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Section 4. Erosion/deposition in plasma experiments

Erosion/deposition issues at JET

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Abstract

Deposition and H-isotope retention in JET is highly asymmetric, with deposition predominantly in the inner divertor, where flaking deposits form on water-cooled louvres shadowed from the plasma. The asymmetry implies drift in the SOL of JET from outboard to inboard under normal operating conditions, which has been measured. In order to model the amounts of deposition, assumptions have to be made about the transport at the inner target. Analysis of divertor tiles shows that material from the main chamber travels along the SOL to the inner divertor wall, from where carbon is preferentially removed leaving a beryllium-rich film. The carbon travels to shadowed areas (such as the louvres) where deposits with high H-isotope content accrue. The analysis indicates that chemical processes must be important.

Keywords: Erosion; Deposition; JET; Tritium retention; Chemical erosion; 2D model

1. Introduction

Deposition in JET has always been asymmetric when operating in a divertor configuration, i.e., heavy deposition is found in the SOL at the inner divertor, and very little at the outer divertor. This phenomenon was first reported for the 1990–1991 campaign when JET was operated with an *X*-point formed within the vessel and the wall protection tiles at the top of the vessel were used as targets [1]. Since the construction of a divertor within the vessel in 1992–1994, the asymmetry has been reported for both the Mk I (using both carbon and beryllium target tiles) [2] and the Mk IIA divertor campaigns [3,4].

The principal result of divertor modelling is that most eroded material is re-deposited locally, so that there is net erosion close to the strike-point, and net deposition deeper into the scrape-off layer (SOL). Since the greater power flux (and hence the greater erosion) occurs at the outer divertor target, the observed deposition is not easily reconciled with predictions. Furthermore, heavy deposition of carbon leading to flaking was observed on the water-cooled louvres, and the majority of the tritium retained in JET following the first deuterium tritium experiment (DTE1) is believed to be in such flakes that have spalled from these louvres and fallen beneath the divertor structure.

Attempts to correctly model the deposition in JET require the incorporation of additional physical processes such as drift in the SOL, and different parameters to cover interactions at the inner divertor. Some new ideas on processes taking place at the inner divertor are necessary to explain the deposition. This paper presents some new experimental evidence for the processes involved. It is imperative that the mechanisms resulting in this very large deposition rate are understood before one may rely on predictions of deposition in future tokamak devices.

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2. Results

2.1. Modelling of deposition in JET

A cross-section of the Mk IIA divertor including field lines for a typical plasma is shown in Fig. 1(a). The number of carbon atoms deposited was estimated as 4% of the number of ions to the inner target ($\sim 1.2 \times 10^{25}$ carbon atoms) from an analysis of tiles and flakes removed at an in-vessel inspection following 2000 pulses using the Mk IIA divertor (approximately 10000 s of divertor phase operation). It should be noted that the louvres are several centimetres into the pumping aperture at the corner of the inner divertor, and shadowed from the plasma. The flux at the entrance to this aperture thus must be carbon *neutrals*.

The two-dimensional Monte Carlo impurity modelling code 'DIVIMP' [5] has been used to model erosion/deposition in JET at selected time-slices. The results have been compared with the overall erosion/deposition pattern for the campaign by assuming these time-slices were typical. Satisfactory agreement can be obtained with the erosion rate at the outer divertor target [6], but the deposition behaviour could not be explained using the normal values of the code input parameters (such as laboratory data on sputtering rates for carbon, and charge exchange neutral (CXN) fluxes from NIMBUS calculations). More recently experimental data have been obtained in two areas that have a crucial bearing on deposition modelling. Firstly, it has long been postulated that the deposition in JET implies a drift of impurities around the SOL from outboard to inboard in the vessel [1,2]. Such drifts have now been confirmed, and measurements of the drift velocity have been made using the reciprocating probe (RCP) located at the top of the JET vessel [7]. L-mode, H-mode and ohmic pulses all show peak velocities of Mach 0.35–0.6 in the SOL in the direction required to sweep impurities to the inner target, as shown in Fig. 2. Secondly, in order for sufficient impurity particles to travel towards the louvres in the Mk IIA configuration, it is necessary for a much greater percentage of ions incident at the inner target to be converted to neutrals leaving the target. Deposited films are known to exist at the inner divertor, and these films may have quite different properties to bulk material [8]. In particular, high sputtering coefficients (giving C yields of up to 16%) have been derived from optical spectroscopy measurements at the inner JET divertor [9]. Alternatively, von Keudell et al. [10] have demonstrated high release rates from hydrogen-rich ($H/C \sim 0.7$) polymer films for C_2H_x at around 550 K (close to surface temperatures for MkIIA). This would effectively allow the carbon to recycle.

