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The amount and distribution of deuterium retained in the jet divertor after the C and Be phases in 1994–1995

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Abstract

The amounts of D on the graphite and beryllium divertor tiles used in JET campaigns during 1994–1995 have been measured and compared. Deposits primarily of carbon containing very high D concentrations were present in the cold shadowed areas on both sets of tiles. Plasma-surface interactions involving chemical erosion of carbon and D diffusion into Be are evident.

Keywords: JET; Tokamak; Poloidal divertor; Wall particle retention; Tritium inventory

1. Introduction

The amounts of hydrogen isotopes trapped in plasma-facing components (PFCs) in tokamaks (especially in redeposited films in the divertor region) are a major concern for future fusion devices such as ITER, because of the cost and radioactivity associated with retained tritium. Information from JET is particularly relevant since it is one of the largest existing tokamaks, uses a mixture of beryllium and graphite PFCs and has now installed a similar divertor to that envisaged for ITER which is water-cooled in order to increase the power handling capabilities of the target tiles. This paper presents JET data from 1994–1995 on the deuterium retention in the new divertor, which can be compared with previous data from tiles used as the target for X-point discharges [1,2].

The divertor was operated from April 1994 to March 1995 with graphite target tiles made from 2 D carbon-fibre reinforced graphite, arranged with the weave planes normal to the plasma-facing surface. In March 1995 all the graphite divertor tiles were removed and replaced in the following month by beryllium tiles for an intensive two month campaign to compare the two target materials.

2. Experimental

The divertor tiles were fitted in pairs to poloidal water-cooled support bars, there being 19 pairs attached to each bar. A cross-section of the divertor along one of these support bars is shown in Fig. 1. The tiles become narrower as the vessel radius decreases (from 40 mm wide at the outer side of the divertor to ~ 30 mm at the inner side). The tiles were shaped so that each tile protects the edge of the next tile from direct impact from the plasma as shown in the lower part of Fig. 2 to prevent 'blooming': variations in the tile separations/vertical adjustment meant that the size of 'shadow' cast by one tile on the next alternated between ~ 50% and ~ 15% of the tile width. (The upper part of Fig. 2 is discussed towards the end of Section 3.)

The Be tiles were castellated by cutting (to a depth of about 5 mm) the plasma-facing surface into areas about 8 × 8 mm to reduce thermal stresses. In the last week of the Be tile campaign the power flux to the tiles was deliberately increased to levels at which surface melting occurred. The melting was most severe on tile 12 (at the outer strike zone) where approximately two-thirds of the area exposed to the plasma had melted at some time and re-solidified and about 1 mm of material from the surface in the centre of the tile was displaced. Tile 8 (the inner strike point) had also melted and re-solidified over about

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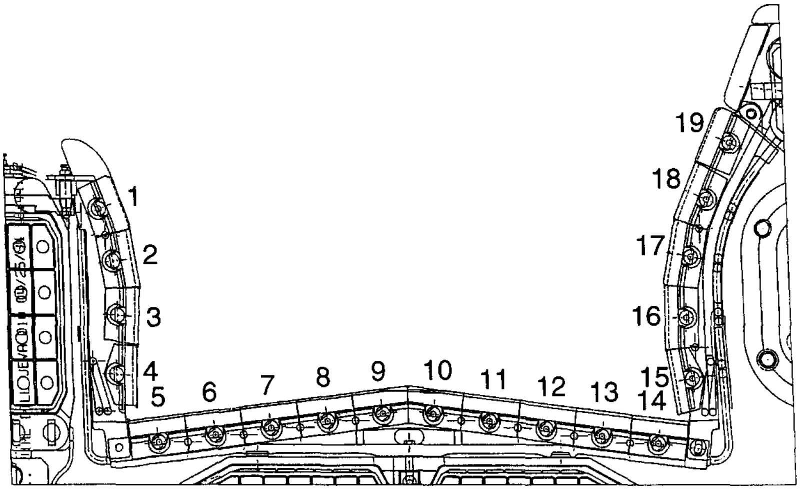

Fig. 1. Radial cross-section of the JET Mark I divertor in use during 1994 and 1995.

one-quarter of the exposed area. Small melt areas were also visible on other tiles, resulting from incidents such as giant ELMS. The plasma-exposed areas in the SOL appeared dark during the latter part of the campaign and when the plasma was moved onto such areas there was an increase in the optical emission from recycled D and Be.

