DISTRIBUTION OF HYDROGEN ISOTOPES, CARBON AND BERYLLIUM ON IN-VESSEL SURFACES IN THE VARIOUS JET DIVERTORS

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JET has operated with divertors of differing geometries since 1994. Impurities accumulated in the inner leg of all the divertors, and operation of the first (Mk I) divertor with beryllium tiles demonstrated that most are eroded from the main chamber walls and swept along the scrape-off layer to the inner divertor. Carbon deposited at the inner divertor is then locally transported to shadowed regions such as the inner louvres, where, for example, most of the tritium was trapped during the deuterium-tritium experiment (DTE1). Factors affecting these transport processes (e.g. temperature) are important for ITER, but are not well understood.

I. INTRODUCTION

Retention of tritium in plasma facing components (PFC) is an important issue for next step controlled fusion devices of a reactor-class [1]. Present modelling suggests that 2 to 5g tritium may be retained in ITER during each pulse, which will mean the limit on mobilisable tritium in the vessel will be reached in ~ 100 ITER pulses [2]. Attention has been focussed on this issue because of the retention of tritium observed during the deuterium-tritium experiment (DTE1) in JET [3-5]. This paper reviews the retention of H-isotopes in JET whilst it has operated with a divertor, and indicates to what extent the data are relevant to ITER, and where there are grounds for optimism.

II. EXPERIMENTAL

Over the past ten years JET has been operated with a series of divertors of differing geometries (Mk I 1994-5, Mk IIA 1996-8, Mk II Gas Box 1998-2001 and Mk IISRP 2001-2004). The different geometries are shown to the same scale in Fig. 1.

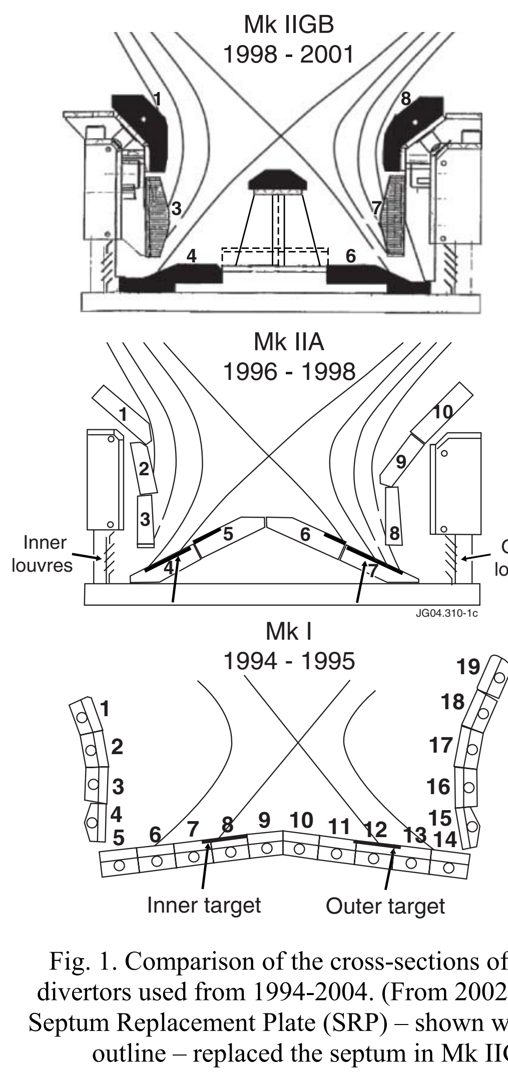

Fig. 1. Comparison of the cross-sections of the JET divertors used from 1994-2004. (From 2002-2004 the Septum Replacement Plate (SRP) – shown with dashed outline – replaced the septum in Mk IIGB.)

[1] See annex of J Pamela et al., Fusion Energy 2002, Proc. 19th Int. Conf. Lyon, 2002, IAEA, Vienna.

The first divertor (Mk I) consisted of 198 poloidal sets of tile pairs bolted to individual water-cooled bars. In a toroidal section, there was a gap between the two tiles of each pair, and to the tiles of the adjacent pair (toroidally) (as shown in the lower part of Fig. 2).