In order to match the Mk IIA deposition data, three principal changes were necessary to the DIVIMP modelling. Firstly, the (measured) flow in the SOL from outboard to inboard was introduced to ensure that the inner divertor becomes the primary deposition zone, as observed, instead of the outer divertor. Secondly, most

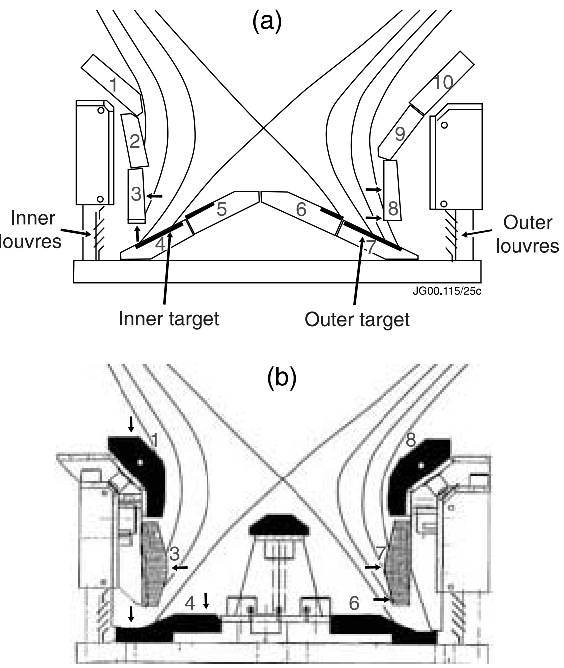

Fig. 1. Schematic cross-sections of (a) the Mk IIA and (b) the Mk IIGB divertors, showing field lines for typical discharges. Arrows indicate analysis points referred to in the text and Table 1.

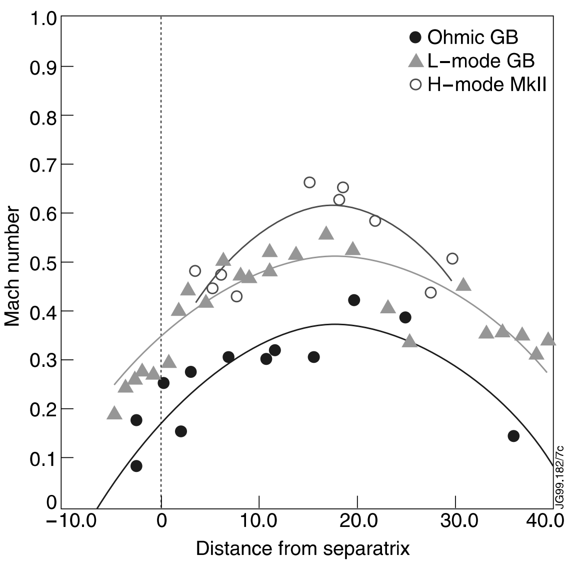

Fig. 2. Drift velocities in the JET SOL measured with a reciprocating probe system at the top of the vessel.

