth, H. Werle, A.A. Haasz, G. Fussmann for useful discussion and contribution in frame of EU fusion R & D Program.

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