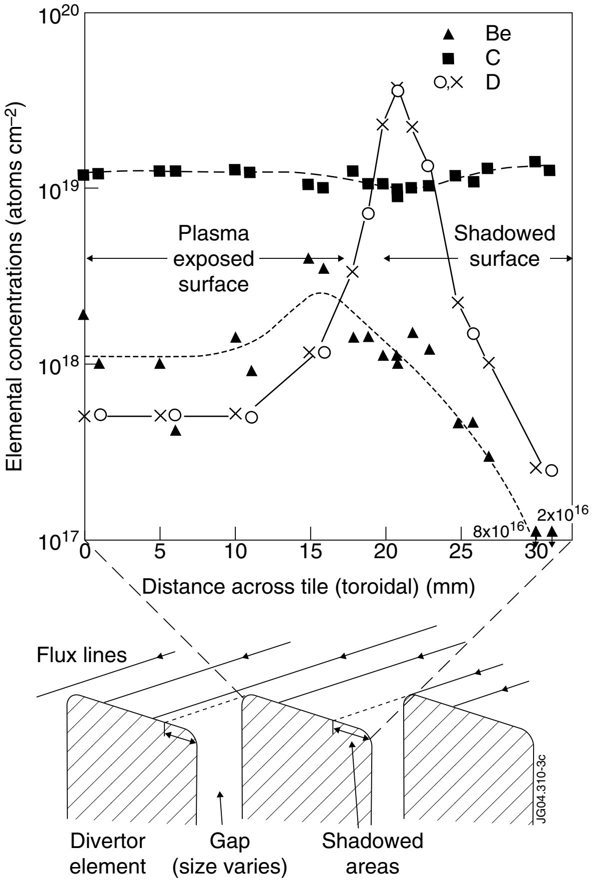

Fig. 2. Toroidal section through tiles of the Mk I divertor, showing the shadowing of edges by adjacent tiles, and the analyses across one of the tile surfaces.

Previous experience in JET (and elsewhere) had shown that if field lines intersect the edges of carbon tiles, carbon blooms may already occur at modest power levels. Accordingly, the Mk I divertor tiles were angled so that each tile protects the edge of the adjacent tile, even allowing for some misalignment. However, as can be seen from Fig. 2, this reduces the effective target area on the tiles to less than one-half of the possible divertor floor area, and increases the angle of incidence at the remaining area. Furthermore, the cooling of the tiles was not direct enough to effectively limit temperature rise during the ~10 seconds of high power divertor phase in a typical JET pulse. Thus the Mk I divertor was replaced with a water-cooled structure to which much larger tiles could be attached rather indirectly. The thermal mass of the tile limits its temperature during a pulse, and the tile cools as heat is conducted slowly to the support structure before the next pulse. The much larger tiles, and the close tolerances of the support structure, mean a much larger effective target area can be achieved, with proportionately greater power handling capability. However, the indirect cooling of the tiles means their base temperature (e.g. after some hours without a JET pulse) is intermediate between the ~293K of the water cooling the structure and the vessel wall temperature, which at that time was normally ~573K. Furthermore, the tile temperature ratcheted up by ~50K during a day of discharges since the tiles do not have time between pulses to return completely to the starting temperature. In contrast, the cooling of the Mk I tiles did ensure that for every pulse their starting temperature was ~323K. It will be seen later that this difference may have important consequences.

Gas from the torus is pumped through the divertor by a cryopump connected to the sub-divertor volume. The Mk I divertor had a rather open structure (a full poloidal slot between each mounting bar), however, for subsequent divertors gas is pumped only through the louvres at the inner and outer corners of the divertor. The cryopump is located outboard of the divertor, so the outer louvres are much closer and the pumping speed there is about twice that at the inner louvres. The Mk IIA divertor is of narrower aspect than the Mk I, whilst for the Mk II GB divertor a full septum was added. This, together with the restricted pumping and resulting higher divertor pressure, represents the closest simulation of the ITER geometry. In 2001 the septum was removed, and a simple “septum replacement plate” (SRP) (of limited power-handling capability) installed (dashed outline in Fig 1). Removing the septum allows some freedom to explore plasma shapes with higher triangularity, as proposed for ITER, but this range will be increased when a load-bearing SRP is installed in 2004.

During every shutdown large numbers of in-vessel components are removed for analysis. The standard techniques are Secondary Ion Mass Spectrometry (SIMS) and Ion Beam Analysis (IBA) methods such as Rutherford Back-scattering (RBS), Nuclear Reaction Analysis (NRA) and Particle Induced X-ray Emission (PIXE). Combination of these techniques enables quantification of deuterium and plasma impurity species (mainly carbon and beryllium) co-deposited on all the PFC surfaces, and in the shadowed areas of the divertor that are particularly important for H isotope retention.