deposition must be at the inner louvres. The louvres are outside the zone modelled with DIVIMP, but neutral particles leaving the corner of the divertor are assumed to deposit in that region. To ensure a large flux of neutral particles travel in that direction, particles incident at the inner target were given a 50% probability of recycling. Thirdly, since almost all the inner divertor appears from analysis to be an area of net deposition, there must be an adequate flux of carbon to the inner divertor from elsewhere. The main chamber is known to be a net erosion zone [11], and, for example, when JET operated with a Be divertor, the principal plasma impurity for most discharges was still carbon, and large amounts of carbon were deposited in the inner divertor [2]. In order to provide sufficient C flux to the inner divertor, it was necessary to enhance the sputtering at the vessel wall by about a factor of 10. Although some of the interaction with the main chamber wall may well be by ions, the DIVIMP code only includes CXN interaction at the present time. Accordingly, the CXN flux used in the modelling has been increased by factors of up to 10 greater than given by the NIMBUS calculations. Mayer et al. [11] (using a different estimate of CXN fluxes) also found that the predicted sputtering by CXN at the inner chamber wall was smaller than the measured erosion (by about a factor of 3).

The result of one DIVIMP calculation, taking a time-slice for an ELMy H-mode discharge, and using the additional factors described above is shown in Fig. 3. The flux of neutrals towards the louvres is within a factor of 2 of the global average for the campaign, and there is net erosion around the vessel (with a maximum at the inner wall), as has been shown experimentally [11]. Fig. 3 still shows significant deposition at the outer divertor, and too little elsewhere in the inner divertor, so minor adjustments to the model are still required. For example, the drift in the SOL may be 'switched on' closer to the surface of the outer target. In order to deposit the measured amount of carbon at the louvres, the average erosion from carbon-based surfaces in the main chamber ($\sim$100 m^2) must be $\sim 1.2 \times 10^{19}$ C atoms cm^{-2}. This is consistent with values obtained by Mayer et al. ($>3.6 \times 10^{18}$ C atoms cm^{-2}) for an earlier campaign [11]. A comparison between the original and the revised modelling predictions and the experimental data for the CII emission (visible spectroscopy, looking down into the divertor) is shown in Fig. 4. It will be seen that (at least for this particular time-slice) the revised model gives better agreement with the experimental data.

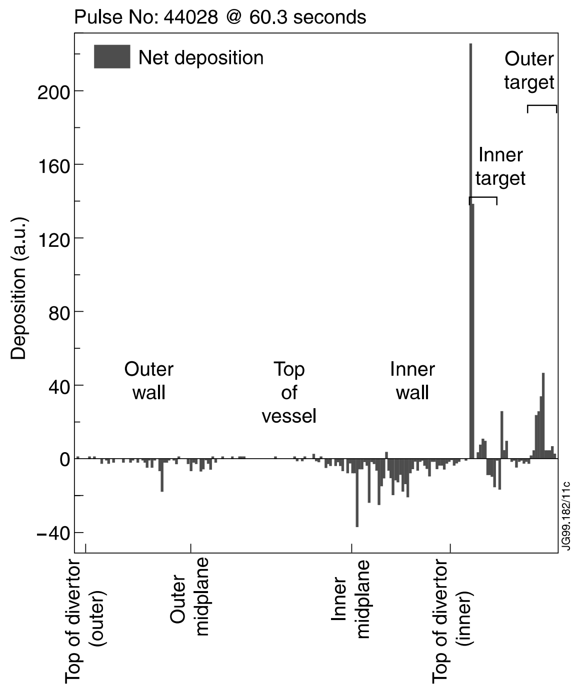

Fig. 3. Net erosion/deposition in the JET Mk IIA divertor obtained by DIVIMP after introducing additional flow in the SOL, enhanced wall sputtering and partial reflection of C-ions incident on the inside target.

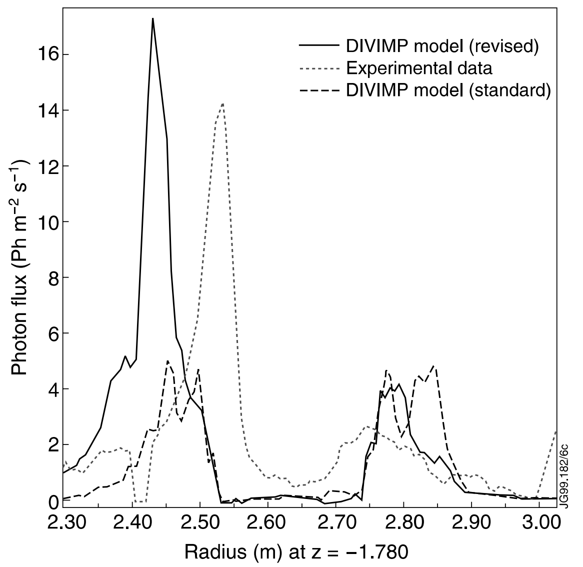

Fig. 4. Plot of CII radiation seen experimentally across the JET MkIIA divertor and compared to values calculated by DIVIMP using standard and revised parameters.