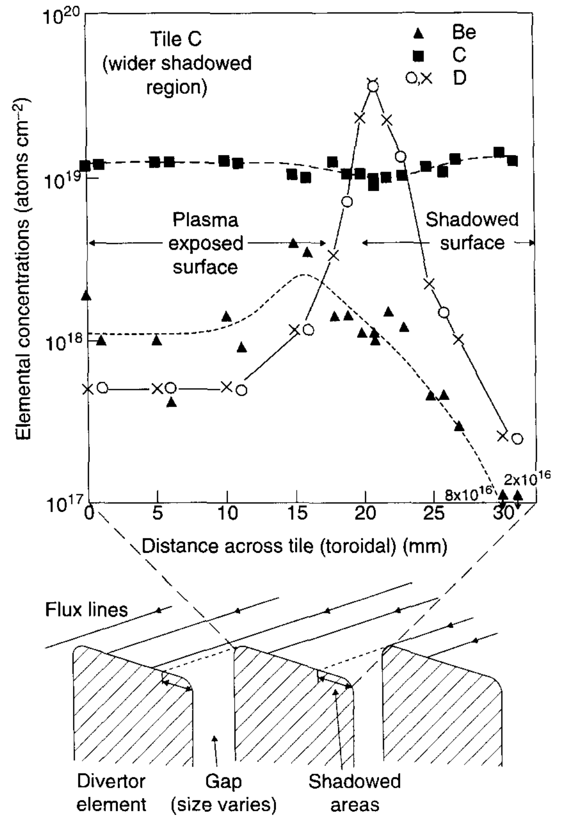

Fig. 2. Upper part: C, Be and D analyses by NRA along two adjacent lines across (toroidally) graphite tile 12 A. (D results for one line indicated by crosses, the other by circles.) Lower part: a schematic toroidal cross-section of some divertor tiles to show the shadowing of part of each tile by its neighbour.

The divertor tiles were analysed using ion beam analysis (IBA) techniques. The elements D, Be and C were analysed by nuclear reaction analysis according to the reactions:

$$^{2}\mathrm{D}(^{3}\mathrm{He},\mathrm{p})^{4}\mathrm{He},\quad ^{9}\mathrm{Be}(^{3}\mathrm{He},\mathrm{p})^{11}\mathrm{B},\quad ^{12}\mathrm{C}(^{3}\mathrm{He},\mathrm{p})^{14}\mathrm{N}$$

The three elements can be analysed simultaneously by using a ^{3}He ion beam and detecting the secondary protons produced at different energies by the reactions. To detect C and Be a beam energy well above the threshold for those reactions ($\sim$ 1.2 MeV) was employed, typically 2.5 MeV. For D the reaction cross-section is a maximum at 0.7 MeV, for lower energies it falls rapidly to zero and above falls steadily [3]. As the ^{3}He beam passes through the surface region and loses energy it continues to react with D (with increasing cross-section) until it has slowed below 0.7 MeV (which occurs ~ 8 μm into a graphite matrix): the energy of the emitted proton also changes. Thus D can be analysed in thick films up to ~ 8 μm thick if the proton peak shape is correlated with ^{3}He stopping and reaction cross-section data, the correction for a thick film of uniform concentration being 30–50%. For C and Be the cross-section decreases rapidly with beam energy so the analysis is dominated by the concentration at the surface (mean analysis depths in a predominantly carbon surface ~ 1 μm and ~ 1.7 μm, respectively).