III. RESULTS

III.A. Mk I Divertor

The Mk I divertor was first fitted with carbon-fibre composite (CFC) tiles. The inner and outer strike points were typically located on tiles 8 and 12, respectively, though on occasions the strike points were swept poloidally by about 10 cm at a frequency of 4 Hz to spread the power over a larger area. In the strike point regions, the area exposed to the plasma is an area of erosion, especially at the outer divertor. The tiles appear somewhat polished, and the D content in the region is very low, as seen in the upper part of Fig. 2, the residual amount being D implanted into the surface ahead of the advancing erosion front. However, immediately next to the erosion zone in the region shadowed by the adjacent tile (toroidally) there is a very large deuterium peak [6]. This D is co-deposited with carbon in a film some microns in thickness. The film attenuates within a few millimetres into the shadowed zone, indicating that the source is carbon sputtered from the outer strike region being promptly re-deposited. Note that there is not a significant peak of Be, suggesting that much of the carbon may be eroded by chemical sputtering, which would not occur for beryllium.

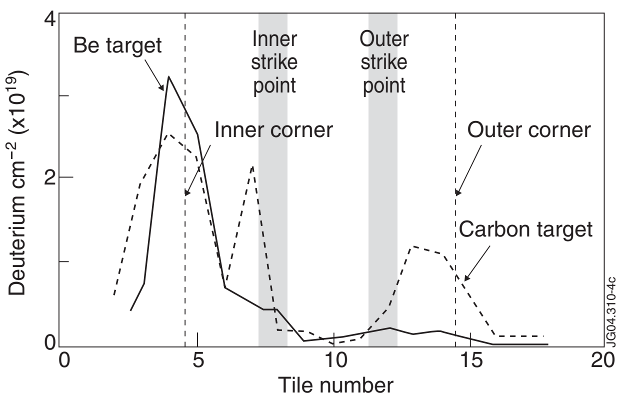

Fig. 3. Amount of deuterium retained on a poloidal set of Mk I JET divertor tiles, following operation with carbon (solid curve) and beryllium (dashed curve) target tiles.

D retention in the Mk I divertor is shown in Fig. 3. The peaks at the inner and outer strike point regions are due to the promptly re-deposited material mentioned above, but there is a larger amount of deposition well into the scrape-off layer (SOL) at the inner corner of the divertor. This peak is reproduced for the phase when the carbon tiles were replaced with solid Be tiles, however, there are no corresponding peaks of D retention at the strike point regions. The retention at the inner divertor for the Be phase is in a carbon matrix, which cannot originate in the divertor [6]. The distribution of the deposits in the divertor indicates that they form during plasma discharges, and cannot arise from, for example, glow discharge cleaning. Furthermore plasma-main chamber wall interactions in JET are clearly important, since during the divertor phases with the Be target, carbon was generally the main plasma impurity. Thus there was only significant Be in the plasma for high target power densities, such as during the experiment to deliberately melt Be target tiles [7].

The outer divertor in the Mk I (Be) phase exhibits no peak of retained D, and for the carbon phase there is only the local re-deposition peak at the strike point. This in-out asymmetry in deposition is seen for all JET divertors, as indeed it was for X-point operation in JET prior to fitting the divertor [8], and shows that all impurities generated in the main chamber are swept to the inner divertor.

III.B. Mk IIA Divertor

During the early operation with the Mk IIA divertor in 1996, the strike points were normally on the divertor floor tiles, as shown in the section in Fig. 1. After these operations, a poloidal set of divertor tiles was removed for analysis. At this time it was noticed that there was heavy deposition (films typically 40 μm thick) in the shadowed areas at the inner corner, such as the ends of tiles 3 and 4 and the inner louvres [9,10]. During subsequent operations with this divertor (which included DTE1 in 1997), similar numbers of discharges were run with the strike points on the divertor floor to those on tiles 3 and 8.