2.2. Tritium retention following DTE1

In 1997 JET operated for several months with deuterium/tritium fuelling, the percentage of tritium entering the vessel varying from 1% to 100%; the campaign was called the DTE1. Over the campaign a total of 35 g tritium entered the vessel. Despite a thorough clean-up campaign lasting three months, at the start of the subsequent shutdown 6 g tritium still remained in the vessel

[12]. For the shutdown the vessel was vented to air and continuously purged. During the shutdown all the divertor tiles were removed and stored in ventilated containers, to make way for the installation of the new Mk II gas box (GB) divertor. All flakes and loosely adherent material that remained in the vicinity of the inner louvres were collected with a brush and vacuum cleaner, however it is known that many flakes have fallen beneath the divertor structure and could not be retrieved. A selection of tiles was also removed from the vessel walls. All the air passing through the vessel, and the air ventilating the tile storage containers, was passed through the exhaust de-tritiation system (EDS). The amount of tritium recovered from this airflow was 2 g [12]. It is important for planning and assessing the radiological implications of future work in JET to know the amount and whereabouts of the tritium remaining in the machine. To this end, a detailed tritium analysis programme has been carried out on the material removed from the vessel.

The total tritium content of the flakes removed from JET following DTE1 was determined by calorimetry to be 520 mg, and the weight of the flakes was 154 g [13]. The total T content of the divertor tiles was estimated by sampling from a poloidal set of 10 divertor tiles, which were numbered 1–10 as shown in Fig. 5. The tritium content of the wall tiles was estimated from the analysis of six inner wall limiter tiles and three outer bumper limiters. In each case for each tile a number of cylindrical samples were cut using a hollow drill, and the T content of the plasma-facing surface of each sample (to a depth of 1 mm) was determined by total combustion. The samples were cut from previously agreed locations, to provide an average overall estimate for the tritium

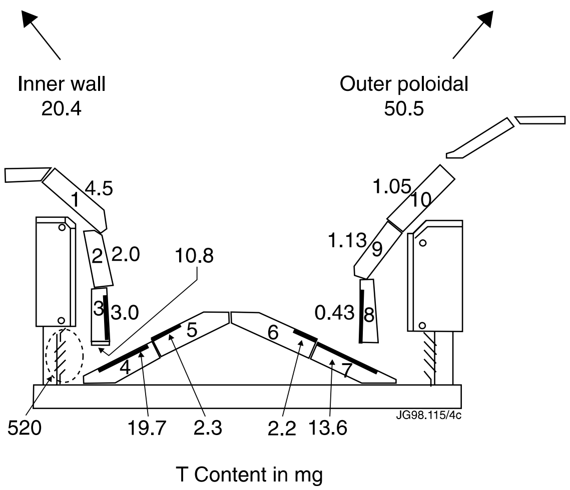

Fig. 5. Distribution of tritium in the JET vessel in the shutdown following DTE1. The amounts at each location are integrated around the torus.

content of the tile. Additional samples were cut from the edge of tile 3 adjacent to the pumping duct between tiles 3 and 4, since a 40 μm layer with high hydrogen isotope concentration was found here on samples removed prior to DTE1. Two samples could be cut from the width of the tile, one from the half nearer the front of the tile, and one from the rear half. A T content of 3.3 GBq cm^{-2} was found over the rear half of this edge (10–100 times the usual T level from plasma-facing surfaces), however, this was less than expected from the pre-DTE1 analyses. The T level from the front half of the edge was similar to levels at the front surface. In total well over 100 T determinations have been made.

