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# Carbon Deposition and Hydrogen Isotope Retention in JET

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## ABSTRACT

Hydrogen retention in tokamaks is dominated by two mechanisms: implantation into plasma-facing surfaces and trapping in deposited layers. The amount of hydrogen implantation saturates at typically ~$10^{21}$ atoms $m^{-2}$, giving ~2 x $10^{23}$ atoms in the JET first wall (which is ~200 $m^2$), whilst codeposition depends firstly on the quantity of carbon deposited, and secondly on the temperature history of the deposits. Generally, codeposition has dominated the retained H inventory in JET, which was typically ~$10^{24}$ atoms.

The installation of a divertor in JET has necessitated the presence of water-cooled components to protect the divertor field coils, whereas previously all plasma-facing components were normally at least 300°C. Thick carbon-based films are deposited on surfaces in the vicinity of the inner corner of the divertor on surfaces shadowed from the plasma. Because of the divertor cooling, these deposits are at low temperature and their H:C ratio is at least 0.5:1; as a result their contribution to the overall in-vessel inventory is increased. No comparable deposition is found at the outer divertor. In the Mk IIA divertor the majority of the deposition occurs on cool surfaces many centimetres from the plasma, although with a line-of-sight to the vicinity of the inner strike point, and the average amount deposited per pulse is much greater than previously observed. The number of carbon atoms forming the basis of the deposits amounts to several percent of the ion flux to the inner strike point. The build-up of material leads to spalling (probably on venting to air) The mechanism for the generation and transport of the carbon to form the films is unknown, but ELMs may have a role: it is important to fully understand the phenomenon because of the similarities between the JET and ITER divertor geometries.

## 1. INTRODUCTION

Impurity transport and the deposition of impurities on the first-wall of the JET tokamak have been studied by the analysis of first-wall components removed at the end of every operational campaign. Hydrogen was the principal fuelling gas for the initial campaigns (1982-4), and since the hydrogen from the fuelling cannot be distinguished from hydrogen from other sources, analyses concentrated on deposited carbon and metals [1]. However, deuterium became the principal fuelling gas for the 1985 campaign, and its retention in the vessel following operations has been the principal focus of post-mortem analysis studies since that time [2-12]. In addition, in 1991 and 1997 there have been campaigns with deuterium-tritium fuelling, and analysis of retained tritium has also contributed to our understanding of the in-vessel retention [13-15].

Over the years the interior configuration of the JET machine has changed greatly. From initially being simply an inconel vessel with discrete contact points for the plasma at the outer midplane, the vessel has been progressively covered with carbon-based protection tiles to more than half the surface area. Be evaporation has also been introduced for the reduction of oxygen in the plasma and to assist density control. In 1992-4 a full toroidal divertor (complete with field

coils and a toroidal cryopump) was built inside the bottom of the vessel [16]. As a result the principal mechanisms for the long-term retention of hydrogen in the vessel are seen to be implantation of ions into all plasma-facing components and the incorporation of hydrogen into films formed by the deposition of wall material that has been eroded by the plasma ("codeposition"). The amount retained by implantation is limited by the range of the ions and energetic atoms into the surface (<0.1 μm); for incident particles of up to 1 keV the saturation level is of the order of $10^{21}$ atoms $m^{-2}$. For a vessel the size of JET with an internal surface of ~200$m^2$ this gives an inventory of ~2 x $10^{23}$ atoms. Although as will be seen this is ~20% of the long-term retention for JET, since it is proportional to surface area but independent of burn time, it is not a concern for large tokamaks. On the other hand, the amount codeposited with impurities depends on the amount of erosion and increases with operating time, and although it depends critically on the temperature of the deposits, it has the potential to be a major problem for future tokamaks operating with tritium [17], particularly if the main deposited impurity is carbon (which has a high affinity for hydrogenic species).

It is important to make accurate predictions of the expected retention rate for tritium in future large tokamaks such as ITER, and JET provides the closest experimental conditions from which to extrapolate. However, it will be shown that the models used for the extrapolation do not match the behaviour of existing tokamaks well. As examples, the asymmetry between deposition in the inner and outer divertor legs, and the extent of interaction with the main chamber cannot be quantitatively modelled. Furthermore, it will be shown that in the latest JET divertor configurations (which provide the closest approach to the ITER geometry possible in a current tokamak) an extra deposition mode is in evidence that is not at all understood.

## 2. EXPERIMENTAL

In order to analyse the retained hydrogen isotopes (and deposited impurities) samples of the first wall must be removed from the vessel. Most of the surfaces interacting with the plasma are tiles made from graphite or carbon-carbon-fibre-composite (CFC) material, and a special analysis chamber has been constructed to accommodate these tiles for non-destructive analysis; many such tiles are removed from the vessel at each opportunity and may be subsequently replaced. Additionally, to monitor the condition of the vessel wall (areas of which are exposed to charge-exchange neutral fluxes from the plasma), special samples have been developed which are attached to the interior surfaces of the vacuum vessel (termed "long-term samples" (LTS) [3]), and which are also removed for analysis and replaced with fresh samples whenever an opportunity arises.