When the divertor was exchanged in 1998 for the Mk II GB a poloidal set of divertor tiles, together with a few inner wall guard limiter (IWGL) and outer poloidal limiter (OPL) tiles, were taken for analysis. Firstly, since the tiles were radioactive due to retained tritium, a series of core samples were cut and analysed for tritium [4]. The results for the overall T retention in the JET vessel (assuming toroidal symmetry) are shown in Fig. 4. Now, during the DTE1 campaign approximately 40% of the tritium entering the vessel was retained after the pulse [3]. A series of clean-up pulses were run after the last T-fuelled discharge, but at the start of the shutdown to exchange the divertors over 6g tritium (~17% of the torus fuelling) remained in the vessel. Of this ~2.5g were released by exchange with the purging gas and pumped to the Exhaust Detritiation System (EDS) during the shutdown. In general the amount of tritium retained in the PFC tiles according to the tile analyses (~ 150 mg) was a small proportion of the missing T inventory. However, once the divertor tiles were removed, it was clear there were a lot of flakes and loose deposits on or near the inner louvres. These were collected, and the tritium content was found by calorimetry to be 520 mg in 154 g of carbon flakes [5]. This leaves over 3g tritium remaining somewhere in the vessel. Due to the geometric arrangement of the louvres, most of the material spalling from them would have fallen to the bottom of the vessel, and only a small proportion onto the divertor structure. In 1999 an inspection of the sub-divertor region was made, and there were indeed large numbers of flakes that appear to have fallen from the inner louvres. Thus the missing tritium is indicated on Fig. 4 as perhaps being below the inner divertor (which implies the presence of about 950g of carbon flakes).

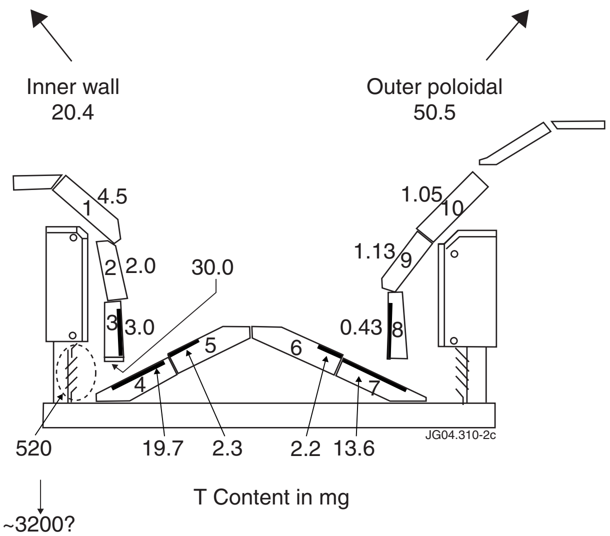

Fig. 4. Amounts of tritium in mg found in tiles in JET following the DTE1 campaign (integrated toroidally). The amount collected from the inner louvres is also shown, and the amount believed to be in flakes that have fallen from the louvres to the vessel floor.

When the tritium at the inner louvres (and below) is included, the retention in the Mk IIA divertor is extremely in-out asymmetric, as is the associated impurity deposition. The outer divertor is essentially clean, the small amounts of T on tiles 8-10 being T implanted into the surface, as was the D in the eroded areas of the Mk I divertor. At the inner divertor, tiles 1-3 are covered with thick films with a composition of ~60% Be and 40% C (discounting the small amounts of nickel and other metals) [5]. (The Be sources in the vessel are ICRH antenna screens, and periodic evaporation of Be over in-vessel surfaces.). The D/C+Be ratio was typical for plasma-facing deposits in JET at a modest ~0.15. By comparison the deposit matrix in the inner corner regions shadowed from the plasma was pure C with a high D/C ratio of ~1.

III.C. Mk IIGB divertor

The Mk IIGB divertor was installed in 1998, and a poloidal set of tiles was removed during a shutdown in 1999. In Mk IIGB the majority of pulses were run with a strike-point on the vertical tiles 3 and 7, as will be the case in ITER. However a significant minority of pulses had strike points on the accessible sections of tiles 4 and 6. Films on tiles 1 and 3 were rich in Be, tile 4 had a thick film of carbon with high D/C ratio at the end shadowed by tile 3, and tiles 7 and 8 appeared clean, all in line with results from Mk IIA [11]. Additionally, in the part of tile 4 shadowed by the septum there was also a film of carbon, but not as thick as in the area shadowed by tile 3, nor with as high D/C ratio.

During the 1999 shutdown some special tiles were mounted to replace the divertor set being analysed. These tiles had been carefully measured at the edge with a micrometer, and were coated with stripes of ~0.5 μm rhenium plus ~2.5 μm of 90%C10% B. Coated tiles were also installed at the IWGL and OPL. The idea of the coatings was to measure erosion of less than a few microns, or in the case of deposition to mark the position of the interface between deposit and substrate. The tiles were removed for analysis in 2001, together with an uncoated set that had been exposed from 1998-2001.

