

Hydrogen isotope retention of JT-60U W-shaped divertor tiles exposed to DD discharges

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Abstract

Deuterium (D) and Hydrogen (H) retention in carbon tiles exposed to DD and HH discharges in the JT-60U W-shaped divertor has been investigated by means of thermal desorption spectroscopy (TDS) and secondary ion mass spectrometry (SIMS). In the thick re-deposited layers on the outer divertor, hydrogen (H + D) was retained rather homogeneously with its concentration of 0.03 in (D + H)/C atomic ratio, which is attributed to the surface temperature rise above 900 K. Owing to the HH discharges performed after the DD discharges for tritium removal, H-dominated re-deposited layers were added on D-dominated re-deposited layers. In addition D retained in near surface layers were replaced by H both for re-deposited and eroded area. Accordingly deuterium concentration peaked at a little inside behind the H dominated surface layers for all tiles. The temperature increase during the discharge very likely causes the saturation of hydrogen retention even in the re-deposited layers. Accordingly the global wall saturation was observed in JT-60U.

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1. Introduction

In a DT fusion reactor, tritium inventory is one of the most important issues for safety [1,2]. Hence extensive studies of hydrogen retention in plasma

facing materials of current tokamaks have been conducted. Most of the present tokamaks employ carbon materials (graphite and carbon fiber composite (CFC)) [1]. Since, the carbon materials retain a large amount of hydrogen isotopes and eroded carbon re-deposits incorporating hydrogen isotopes to substantially increase hydrogen retention, large tritium inventory in the carbon wall

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would require frequent removal of the retained tritium.

It is well known that hydrogen isotope retentions in the carbon materials strongly depend on their temperature as observed in some tokamaks [3]. In order to estimate the tritium retention in ITER and future fusion devices, temperature dependence of the tritium retention above 500 K, ITER baking temperature, should be investigated. In previous papers [4,5], we have examined hydrogen retention in graphite tiles used in the open divertor of JT-60, which was operated with hydrogen only at above ~ 573 K, by means of thermal desorption spectroscopy (TDS), and found that the hydrogen retention in the carbon re-deposited layers on the tiles was as small as 0.03 in H/C atomic ratio.

JT-60 was upgraded to JT-60U changing the open divertor with the W-shaped divertor at 1997. Since then high power deuterium discharges with deuterium neutral beam injection (DD discharges) have been performed. We have been analyzing carbon tiles used in JT-60U under the joint research between Japanese universities and Japan atomic energy agency (JAEA) [6]. Different from JT-60

reported in the previous papers, JT-60U was usually operated by deuterium (D), and hydrogen (H) discharges were employed only for removing tritium produced by the DD reaction. This mixture of H and D could give us important information on D and T behavior in a future reactor. Therefore, we have made detailed analysis of retention characteristics of H and D in plasma facing carbon tiles used in JT-60U and the results are compared with those for JT-60. Taking profiles of re-deposition/erosion, heat load to the tiles and hence changes of surface temperatures during plasma discharges into account, the mechanism of incorporation of H and D in eroded and re-deposited carbon tiles in the W-shaped divertor region is discussed.

2. Experiments

Fig. 1 shows (a) a schematic illustration of the JT-60U W-shaped divertor with an inner pumping slot, and (c) poloidal distributions of the thickness of re-deposited carbon layers and/or the erosion depth, which was measured by a micrometer and scanning electron microscopy (SEM) after experi-

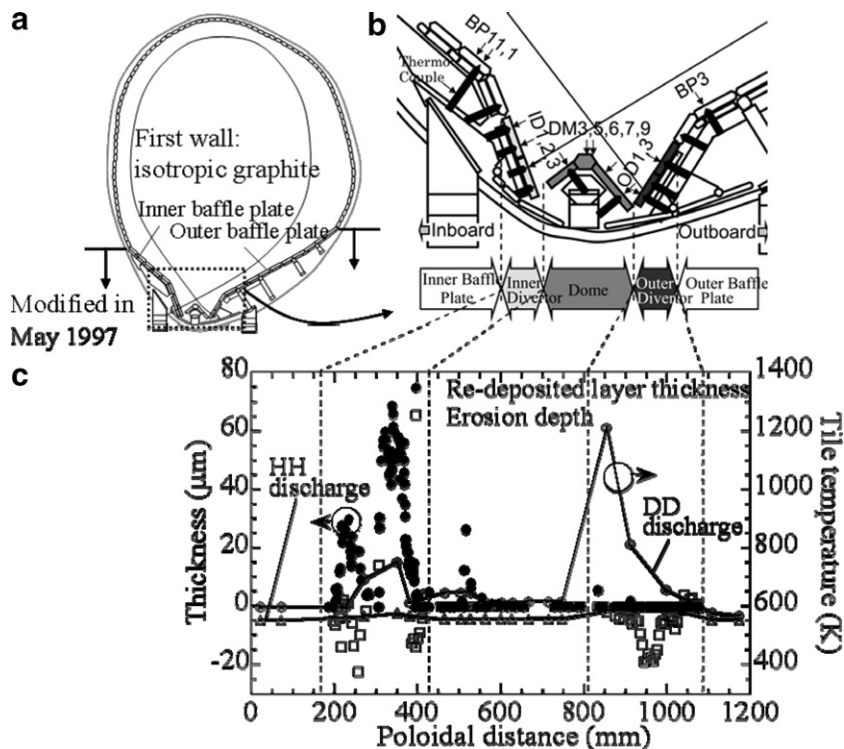


Fig. 1. Schematic view of JT-60U tokamak. (a) Cross-sectional view of JT-60U. (b) Schematic view of W-shaped divertor with inner side pumping slot and sampling points. (c) Poloidal distributions of re-deposition/erosion and maximum tile temperatures of divertor region during plasma discharges.