3. D and impurity analysis of the graphite tiles

Two adjacent rows of tiles need to be analysed to give the overall picture of D retention because of the different

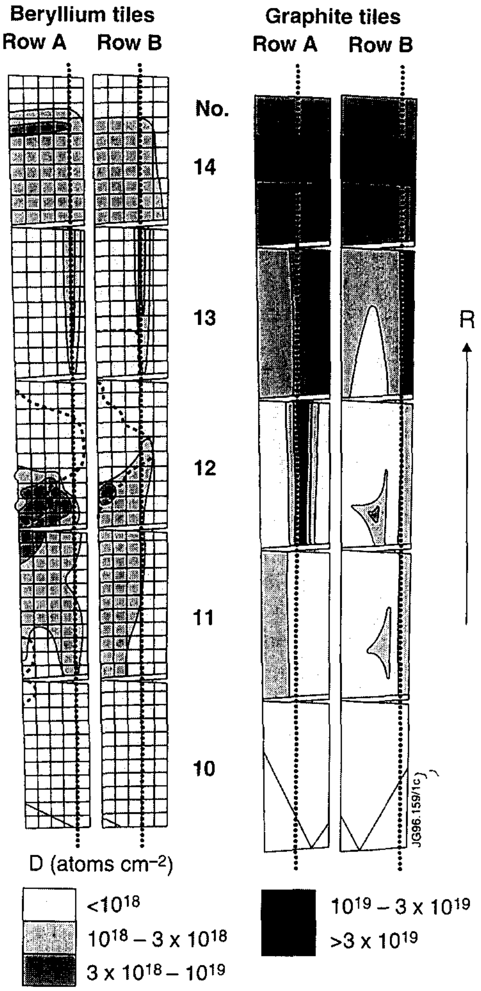

Fig. 3. An overall view of the amounts of D retained on the outer floor tiles of one support bar after operations using graphite tiles, alongside a comparable view for the Be tiles.

shadowing referred to above: by convention the tiles on the anti-clockwise and clockwise sides of a support bar (viewing the torus from above) are designated 'A' and 'B', respectively. The D distributions on the graphite and Be divertor floor tiles after their respective periods of exposure in JET are shown in Fig. 3 (for the outer half of the divertor), and in Fig. 4 (for the inner half). The shadowed regions are to the right of the dotted lines for tiles in Fig. 3 and to the left for tiles in Fig. 4. For the graphite tiles normally within the scrape-off layer (SOL) (tiles 5–7 and 12–14), the areas shadowed by the adjacent tile were covered by a darker, less reflective layer. The areas shadowed by the inner and outer wall tiles on the ends of tiles 5 and 14, respectively, were similarly marked. It is clear that the amount of D present in these shadowed areas is greater than in the regions exposed to the plasma, going through a maximum just within the shadowed region, as is also seen in the upper part of Fig. 2, which shows the D, Be and C levels detected across graphite tile 12 A. (The data from two adjacent scans are superimposed – for D different symbols indicate each scan.)

The most striking feature of the analyses of these graphite tiles is the large concentration of D seen in the shadowed regions, the greatest of all being on tile 5, where a thick film with some localised spalling was visible. (On the innermost tiles the deposition also continues all the way down the sides of the tiles, as evidenced by interference colours, indicating transport of impurities several centimetres down the gaps between tiles.) In the shadowed