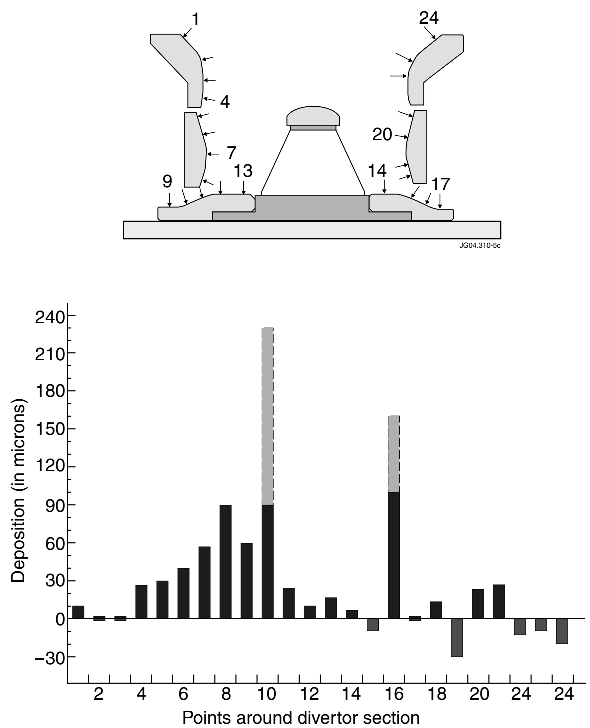

Fig. 5. Amount of erosion/deposition on the Mk IIGB divertor tiles during the 1999-2001 campaign from micrometer measurements.

The changes in divertor tile dimensions following 1999-2001 operations, according to the micrometer measurements, are shown in Fig. 5. There is deposition everywhere at the inner divertor, whereas there is negligible net change at the outer divertor, apart from one point on tile 6 (point 16 in Fig. 5). The film at this point on the sloping part of tile 6 just accessible by the plasma is dusty in nature, and compacts under the action of the micrometer, so that in a series of several repeat measurements, the apparent film thickness reduces. Precisely similar behaviour is seen at the equivalent point at the inner divertor (point 10), whereas elsewhere any film is quite stable, and measurements are repeatable.

IBA shows that the surfaces of tiles 1 and 3 do not have the same very high Be/C ratio as on previous divertors. Instead the Be/C ratio is about 0.13, and there is a much higher D/C ratio that ever previously observed for a plasma-facing surface in JET. SIMS profiling through the films on tiles 1 and 3 reveals that the film has a duplex nature; the IBA analysis is of the outer layer, whilst the inner has a composition akin to previous films at these positions [11]. The outer layer is approximately half the thickness of the inner layer.

The OPL tiles show erosion over most of their surfaces, in some areas just traces of Re remain and in others all signs of the coatings have disappeared. On the edges of the tiles (well into the SOL) some deposition is visible, and this is greater on tiles with greater erosion on the near-plasma part of the tile, indicating some local re-deposition. The IWGL show a visible plasma "foot-print", with erosion at the point closest to the plasma, and deposition deeper into the SOL. While this situation is analogous to the OPL, the deposition is much more extensive, and films >50 μm thick are found on tiles towards the top of the limiters. The Be/C ratio typical for films on the IWGL is ~0.08, which is similar to the ratio of Be and C impurities in the plasma, averaged over a cycle of pulses from one routine Be evaporation (immediately after which more Be is seen) to the next.

The total amount of Be on tiles 1 and 3 in JET (assuming toroidal symmetry) is about 22g, based on SIMS analyses and extrapolating toroidally [12]. This implies about 400g carbon also arrived at the divertor. Estimations on deposited C amounts can be obtained from SIMS, RBS and quartz micro-balance (QMB) [13] data in a similar manner as the Be amount was determined. The amount of deposited C at the inner divertor including tiles 1, 3 and 4 is estimated to be 310g. At the louvres estimates of the amount of deposited C vary between 20g and 60g based on measurements using the QMB, but this may be an underestimate due to the sampling methods, so the upper figure is more probable. (However, this is still a much lower rate of transport to the louvre region than occurred with the Mk IIA divertor.) It is quite difficult to determine the amount of C deposited on the septum due to its very complicated structure. The amount of deposited C is estimated to be 10g. Thus, the total amount of deposited carbon is about 380g, which is in good agreement with that calculated from the amount of deposited Be.