mental campaign of June 1997–October 1998 [7,8] and the maximum tile temperature measured by thermocouples embedded at 6 mm beneath the plasma facing surface during a typical NBI discharge [9]. All tiles in the divertor area exposed to high heat load were made of CFC; the divertor tiles were CX-2002U, Toyo Tanso Co. Ltd., the dome top tiles and the inner baffle plates were PCC-2S, Hitachi-chemical Co. Ltd. Tiles of the other area were made of graphite (IG-430U, Toyo Tanso Co. Ltd.). These tiles were exposed to ~ 3600 shots of DD discharges with the W-shaped divertor configurations with pumping slot at the inner divertor (inner side pumping). Among the DD discharges, 300 shots were heated by NBI with the power of 14–23 MW. Boronization was carried out two times during the experimental campaign of June 1997–October 1998. After the DD discharges, totally 700 shots of HH discharges were carried out in order to remove tritium retained in the tiles, which was produced by the DD discharges. The NBI power for the HH discharges was about a half of that for the DD discharges.

Usually the JT-60U vessel was kept at 573 K using a baking system. During a discharge, the tile temperature further increased owing to plasma heat load to the maximum appeared at the end of the discharge. The maximum temperatures observed at the inner divertor, the dome, and the outer divertor during the DD discharges were 750, 600 and 1200 K, respectively (see Fig. 1(c)). Based on these tile temperature profiles, the maximum surface temperatures of the respective area were estimated by Masaki et al. using the finite element modeling (FEM) analyses [9] as ~ 1000 , ~ 800 and ~ 1400 K.

Most area of the open divertor tiles of JT-60 was found to be deposition dominated as reported in the previous paper [5,7]. In JT-60U, the inner divertor tiles were re-deposited, whereas the outer divertor tiles were mostly eroded [7,8]. The maximum deposition thickness appeared at the inner divertor was 60–70 μm . The maximum eroded depth (20 μm) was found near the outer strike region. These positions were nearly the same to the most frequent hit points of the divertor legs for the inner and outer divertor. For the dome region, different from the divertor region, the inner dome wing was eroded, whereas the outer dome wing re-deposited.

In JT-60U, the averaged thickness of the re-deposited layers and erosion were ~ 27 μm and ~ 8 μm , respectively. Considering the total NBI heating time (1.2×10^4 s), the averaged deposition

rate was estimated to 2.3 nm s^{-1} . This value was a little smaller than that for the open divertor tiles of JT-60 but nearly the same to other tokamaks [8,9].

As indicated in Fig. 1(b), samples ($8 \times 8 \times 0.5 \text{ mm}^3$) were cut from the tiles including the top surface just above the thermocouples. The tiles from the baffle plates, the inner divertor, the dome and the outer divertor were referred respectively as BP, ID, DM, and OD samples, and were numbered as ID1, ID2, ... and so on from the inner side to the outer side. In order to estimate hydrogen retention in bulk, three samples were additionally prepared, two cut from the inner divertor and the outer divertor tiles of which re-deposited layers were mechanically removed (removed sample), and the other cut from the inside of the divertor tile (bulk samples).

A sample was put on a ceramic heater and heated from room temperature to 1273 K with a constant heating rate of 0.42 K/s and kept at 1273 K for 10 min for TDS analysis. The amount of the released gases from the sample was evaluated from partial pressure rises in the vacuum chamber measured by a quadrupole mass spectrometer (QMS) (scanning range: 1–55, scanning rate: 6–8 s/scan) multiplied by the pumping rates separately determined. Details of TDS measurements were reported elsewhere [5].

3. Results

3.1. TDS

The dominant species released from samples were H_2 , HD and D_2 . Various hydrocarbons with one carbon atom such as CH_4 , CHD_3 and CD_4 (denoted as C_1 hydrocarbons), with two carbon atoms, C_2H_4 , C_2H_6 , (C_2 hydrocarbons), three carbon atoms like C_3H_8 (C_3 hydrocarbons) and their isotopomers were released as minor species. Assuming all hydrocarbons being stable molecules, the amounts of hydrogen released as those hydrocarbons were evaluated using the fragmentation patterns of respective hydrocarbons in a literature [10]. Fig. 2(a)–(c) shows typical TDS spectra of H_2 , HD and D_2 for samples, respectively for (a) at the re-deposition dominated area in the inner divertor with the thickest re-deposited layers of 60–70 μm (ID3), (b) at the re-deposition dominated area with the lowest temperature on the outer dome wing (DM9), and (c) the most eroded area on the outer divertor (OD1). The largest desorption was found for the ID3 sample with