From the average T content and the number of tiles in the torus at that poloidal position, the total amount of T in the torus can be plotted, as shown in Fig. 5. The 520 mg T at the louvres represents the T contained in the collected flakes. The total T near the surface of the divertor tiles (which have been removed from the vessel) is only 78 mg (29.4 TBq), and the T content of the various wall tiles (which, apart from the sample tiles, remain in the vessel) is 71 mg (27.3 TBq). Profiles for T through the bulk of a number of tiles have also been made and are reported elsewhere [14]. They suggest that there is not a large additional contribution to the total tritium inventory.

At the end of the post-DTE1 shutdown (allowing for the removal of 0.52 g T with the flakes and the (estimated) removal of 0.1 g tritium with the divertor tiles), $\sim$3.4 g tritium remained in the vessel. The analyses of wall tiles suggest that they do not contribute more than about 0.1 g to this figure. We assume the remaining tritium is retained in the flakes that have spalled from the louvres and fallen beneath the divertor structure. Since 154 g of flakes contained 0.52 g tritium, this implies about 1 kg of flakes remain in the vessel. A further 1.25 g T has been recovered from the torus by the advanced gas handling system (AGHS) since the post-DTE1 shutdown from venting/purging during a subsequent shutdown, and outgassing while baking the machine [13]. This has reduced the quantity of T assumed to remain in the torus to $\sim$2.1 g. The T content of the flakes remaining in-vessel must be proportionately reduced, from $\sim$1.3 TBq g to $\sim$0.8 TBq g^{-1}. An attempt to recover as many flakes as possible from underneath one section of the divertor is planned for the next shutdown, so that the total quantity remaining in the torus may be estimated, and the present activity measured.

2.3. Analysis of Mk IIGB Tiles and Comparison with Mk IIA

A cross-section of the Mk IIGB divertor is given in Fig. 1(b), together with a set of field lines for a typical plasma. A poloidal set of six divertor tiles, together with a septum tile, were removed in June 1999 after an eight-

Table 1
Surface analyses (of outermost ~1 μm) at selected points on JET divertor tiles by nuclear reaction analysis (NRA) and Rutherford backscattering (RBS)

Divertor	Tile/Position	Be/C (NRA)	Be/C (RBS)	D/C+Be (NRA)	D/C+Be (RBS)	Ni/C (RBS)
Mk IIA	3 front face	1.5	–	~0.15[a]	–	–
Mk IIA	3 bottom edge	<0.003	–	0.77	0.81	–
Mk IIA	8 centre front	<0.003	–	0.017	–	–
Mk IIA	8 lower front	~0.01	–	0.02	–	–
Mk IIGB	1 top edge	0.31	0.34	0.12	0.13	0.027
Mk IIGB	3 front face	1.0	1.03	~0.2[a]	0.07	0.06
Mk IIGB	4 private region	<0.007	–	0.31	0.25	–
Mk IIGB	4 end under tile 3	<0.003	–	0.8	0.65	–
Mk IIGB	7 centre front	~0.02	~0.027	0.05	~0.056	~0.0056
Mk IIGB	7 lower front	~0.04	–	~0.2[a]	–	–

[a] Approximate value for outermost micron, when D concentration varies through surface region.

month campaign of approximately 2500 plasma discharges. The tiles have been analysed using the ion beam analysis (IBA) techniques nuclear reaction analysis (NRA) and Rutherford backscattering (RBS). The overall appearance of the tiles indicated heavy deposition on the inner divertor wall tiles 1 and 3 and negligible deposition on the outer divertor wall tiles 7 and 8, as for Mk IIA. There was evidence of strong plasma interaction with the section of tile 4 exposed to the plasma, with deposited films evident in the sections of this tile shadowed by tile 3 and the septum. Tile 6 showed a similar strong plasma interaction zone, but no evidence of films in the shadowed areas. No sampling from the louvres was possible at this time. The strike points for operation with Mk IIGB are normally close to the corners of the divertor. The campaign was dominated by experiments aimed at developing optimised shear discharges, for which the strike points were normally on the horizontal tiles 4 and 6. For the (smaller) divertor physics programme, the (vertical) tiles 3 and 7 acted as targets.