IV. DISCUSSION

The retention of deuterium (the fuel normally employed in present-day tokamaks) may be used to infer the likely retention behaviour of tritium. However, more direct information was available on tritium retention from the DTE1 campaign in 1997 when an extensive series of experiments using D-T fuelling was carried out. This has given interesting additional information, including isotope exchange effects, long-term tritium retention, and chronic release from tritium remaining in the vessel. Isotope exchange is believed to explain why the tritium retention during the DTE1 campaign was 40% of the input, much more than for deuterium retention. ~6g (17%) remained in the vessel after a three-month clean-up campaign, and part of this inventory is still a major source of tritium release during JET shutdowns.

In general, the deposition patterns of fuel atoms, beryllium and carbon were similar in the various divertors. Heavy deposition and fuel accumulation was found in the inner divertor and much less in the outer channel. This is not expected from classical modelling of erosion/deposition [2], but is also seen in DIII-D and ASDEX Upgrade [14]. DIVIMP was used to reproduce the asymmetry in the JET deposition pattern [5]. To match the pattern, drift in the SOL had to be included, and to get sufficient deposition in the inner divertor channel, it was necessary to increase the erosion by the plasma in the main chamber and the sputtering at the inner divertor surfaces. All these effects have since been observed.

The JET experience, particularly with the Mk I divertor (Be phase) (section IIIA), suggests the source of most of the impurities accumulating at the inner divertor is the main chamber. Since the main chamber of ITER will be of Be, it will be Be arriving in the divertor, and as already shown, this does not migrate to the shadowed areas of the divertor where most of the retention occurs. Thus the retention of T in ITER may be much reduced, in comparison to JET: it would be useful to validate this assumption which has such important implications for ITER by operating JET with a Be wall.

In JET the H isotopes were accumulated in thick carbon films formed predominantly in remote areas shadowed from the direct plasma line-of-sight, most clearly demonstrated in the Mk IIA divertor (section IIIB). However, a significant change in the deposition at tiles 1 and 3 at the inner divertor was observed for tiles removed in the 2001 shutdown (section IIIC). The composition at the outer part of the deposited film is much closer in terms of Be/C ratio to deposits on the IWGL, and a much greater concentration of D was found than normal for JET PFC.. The most likely explanation seems to be that for the last 3 months of operation in 2001 the JET vessel temperature was reduced from 593K to 473K. This resulted in lower bulk temperatures of the divertor tiles by about 70K, as seen in Fig. 6, and surface temperatures must be similarly lower.

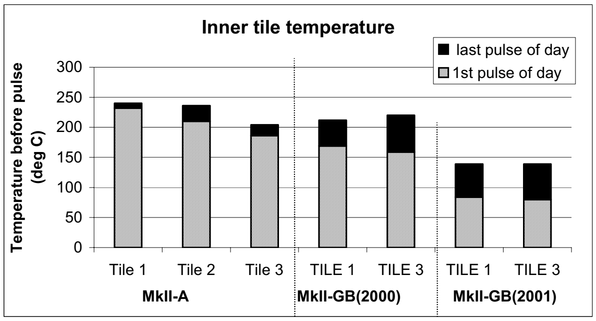

Fig. 6. Bulk temperatures (from thermocouples) of inner divertor tiles for the Mk IIA divertor and the Mk IIGB divertor when operating with a vessel wall temperature of 593K (2000) and 473K (2001)

Transport to shadowed areas of the divertor (which is much more evident in JET than in any other tokamak) involves a number of steps, some of which such as radical formation are very temperature dependent [15]. The variation in overall deposition rate with temperature will compound the variations for each step. Thus the differences in deposition behaviour between the JET divertors, and between JET and other tokamaks, may be partly due to the operating temperatures. Knowledge of this functionality would seem to be very important for ITER, which is designed to operate with similar temperatures to JET. Changing the temperature of components in the ITER divertor may provide a handle with which to mitigate tritium retention.

V. CONCLUSIONS

Erosion/deposition in the JET divertor is very in-out asymmetric, with deposition in shadowed regions of the inner divertor dominating H-isotope retention for all the configurations tested. The main source of the deposited material is interaction with the carbon PFC in the main chamber, and the transport processes at the divertor seem to be a strong function of temperature. Both these conclusions suggest avenues that may lead to less tritium retention in ITER.

ACKNOWLEDGMENTS

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