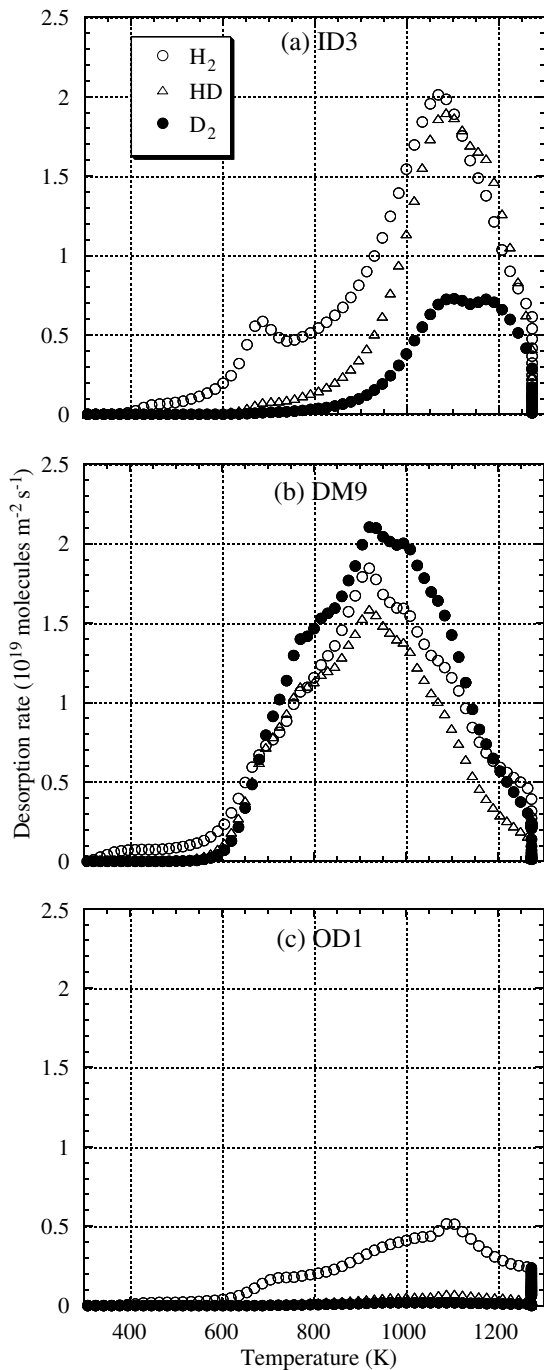


Fig. 2. TDS spectra of (a) inner divertor (ID3), (b) dome outer wing (DM9) and (c) outer divertor (OD1).

the maximum H₂ desorption rate (desorption peak) appeared at ~1070 K and those for HD and D₂ at a little higher temperatures. The DM9 sample (Fig. 2(b)) showed the lowest desorption peak temperature at ~930 K. The OD1 sample subjected to

the highest temperature of ~1200 K (Fig. 2(c)) showed the highest desorption peak at 1080 K.

Desorbed amounts of hydrogen isotopes as hydrogen isotope molecules and hydrocarbons, and the total amount of desorbed hydrogen isotope atoms and the ratio of the desorbed hydrogen isotopes (D/H ratio) for all samples are compared in Fig. 3. On the deposition dominated area at the inner divertor (ID1–3) and the outer dome wing (DM7–9), the total retention of hydrogen isotopes (H + D) were larger than those for the eroded area at the inner dome wing (DM3), the dome top (DM5, 6) and the outer divertor (OD1, 3). The largest retention (H + D) was observed at DM9 with 1.4×10^{23} atoms m⁻². This value is nearly the same as observed for the open divertor tiles exposed to HH discharges ($1\text{--}10 \times 10^{22}$ atoms m⁻²) which was reported on previous papers [5,7]. For the deposited area (the inner baffle and the inner divertor) except for ID3, the contribution of hydrocarbon on the total hydrogen release was nearly the same (around 30%), indicating the same hydrogen retention and desorption mechanisms in the re-deposited layers.

In the divertor region, the amount of H desorbed as H₂ molecules was the largest for ID3 at the re-deposited inner divertor with 3×10^{22} atoms m⁻², while the minimum of 8×10^{21} atoms m⁻² appeared for OD3 at the eroded outer divertor. Although HD desorption was similar to that for H₂, the difference of desorbed amount between the maximum and the minimum ($2 \times 10^{21}\text{--}2 \times 10^{22}$ atoms m⁻²) was a little larger than that for H₂. The largest release of D₂ (4×10^{22} atoms m⁻²) was observed for DM9, while the minimum for OD1 located at the outer divertor (4×10^{20} atoms m⁻²). The difference was as larger as a hundred times. The D₂ desorption for the samples at the inner divertor was smaller than those of H₂ and HD. The ratio of the total desorbed D atoms and H atoms (denoted as D/H ratio) was the largest for DM9 (D/H = 1.1) and the smallest (D/H = 0.1) for OD1 (see Fig. 3). All samples except DM3, DM7, DM9 and OD1, show nearly constant D/H ratios of 0.4. In Fig. 4, the amounts of the total desorbed H and D for all samples were compared. The figure clearly distinguishes the samples at the dome area and the others areas, with D/H of 1.6 for the dome samples while 0.47 for the other samples. The D/H ratio of the Bulk and Removed samples were much smaller than those of the plasma facing samples, indicating less penetration of D atoms into the bulk. Extrapolations of two linear relationships

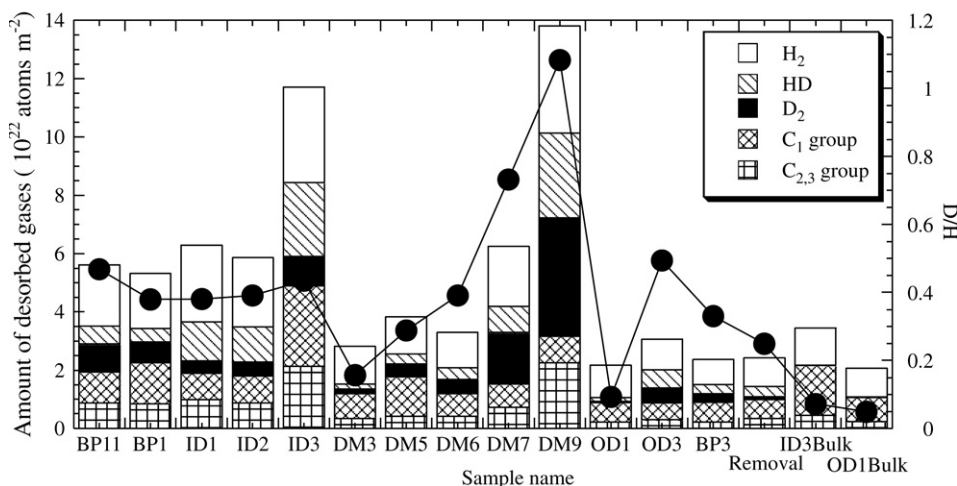


Fig. 3. Amount of released hydrogen isotopes as each chemical species and D/H ratio.