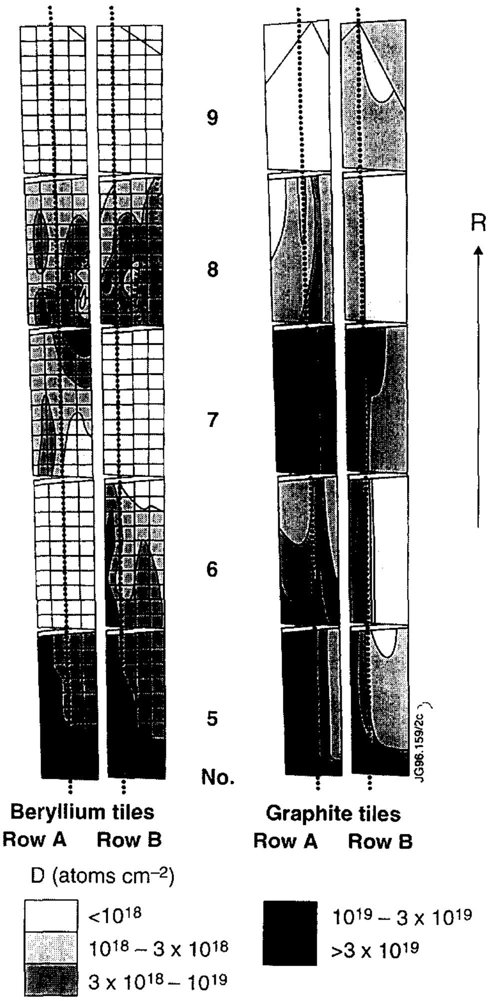

Fig. 4. An overall view of the amounts of D retained on the inner floor tiles of one support bar after operations using graphite tiles, alongside a comparable view for the Be tiles. (The unshaded tiles have not been analysed.)

region of tile 5, D is clearly present in a film of greater thickness than the ~ 8 μm analysis depth and the concentration of D is approximately 5–6 × 10^{22} cm^{-3} within the film, which gives a D:(C + Be) ratio of ~ 0.5:1. This ratio is similar to the saturation concentration of D in graphite found for surfaces implanted with D ions [4], and for C layers formed from methane in a glow discharge [5].

In areas of tile exposed to the plasma the amount of D retained near the surface is relatively low, typically 5 × 10^{17} atoms cm^{-2}, but no areas were found with very low levels such as occurred at the strike points on the upper X-point tiles after 1991–1992 operations [2]. This may be because during most discharges in the 1994–1995 campaign the strike points were each swept at 2 Hz over a radial distance of several centimetres, which together with the larger contact area in 1994–1995 meant the surface temperatures of the tiles were much lower than for an equivalent plasma power in 1991–1992. Furthermore the support bars are water-cooled, so that the starting temperature before a pulse is ~ 50°C and the tile surface rapidly returns to this temperature, whilst for the X-point tiles the base temperature was 250–300°C (the vessel temperature) with heat-loss only by radiation.

Shadowed regions close to the areas of greatest erosion (the strike zones) also existed on the upper X-points and likewise were covered with thick redeposited films. However, the greatest D concentration in these previous deposits was considerably less than the maximum observed from shadowed regions on the 1994–1995 divertor tiles. This may also be due to the higher tile temperatures in 1991–1992, for example the saturation level for D implanted into graphite at 300°C is 60% that implanted at room temperature [6].

Tiles that were invariably within the private flux region (i.e. tiles 9 and 10) retained low levels of D (~ 5 × 10^{17} cm^{-2}) at all points, whether within or outside the shadowed area.

In Fig. 2 the C concentration of ~ 10^{19} atoms cm^{-2} merely indicates the outer micron is predominantly C across the tile, with some dilution by D in the redeposited film. Although the quantification for Be in a C matrix is very approximate, relative changes can be instructive. The Be level within the outermost 1–2 μm is shown in Fig. 2 to be ~ 10^{18} cm^{-2} across the plasma-exposed surface and this was typical of the Be level over all areas in the SOL. In the private region the Be level was an order of magnitude lower and as seen in Fig. 2 there was a sharp decrease in Be (along with the D) into shadowed regions. The principal sources of Be in the machine were the regular Be evaporations from four equispaced heads at the outer midplane and the RF antennae screens. Since there is a very low probability of evaporated Be reaching the divertor directly, the Be must be transported along the SOL into the divertor, following erosion either of evaporated deposits on the walls of the main discharge chamber or of the RF screens: Be would then be deposited with the observed distribution. Note, however, that unlike the D there is no significant peak of Be just into the shadow. This suggests that if the film in this area is formed by carbon eroded from the divertor and redeposited locally (and saturated with codeposited D), then the Be is not re-eroded with the same probability as C.

There was also deposition containing D, Be and other impurities on the inner wall tiles similar to that on floor tiles in the inner SOL, with, for example, co-deposited D in the shadowed region of tile 2 also at the saturation level for films > 8 μm thick. In contrast, however, the outer wall tiles appeared much cleaner than either the floor or inner wall tiles, with little evidence of redeposited films. A similar effect occurred with the upper X-point tiles in 1991–1992, in that beyond the outer strike-point region the tiles were quite clean whereas there was heavy deposition around the inner strike zone [2].