A selection of results of IBA analyses from the Mk IIGB divertor tiles is given in Table 1. For comparison, IBA data from similar points on tiles from the Mk IIA divertor are included. The sensitivity of NRA depends on the depth distribution of each element, so the quantification may be in error by up to a factor of 2. The Mk IIA tiles were removed prior to the DTE1 campaign after 2000 discharges, and have been analysed previously [5]. A feature of the IBA results is that the films deposited on the surface of the divertor wall tiles 1 and 3 from Mk IIGB have a very high beryllium/carbon ratio. The NRA data indicate the presence of a film over tile 3 of up to 7 μm thickness, with the greatest D concentration at the surface. Analysis of the top (horizontal) surface of tile 1 reveals a slightly lower Be/C ratio than on tile 3, and the D results suggest a film of about 5 μm with a more uniform D concentration. A small peak appears in each RBS spectra from the inconel constituents Ni, Cr and Fe (referred to in the Table as 'Ni'), and it is noticeable that the peak always has the same spatial distribution as the Be. It is significant that heavy deposition occurs over all the inner divertor wall, to points deep into the SOL. It can be seen from Table 1 that similar films existed at the inner divertor wall in the MkIIA configuration.

Data from the Mk IIGB tile 4 are also given in Table 1, from the regions shadowed by tile 3 and by the septum. In contrast to analyses of tiles 1 and 3, there is negligible Be (or Ni) on these areas of tile 4. There is also a much greater ratio of D to C. The film composition from the region shadowed by tile 3 is similar to that from the end of tile 3 in the Mk IIA divertor (which was indistinguishable from the composition of flakes from the inner louvres). The D concentration in the shadow of the septum is somewhat lower.

Analyses of the outer divertor tiles confirm that their surfaces are much cleaner than those from the inner tiles. In Table 1 are values for the Mk IIGB tile 7, which may be compared with those for the Mk IIA tile 8 (which was in the equivalent position on the outer divertor wall, as shown in Fig. 1). Just trace amounts of Be were found, and much lower D concentrations than elsewhere, except for the lower region of the plasma-facing surface of Mk IIGB tile 7.

3. Discussion

If drift in the SOL is included in the DIVIMP modelling, the asymmetry in the JET deposition pattern can be reproduced. To get sufficient deposition in the inner divertor channel, it is necessary to increase erosion by the plasma in the main chamber. This is in accord with erosion/deposition measurements on wall components, and the observation that the first wall (rather than the divertor) is the major source of plasma impurities. However, to convert the impurity flux to the inner strike zone into the massive deposition at the JET louvres requires very different processes at the target to that normally assumed in divertor modelling. Recent laboratory experiments [10], and spectroscopic data [9] suggest that the recycling parameters used previously are inappropriate.

The results above provide a number of new pointers to the processes involved. Firstly, the T analyses for Mk IIA confirm that the vast majority of the T retention is, indeed, in flakes that form on the water-cooled louvres, and that all the plasma-facing surfaces contain much lower T concentrations (in line with the previous D retention data [4]). The films formed on the edge of the Mk IIA tile 3 (adjacent to the divertor corner) prior to DTE1 were identical to those on the louvres. Following DTE1 even thicker films would be expected to have accumulated, but the T retention data do not agree. The T present on the half of the edge farthest from the front face of the tile would correspond to a relatively thin (~12 μm) film. The half of the edge nearer the front face was blueish in colour, which may indicate a thin (submicron) film. A number of explanations are possible. It may be that during DTE1 tile 3 reached higher temperatures than previously, which greatly reduced the probability of incident particles sticking at the surface. The experiments of von Keudell et al. [10] suggest that sticking coefficient is a critical function of temperature, and this would fit in with the gradation from front to back across the edge. Alternatively, although the 40 μm films formed prior to DTE1 were still adherent to the tile whereas they had started to spall from the louvres, it may be that as the film thickness increased sufficient internal stresses built up so that it spalled off the tile. Further analyses are to be carried out on more of these Mk IIA tiles.