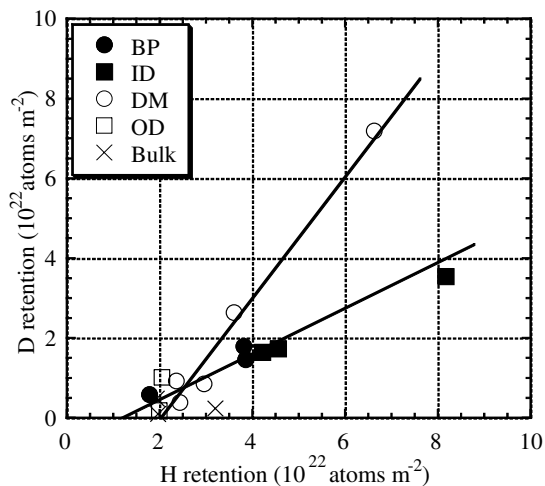


Fig. 4. Comparison of H and D retentions.

to zero retention of D give about 2×10^{22} atoms m^{-2} and zero for the H retention and the D retention, respectively. This is a clear indication of different retention mechanisms of H and D. Furthermore, the extrapolated H retention of 2×10^{22} atoms m^{-2} is very close to the H retentions in the removal and bulk samples. It is also important to note that the above D/H ratios were much smaller than the ratio of the number of DD discharges and HH discharges, which is about 5. This indicates that significant part of D retained during the DD discharge period must be replaced by H during the HH discharges succeedingly made, as discussed in the following section.

3.2. Depth profiles by SIMS

Fig. 5(a)–(c) shows typical depth profiles of H and D by SIMS for samples, respectively at (a) the deposited area in the inner divertor with the thickest re-deposited layers of 60–70 μm (ID3), (b) the deposited area with the lowest temperature on the outer dome wing (DM9), and (c) the most eroded area on the outer divertor (OD1). In the figures, SIMS intensities of negative ions of H^- and D^- are normalized by that of C^- . The profiles were limited to only 1.7 μm in depth and cannot be directly compared to the total hydrogen retention given by TDS. Nevertheless, the profiles give quite consistent information with TDS.

DM9 shows the highest surface H + D concentration (Fig. 5(b)). H retention was the highest at the surface and gradually decreased with depth, whereas D concentration significantly increased with depth, well corresponding to the highest D/H of DM9 in Fig. 3. It is interesting to note that H + D retention of ID3 (Fig. 5(a)) was the smallest in spite of large total H + D retention observed by TDS (see Fig. 3). Although ID3 showed a little high H concentration at the surface, the concentration decayed rapidly to a certain level. Both H and D kept nearly constant levels at deeper region. Considering the total H + D retention of DM9 being similar to ID3, (H + D)/C concentration in the thinner re-deposited layers must be larger than that in the thicker re-deposited layers of ID3, in accordance with the less temperature increase of DM9. For OD1 (Fig. 5(c)), H concentration peaked at

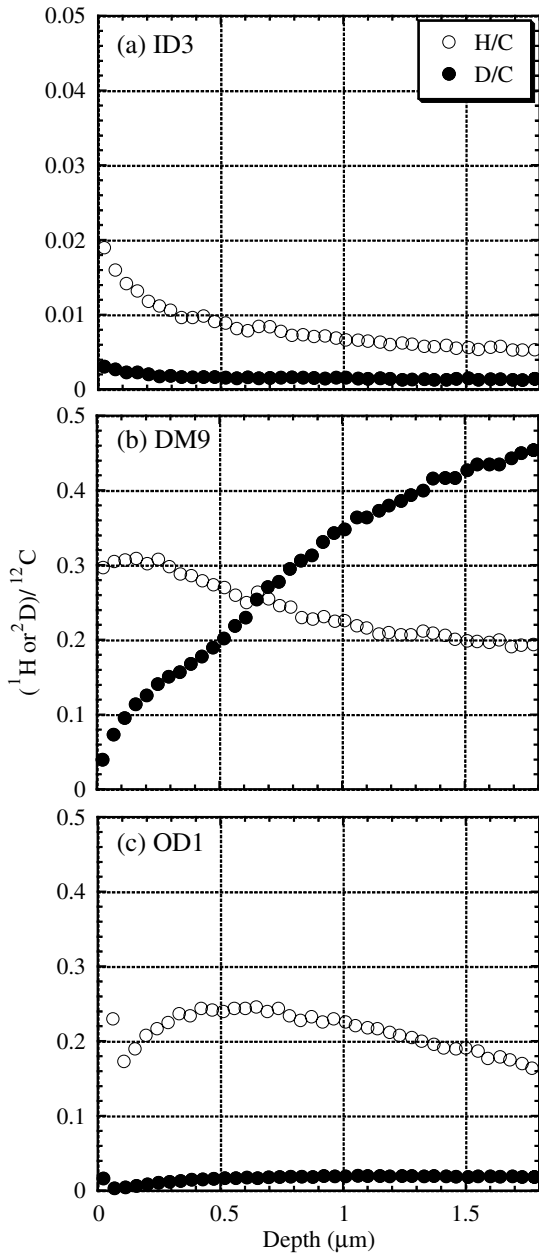


Fig. 5. Depth profiles of H and D measured by SIMS (a) ID3, (b) DM9 and (c) OD1.