4. D and impurity analysis of the beryllium tiles

The overall pictures of the D retained on the Be divertor tiles in use from April to June 1995 were included

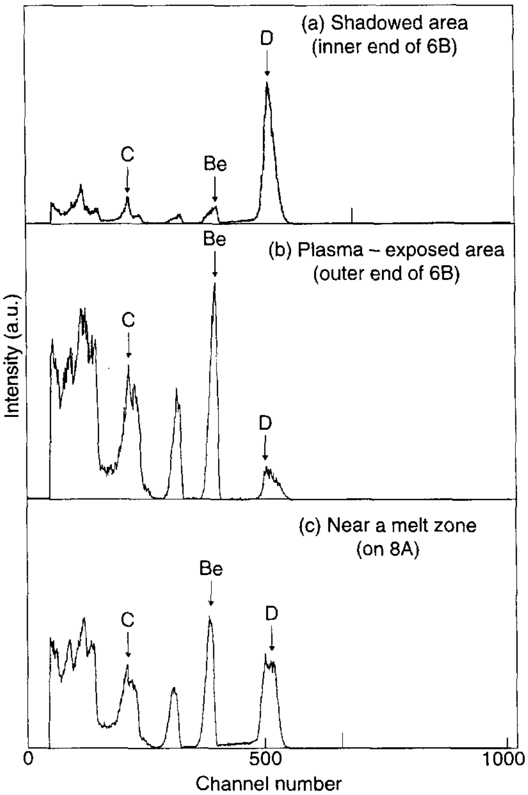

Fig. 5. NRA spectra from Be tiles (a) within the shadowed region on 6A (b) in the plasma-exposed region of 6A (c) an area of 8A just outside the region which had been melted during plasma operations.

in Figs. 3 and 4. Firstly, the amount and distribution of D retained on the Be tiles in the inner half of the divertor is similar to that for the graphite tiles. High concentrations of D are retained in deposits in the shadow areas (which are similar in size to those on the graphite tiles) and thick films are clearly visible at the inner corner of the divertor. However, on the outer half of the divertor there is appreciably less retained D than in the graphite case. Many of the features of the D distribution on Be correlate with amounts of *carbon* present on the surface, for example there are large amounts of C present in the shadowed areas in the innermost part of the divertor (and where thick films are present the Be substrate is almost completely masked by C) and there is relatively little C present in the outer half of the divertor.

The points above are illustrated by the NRA spectra in Fig. 5. There is a large D feature in the spectrum from the shadowed area of the Be tile 6B and the size of the peak characteristic of C is comparable with the one for Be. However, in the spectrum from the plasma-exposed region of the tile the C peak (which sits on a subsidiary Be feature) is now much smaller than the Be peak and the amount of D is greatly reduced. Note, though, that the D peak though small is broad, indicating that the D is present for several μm into the surface at a low concentration of $\sim 0.02(\mathrm{Be} + \mathrm{C})$. This area is exposed to the plasma SOL and appears dark, as mentioned in Section 2.

In the centre of the melt region of tile 12 B (where ~ 1 mm has been lost from the surface during the controlled melt experiment) the D was at a very low level ($\sim 1.5 \times 10^{17}$ cm^{-2}). (There was a small C peak still visible, but no spectra from Be samples have been recorded with smaller C features than this (eg. a similar level is found on the back of the tile), so it may be that a few times 10^{18} cm^{-2} of C comes from atmospheric exposure, handling and packaging during transport.) The melted (and re-solidified) areas of tiles 12 and 8 have experienced surface temperatures of > 1300°C (the melting point for Be) on occasion and might therefore be expected to have lost any previously retained D by outgassing. Likewise, the areas adjacent to the melt regions must also have been very hot at such times and would be expected to have outgassed. However, this does not appear to be the case. Fig. 3 shows areas of high D content close to melt areas and Fig. 5(c) is from an area close to the melt region on tile 8A. The C appears in the NRA spectrum at its minimal value, but there is quite a large D feature indicating D at a low level in the outermost 1–2 μm but then at ~ 10% through the remainder of the analysable depth (i.e. for many μm).