It was estimated above that nearly 1 kg of flakes might remain in the JET vessel. Figs. 1 and 5 show, correctly, that the louvres are angled such that loose material on the surface would under gravity fall away from the divertor centre. However, the figure also includes the (occasional) louvre support pillars. This gives a false impression, as around most of the torus flakes spalling off the louvres would be able to fall directly down through the divertor support structure towards the bottom of the vessel. It is therefore possible that the material collected in the shutdown following DTE1 from between the inner louvres and tile 4, plus material still loosely adhering to the louvre surfaces, amounted to less than 20% of the total material condensed at the louvres.

There is a buildup of Be on the inner side-wall of both divertors, and the formation of thick carbonaceous films with no Be content elsewhere (on tile 4 in Mk IIGB, and mostly on the louvres in Mk IIA). Impurities are transported to the inner divertor wall tiles along the inner SOL, having been eroded from the walls of the main chamber. No measurements are made in JET of the impurity composition in the SOL. Likely sources of impurities in the inner SOL are the surfaces of the inner wall limiter tiles closest to the plasma, which from the visible 'footprint' are erosion zones. The Be/C ratio in these areas of the tiles sampled is typically close to 10%. Furthermore, the relative amounts of C, Be and Ni in the plasma are (relative to the average electron density) typically 1–10%, 0.2–0.3% and 0.001–0.008%, respectively. (Be levels may be higher immediately following a Be evaporation, but decrease within a few pulses. There are often short bursts of much greater Ni influx during a pulse.) Although there may be no direct correlation between the concentrations of impurities transported along the SOL and those entering the plasma, let us assume that the relative values are similar. On that basis there might be typically ten times more C than Be deposition at the divertor wall whereas the observed C:Be ratio is ~1:1. It is possible for the C to be re-eroded chemically as C_xD_y by the D ion flux, whereas the Be and Ni will remain on the surface, since ion energies are insufficient for physical sputtering. These hydrocarbon species then have a probability of travelling to the shadowed regions at the inner divertor, where their probability of sticking may be temperature dependent (as suggested in [10]), and the resultant deposits will be based purely on carbon (as described above). The amount of the carbon re-deposition would thus, on the basis of the above approximation, be ten times that remaining on tiles 1–3, i.e., if the deposits at the inner divertor wall average 5 μm in thickness, then about 50 μm may be re-deposited over a similar area. This is certainly of the correct order of magnitude to explain the deposition found in Mk IIA. The total deposition in Mk IIGB cannot yet be quantified, but gas balance measurements show average D retention over many months as about 9%, which is a little less than retention of D + T in the Mk IIA divertor (~15% [12]).

Tiles in the outer Mk IIGB divertor channel appeared much cleaner than in the inner channel, as has always been the case in JET. However, there was an extra D surface peak on the lower part of tile 7, and there was some discoloration of surfaces around the outer louvres, which was not visible in the Mk IIA campaigns. The D may be the result of operation towards the end of the campaign with the strike-point on the end of tile 7. Alternatively, for a week just before the end of the MkIIGB campaign prior to the shutdown in which the tiles were removed, JET operated with reverse ∇B. Measurements with the RCP showed that at this time the SOL flow was also reversed (though its magnitude was much less), and the power was more equally balanced on the divertor legs. For the ~100 pulses in this period the deposition in the two divertor legs may also be more equitable.

4. Conclusions

Analyses of JET Mk IIA tiles following DTE1 show that only ~0.1 g tritium is contained in the divertor tiles that have been removed from the machine. This implies that about 1 kg of flakes is still in the vessel and has fallen below the divertor structure, containing about 2 g tritium.

If drift in the SOL is included, DIVIMP modelling can give the correct balance of deposition/erosion in the divertor legs, by adjusting the amount of erosion in the main chamber. However, to get the precise pattern of deposition at the inner divertor requires rather different sputtering (or reflection) values to those used previously.

There are deposits on the tiles of the JET inner divertor wall that are several microns thick, and rich in Be and other metallic impurities. This implies that the great majority of the C incident at these areas has been chemically eroded, and transported with high efficiency to shadowed areas.

Acknowledgements

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