the depth of 0.5 μm from the surface and D concentration seems peaked at deeper region. This suggests injection of energetic hydrogen and deuterium originated from NBI injection. In the previous work [9], significantly high tritium retention was observed at the dome area and attributed to direct injection of tritons produced by DD reactions. Similarly, some deuterons injected by NBI are most likely implanted

in the dome area without fully losing their initial energy.

4. Discussions

4.1. Analysis of TDS spectra in relation with depth profiles

On the open divertor tiles of JT-60, hydrogen was uniformly retained in the re-deposited layers [4,5]. Here we have also found the good linear relationship between the thickness of the re-deposited layers and the total hydrogen isotope retentions for the samples taken from of the re-deposition dominated inner divertor tiles as plotted in Fig. 6. This again suggests that except very near surface, both hydrogen isotopes were uniformly retained throughout the re-deposited layers, though the contribution of H on the total retention decreased with increasing the thickness. From the gradient of the lines in Fig. 6, the concentrations of hydrogen isotopes in the re-deposited layers on the inner divertor tiles were determined to be 0.032 in (H + D)/C atomic ratio. The value is nearly the same to that obtained for the open divertor tiles of JT-60 exposed to the HH discharges (H/C = 0.030) [4,5].

Since the depth profiles given by SIMS were limited only within 1.7 μm in depth, we discuss how H and D were retained in the thick re-deposited layers and the eroded areas from the detailed TDS spectra analysis in the following.

Generally, TDS spectra would reflect diffusion, detrapping and release kinetics like recombination. However, the diffusion coefficient of hydrogen in

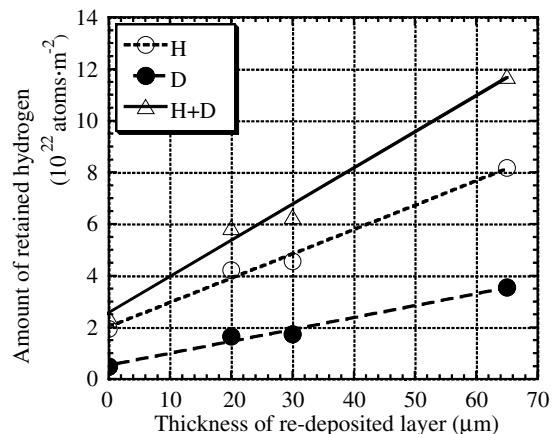


Fig. 6. Correlations of thickness of re-deposited layers and hydrogen isotope retentions of inner divertor samples.

bulk graphite is too small to allow atomic hydrogen to diffuse out below 1000 K [11]. Because of the porous nature of graphite, hydrogen in graphite recombines into H_2 or makes gaseous species like methane if hydrogen concentration is high enough, and these gaseous molecules can easily permeate through the pores to the surface during the TDS process. Thus, TDS spectra for hydrogen in graphite reflects formation processes of gaseous molecules, i.e. detrapping (desorption) energy of hydrogen in graphite as indicated in TDS experiments for H^+ and D^+ implanted graphite [12]. Hence TDS spectra were analyzed simply by the first order desorption kinetic, which has successfully applied for the HH tiles in JT-60 [5]. The present TDS spectra for H_2 , HD and D_2 were also well represented by the superposition of three first order desorption peaks with different desorption energies or peak temperatures, i.e. the first peaked at 800 K (peak 1, activation energy (E_a) = 2.40 eV), the second at 1000–1050 K (peak 2, E_a = 3.00–3.15 eV) and the third at 1200 K (peak 3, E_a = 3.60 eV), as shown in Fig. 7. Fig. 8 shows the areal intensities of each peak for (a) H_2 , (b) HD and (c) D_2 spectra thus obtained against the poloidal directions. The first peak (peak 1) and the third peak (peak 3) were less intensive compared to the second peak (peak 2), except for H_2 desorption. For DM9, peak 1 has significant

contribution for all of H_2 , HD and D_2 desorptions. This is most probably because DM9 was subjected to the least temperature rise resulting in the largest hydrogen (H + D) retention (Fig. 3) and the highest surface H + D concentration (see Fig. 5(b)) as discussed below.

If there was no carbon atoms, H and D mixture would be equilibrated as



The equilibrium coefficient K is given by partial pressures of H_2 , HD, and D_2 as follows:

$$K = \frac{\{P(HD)\}^2}{P(H_2)P(D_2)}. \quad (2)$$

At higher temperatures, H and D are completely mixed up to give

$$K = \frac{\{P(HD)\}^2}{P(H_2)P(D_2)} = 4, \quad (3)$$

while at lower temperatures H and D are not well mixed up and K decreases with decreasing the temperature. Although H and D in carbon do not necessarily behave the same as described above, the relation (2) for desorbed species would give useful information on how H and D were retained. Thus, the relations of $\{P(HD)\}^2/\{P(H_2)P(D_2)\}$ were calculated from the TDS spectra at each temperature