The C must arrive on the divertor tiles via the plasma, having been eroded from PFCs in the main chamber together with some Be. An experimental confirmation of this mechanism is that even when the Be divertor tiles are the contact points, the C impurity level in the plasma is at least as large as that of Be for most discharges [7]. The C must be deposited initially therefore in the plasma-exposed regions, however this is not where it is found. Local recycling occurs at the divertor surface and this mechanism leads to a probability of redeposition in shadowed areas, which act as sinks. The films built up in these areas are predominantly C, yet the surface composition in the plasma-exposed areas is mostly Be, which seems to imply that chemical erosion of carbon plays an important role in the local recycling process (as was implied in Section 4 by the absence of a Be peak in the deposits on graphite tiles). The layer appearing black on the surface of tiles in the SOL may thus be a honeycomb of Be from which C has been chemically etched and which may act as a conduit for D diffusion into the Be. The release of gas from these areas when they experience a plasma power loading may result from poor thermal conductivity through the layer.

This model can clearly account for the observed progressive accumulation of carbon in the shadowed regions. However, one might expect the C to form a layer on the surface, whereas other ion beam analysis techniques such as Rutherford backscattering suggest that some Be diffuses through the arriving C to the surface. Whilst this might be expected on the plasma-exposed area of tile 5 where there is frequent ion bombardment and occasional plasma heating, it is surprising in a normally cold shadowed area. The apparent interactions on these divertor tiles between C and Be is an area for further study of obvious importance to ITER.

5. Conclusions

The patterns of redeposition and the amounts of D retained in the inner half of the JET divertor during 1994–1995 are similar for operations with graphite tiles and with Be tiles. Rather less D is retained on the *outer* half of the divertor during the Be phase, however.

Be is deposited on the graphite tiles and C on the Be tiles, due to erosion from the walls surrounding the main plasma volume and transport along the SOL down into the divertor. (The impurities in the plasma seem to arise principally from this erosion and not from the divertor target.) For each type of tile the composition of the D-containing deposits on the divertor is thus a mixture of C and Be. Much more C was deposited on the inner half of the divertor during the Be phase than on the outer half, parallelling the D retention picture.

In areas of tile shadowed from the plasma by adjacent tiles, where the base temperature was 50°C and the maximum temperature excursion (for a few seconds during plasma pulses) was 200°C, the ratio of D:(C + Be) reached ~ 0.5:1, through redeposited films > 8 μm thick in some places. The amounts of D are much greater than ever found in JET prior to installation of the water-cooled divertor, even though those earlier JET surfaces were a similar mixture of C and Be: reassessment of previous analysis data shows that the maximum concentration through thick films with a hot vessel (minimum PFC temperature of ~ 300°C) was probably well below the saturation ratio of D:C of 0.4:1 [4,5]. The entire first-wall of ITER will be water-cooled to facilitate adequate power handling, so H-isotope retention may occur on shadowed areas receiving impurity fluxes without attendant power deposition: in plasma-facing areas higher surface temperatures will limit the level of retention possible.

On the areas of graphite tiles exposed to the plasma the D concentration is relatively low, $\sim 5 \times 10^{17}$ atoms cm^{-2} near the strike points rising to a few times 10^{18} cm^{-2} deeper into the SOL: such levels do not make an appreciable contribution to the overall inventory. Comparable levels are seen in the outermost few μm of the Be tiles. However, there is evidence of diffusion of D into the Be surfaces to many microns at significant concentrations (~ 10%) even though the tile surfaces reached high temperatures during plasma exposure (areas of some tiles were deliberately melted as part of the Be tile assessment programme). The extent of this diffusion into the bulk requires further investigation, since it may have an important bearing on the retained H-isotope inventory if Be is used in ITER.

Acknowledgements

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