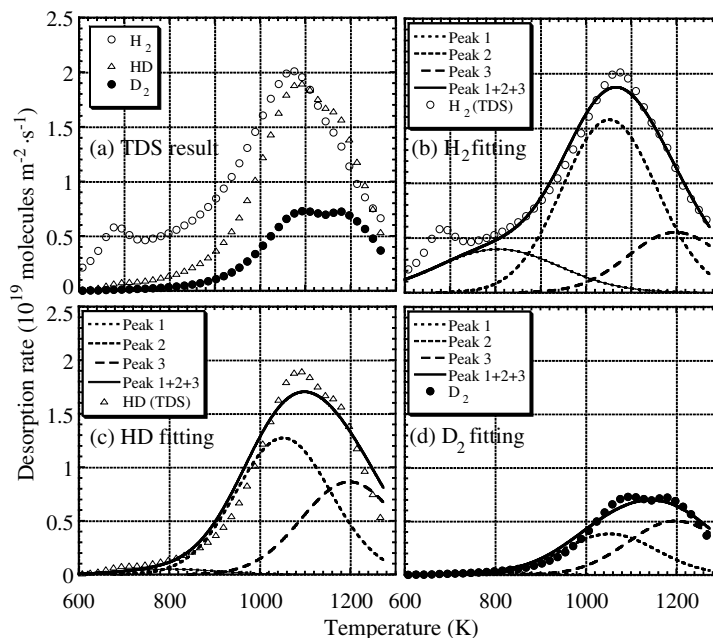


Fig. 7. Deconvolution of observed TDS spectra into three first-order desorption spectra for ID3 sample. Each spectrum shows: (a) experimental results, (b) H_2 , (c) HD and (d) D_2 fitting results.

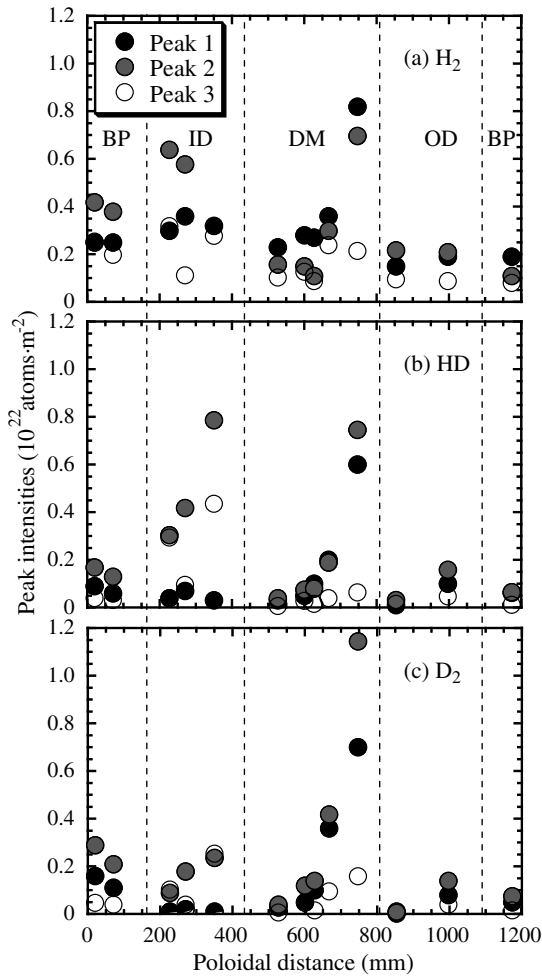


Fig. 8. Comparison of areal peak intensities obtained from TDS spectra.

during the heating as given in Fig. 9 for ID3, DM9 and OD1. ID3 shows the highest value of 2.5 at higher temperature, which is near the equilibrium. As seen in Fig. 2(a), ID3 shows the highest desorption peak temperature of 1050 K, where methane is no more stable. Thus both H and D were retained with a similar manner having higher trapping energy. Accordingly H and D were released at higher temperature with good mixing. DM9 has the maximum at a lower temperature, as appeared the lowest desorption temperature (Fig. 2(b)), but D release occurred clearly at higher temperature indicating a higher trapping energy than H and deeper retention if diffusion was involved. Although the absolute value for OD1 is smaller than that for ID3, both show similar temperature dependence, indicating similar retention manner. In TDS spectra, the lower tem-

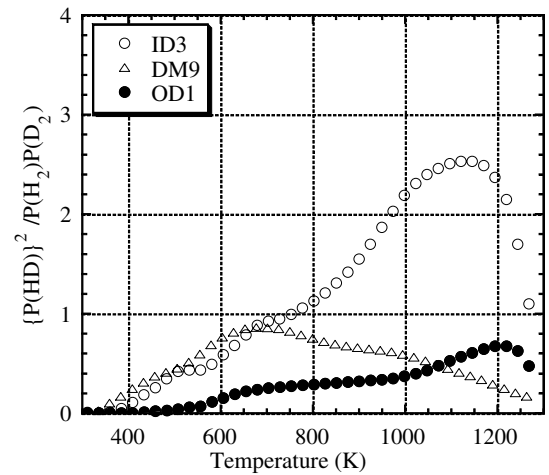


Fig. 9. Temperature dependencies of the square ratios of partial pressures released as hydrogen isotope gases.

perature release of H than D is seen for all tiles as show in Fig. 10. For most samples, H release started below 600 K irrespective of the H retention. In particular the DM samples showed the lowest. D was released above 600 K, except the DM samples. And the ID showed the highest.

Taking all these into account, we can characterize ID, OD and DM tiles as follows:

- (1) The ID tiles were covered by thick re-deposited layers with a little higher H concentration near

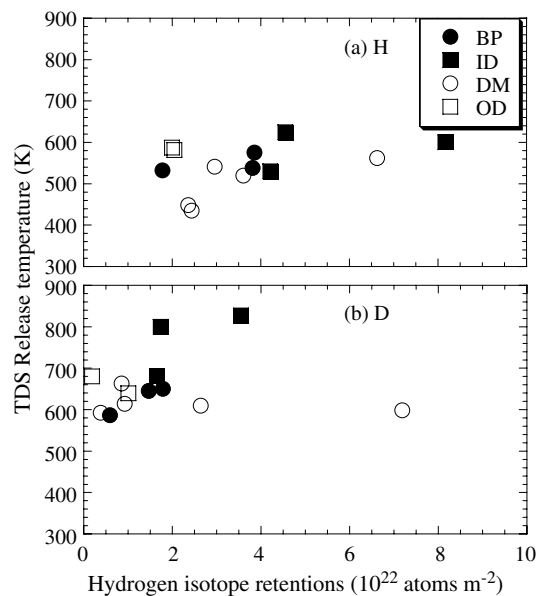


Fig. 10. TDS release beginning temperatures against the hydrogen isotope retentions for: (a) H and (b) D.

the surface and rather uniform retention of H and D with $(H + D)/C = 0.03$ in the whole re-deposited layers. (2) The OD tiles retained the least H and D only near surface regions owing to the erosion of the tiles and the subjection to high heat load. (3) The DM tiles were kept at lower temperature. In particular, DM9, the outer dome, retained the H and D in its re-deposited layers with the high concentration as observed by the SIMS measurement.

4.2. Mechanism of H and D incorporation

The mechanism of hydrogen isotopes retention can be well explained as follows, based on the above discussions and taking discharge conditions and tile temperatures into account.

For DD discharges, as already noted in Fig. 1, the maximum temperatures of the tile observed by thermocouples were 750, 600 and 1200 K, respectively for the inner divertor, the outer dome and the outer divertor, and their surfaces were further heated up to ~ 1000 , ~ 800 and ~ 1400 K, respectively. For a higher NBI heating discharge, the temperature near the outer divertor strike point was further heated up to 1400 K or more from ~ 573 K during the shot. For the HH discharges, due to less NBI heating power to the divertor area, nearly a half of that for the DD discharges, the temperature increase during the HH discharges was much smaller than that for the DD discharges as seen in Fig. 1.

At the beginning when the re-deposition starts on the inner divertor for DD discharges, the deuterium was incorporated in the carbon layers with D/C saturated at the temperature of the re-deposited layers (area). Since the vacuum vessel of JT-60U was kept at 573 K, the tile temperature increased with time during a discharge owing to the plasma heat load, and attained the maximum temperature just before the discharge termination. Since the saturated concentration decreases with temperature, the temperature increase would result in deuterium release from the re-deposited layers made during the shot as evidenced by deuterium recovery after the termination of the discharge [13]. Hence the D/C in the re-deposited layers must be a little smaller than that at the beginning. Succeeding discharges would pile up the re-deposited layers with similar D/C, but maybe somewhat different by each discharges depending on the plasma heat load, which enables to distinguish the re-deposited layers piled up by shot as clearly shown by Gotoh for the divertor tiles of JT-60 [14]. With piling-up the re-deposited layers

by the following discharges, their thermal contact to the substrate became poor [15] and the temperature of the whole re-deposited layers would rise higher during the shot. When a particular shot with larger heating power was made, the temperature of the re-deposited layers would increase uniformly, resulting additional deuterium release to homogenize D/C over the whole re-deposited layers. This makes D/C in the re-deposited layers uniform throughout the layers with such a small value of around 0.03, corresponding the saturated hydrogen concentration in hydrogen implanted graphite at around 900 K [16].

Succeeding HH discharges would add re-deposited layers on the re-deposited layers made by DD discharges. Since the heat load of the HH discharge is nearly a half of that of the DD discharges, the temperature increase during the shot would remain less than that for DD discharges. Thus H/C in the newly made re-deposited layers by the HH discharges must be larger than D/C for the DD discharges. During the HH discharges, isotope exchanges of D by incoming H would further reduce D/C near the surface region. Accordingly depth profiles of H and D in the re-deposited layers become as the SIMS depth profiles show. This also happens on the outer dome tile. But the temperature increase of the outer dome wing was quite small because of less heat and particle load compared to those for the divertor region as appeared in a higher hydrogen concentration in the redeposited layers on the outer dome wing tile.

The re-deposited layers showed columnar and porous structure to permit hydrogen molecules penetrate through the pores. Accordingly both D_2 and H_2 could penetrate deep into the tile bulk and be absorbed at so to speak the inner surface or surface of columnar grains. Thus certain amount of D retained during the DD discharges would be replaced by H. The penetration of D_2 and H_2 into the bulk was also evidenced by the same H/D for the re-deposited samples and the Bulk samples.

At the eroded area, in contrast, higher heat load results in smaller D retention but still not allow D diffusion deep into the bulk, remaining D only near the surface. The HH discharge would add H retention to result in higher $(H + D)/C$ owing to lower heat load for the HH discharges than that of the DD discharges. In addition, some of D was isotopically replaced by H. Consequently the least D/H as well as the least $(H + D)/C$ appeared for OD1 as seen in Figs. 2 and 3.

According to this mechanism, retention of hydrogen isotopes did not simply increase with discharge numbers. Actually, global wall saturation was observed at JT-60U [13]. This indicates that tritium retention in the re-deposited layers on the plasma facing surface would not be a problem, but that at plasma shadowed region such as pumping slots and gaps of the tiles tritium must be piled up and tritium inventory could continuously increase. H and D retention on the tile sides of JT-60U tiles are now under the investigation and the result will soon appear [17].

5. Conclusions

Deuterium (D) and Hydrogen (H) retention in carbon tiles exposed to DD and HH discharges in the JT-60U W-shaped divertor has been investigated by means of thermal desorption spectroscopy (TDS) and secondary ion mass spectrometry (SIMS). Considering (1) profiles of re-deposition/erosion, i.e. the inner divertor and the outer dome wing were mainly deposition dominated areas, and the inner dome wing and the outer divertor were mainly erosion dominated areas, (2) heat load to the tiles and (3) changes of surface temperatures during plasma discharges, the mechanism of incorporation of H and D in eroded and re-deposited carbon tiles is discussed.

In the thick re-deposited layers on the inner divertor, hydrogen (H + D) was retained rather homogeneously with its concentration of 0.03 in (D + H)/C atomic ratio, which is attributed to the surface temperature rise above 800 K. (D + H)/C in the re-deposited layers on the outer dome wing was a little higher corresponding to the lower heat load.

Near surface layers, however, the HH discharges performed after the DD discharges for tritium removal results in significant H retention. On the D-dominated re-deposited layers produced during the DD shots, the H-dominated re-deposited layers were added. Simultaneously, D retained near surface layers was replaced by H. This isotope replacement of D by H also appeared in the eroded area. In consequence, deuterium concentration peaked at a little inside behind the H dominated surface layers both for the re-deposited and eroded tiles. The effect of temperature increase appeared in the large difference between the ratio of the total retained H and D (D/H = 1.1) and the ratio of the number of the DD discharges and that of the HH discharges of

(D/H = 5.1). Since the plasma heat load by the HH discharges was nearly a half of that of the DD discharges, the temperature increase of the divertor tiles was less for the HH discharges than the DD discharges, resulting in higher H retention. This indicates that hydrogen retention in the re-deposited layers on the plasma facing surface would not linearly increase with the number of discharges. Accordingly the global wall saturation could be attained as observed in JT-60U. However, hydrogen retention in the re-deposited layers on plasma shadowed region such as pumping slots and gaps of the tiles could continuously increase. And further studies are needed.

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References

- [1] R.A. Causey, *J. Nucl. Mater.* 300 (2002) 91.
- [2] IAEA, ITER Technical Basis, ITER EDA Documentation Series 24 (2002) Vienna, Chapter 2.7, p. 5.
- [3] C. Brosset, H. Khodja, Tore Supra team, *J. Nucl. Mater.* 337–339 (2005) 664.
- [4] Y. Hirohata, T. Shibahara, T. Tanabe, T. Arai, Y. Gotoh, Y. Oya, H. Yoshida, Y. Morimoto, J. Yagyū, K. Masaki, K. Okuno, T. Hino, N. Miya, *J. Nucl. Mater.* 337–339 (2005) 609.
- [5] T. Shibahara, T. Tanabe, Y. Hirohata, Y. Oya, M. Oyaidzu, A. Yoshikawa, Y. Onishi, T. Arai, K. Masaki, K. Okuno and N. Miya, *Nuclear Fusion*, in press.
- [6] N. Miya, T. Tanabe, M. Nishikawa, K. Okuno, Y. Hirohata, Y. Oya, *J. Nucl. Mater.* 329–333 (2004) 74.
- [7] Y. Gotoh, J. Yagyū, K. Masaki, K. Kizu, A. Kaminaga, K. Kodama, T. Arai, T. Tanabe, N. Miya, *J. Nucl. Mater.* 313–316 (2003) 370.
- [8] Y. Gotoh, T. Arai, Y. Ishimoto, K. Masaki, N. Miya, H. Kubo, K. Tsuzuki and T. Tanabe, *J. Nucl. Mater.*, in press.
- [9] K. Masaki, K. Sugiyama, T. Tanabe, Y. Gotoh, K. Miyasaka, K. Tobita, Y. Miyo, A. Kaminaga, K. Kodama, T. Arai, N. Miya, *J. Nucl. Mater.* 313–316 (2003) 514.
- [10] Inficon, *Partial Pressure Measurement in Vacuum Technology*, 2002, 27.
- [11] K.L. Wilson, R. Bastasz, R.A. Causey, D.K. Brice, B.L. Doyle, W.R. Wampler, W. Möller, B.M.U. Scherzer, T. Tanabe, *J. Nucl. Fusion* 1 (1991) 31.
- [12] S. Chiu, A.A. Haasz, *J. Nucl. Mater.* 210 (1994) 34.

- [13] H. Takenaga, T. Nakano, N. Asakura, H. Kubo, S. Konoshima, K. Shimizu, K. Ttsuzuki, K. Masaki, T. Tanabe, S. Ide, T. Fujita, *Nucl. Fusion* 46 (2006) S39–S48.
- [14] Y. Gotoh, J. Yagyū, K. Masaki, K. Kizu, A. Kaminaga, K. Kodama, T. Arai, T. Tanabe, N. Miya, *J. Nucl. Mater.* 329–333 (2004) 840.
- [15] Y. Ishimoto, Y. Gotoh, T. Arai, K. Masaki, N. Miya, *J. Nucl. Mater.* 350 (2006) 301.
- [16] J.W. Davis, A.A. Haasz, *J. Nucl. Mater.* 217 (1994) 206.
- [17] Y. Horohata et al., in: 17th International Conference on Plasma Surface Interactions in Controlled Fusion, May 21–27, 2006, Hefei, China.