The principal methods of analysis used on the JET components are the Ion Beam Analysis (IBA) techniques such as Rutherford Backscattering, Particle Induced X-ray Emission (PIXE), Elastic Recoil Detection (ERD) and Nuclear Reaction Analysis (NRA). Many other analysis

techniques have also been used over the years [18-20]. However, the method that is most important for the analysis of D (and hence for the retained inventory) is NRA. The sample is bombarded with $^{3}$He ions, and protons are emitted from the surface by the $^{2}$D($^{3}$He,p)$^{4}$He reaction; the number of protons detected is proportional to the D concentration in the surface. The maximum sensitivity to D atoms at the surface is obtained at a bombarding energy of 0.78 MeV, but if an energy of ~2.5 MeV is used D is detected to a depth of about 8 μm, and C and Be in the surface region can be detected simultaneously from the protons released by the reactions $^{12}$C($^{3}$He,p)$^{14}$N and $^{9}$Be($^{3}$He,p)$^{11}$B, respectively.

## 3. D RETENTION IN JET

### 3.1. Retention in the "all-carbon" machine

In the period 1983-1988 an increasing proportion of the plasma facing area was covered with carbon-based tiles. Eventually all parts of the vessel which might be in contact with ions travelling along field lines were covered with tiles, and this is referred to as the "all-carbon" machine. In fact about 55% of the geometric surface area was covered, and the remaining area was still bombarded with charge-exchange neutrals (CXN). To further reduce the possibility of metallic impurity production the walls were covered with carbon by Glow Discharge Carbonisation in 1984-5 [21]. However, problems with density control on restart were judged to outweigh the possible benefits of Glow Discharge Carbonisation, and the procedure was discontinued; since due to the CXN flux the vessel wall is a region of net erosion [22,23], after some time the wall would once again be a possible source of metallic impurities.

Detailed maps of the D retention throughout the vessel charted the development of the "all-carbon" machine, and demonstrated that the amount of D retained increased with the amount of carbon first wall protection [8,11]. For the "all-carbon" campaign completed in May 1988, a total long-term D retention in the vessel of 10.8 x $10^{23}$ atoms (corresponding to ~17% of the D input during the campaign) was derived. For the same campaign gas balance measurements were made (comparing the total D input by gas puffing plus Neutral Beam injection with the amount subsequently pumped out of the vessel). These showed a mean retention in the vessel resulting from each day of operation of ~40% of the gas input [24]. The difference between these numbers can be largely explained by loss of D on venting the vessel. Experiments performed over the same period showed that at each venting of the vessel ~ 1.3 x $10^{23}$ atoms of D were released [25]. Since there were six ventings of the machine during the campaign, a total of 8 x $10^{23}$ atoms may have been lost before samples were retrieved for analysis. If this amount is added to the retained inventory, and allowance made for D removed during the frequent periods of He glow discharge cleaning (GDC) during operations, then the gas balance and retained inventory are in good agreement. The figure of 40% retention is totally consistent with values obtained in TFTR, which was also an "all-carbon" limiter machine [26].

### 3.2. Influence of Beryllium on retention

In 1989 Be was introduced into the JET machine in two stages. Firstly Be was evaporated over the interior of the vessel from four evaporator heads equi-spaced round the outer wall near the midplane. Typically a thin layer was evaporated each night prior to a day of operations. After a few months the graphite belt limiter tiles were replaced with Be tiles, so that Be became the predominant plasma impurity during limiter discharges: Be evaporation was still employed on a regular basis. Following the introduction of Be the control of the plasma density was much easier and He GDC was no longer necessary to prevent uncontrolled release of gas at the start of a pulse [27].

The fraction of D released after a pulse increased to over 80% [24], and later including overnight collection increased to just over 90%. However, the ratio of the plasma content to the amount of fuelling (the fuelling efficiency) fell following Be introduction initially to ~15% and subsequently averaged about 10%, compared with 30-40% for the “all-carbon” machine. Thus with Be in the machine the mean amount of D retained long-term within the torus is, as with the “all-carbon” machine, approximately equal to the mean plasma content, as the smaller percentage of gas retained is completely offset by the larger gas input. The distribution of D within the vessel was similar to that for the “all-carbon” phase of 1988; even the Be belt limiters surfaces supported films of similar D concentration [10], though it was unclear whether the D was associated with the Be or with the C also found on the surface.

### 3.3. The JET Mk I divertor

After the installation of the divertor in the bottom of the JET vessel [16], the first divertor configuration (Mk I) was operated from April 1994 to March 1995 with CFC tiles, and from April to June 1995 with Be tiles. A cross-section of the divertor is shown in Figure 1(a). The target tiles were attached in pairs to a water-cooled structure so that the bulk tile temperature during a pulse might reach a maximum of 200°C at the strike point, but would rapidly return to the ambient temperature of ~50°C afterwards.

Detailed mapping of the D concentrations over the tile pairs [12] showed that for carbon tiles there is a high level of D within the region shadowed by the adjacent tile alongside the outer strike zone and the outer SOL. However, there was much less deposition in the shadowed regions of the outer Be tiles. Even higher levels of deposition occurred in the shadowed regions of the inner divertor in the carbon phase, and deposition on the Be tiles appeared similar in magnitude to that on the carbon tiles.

The Be tiles were deliberately taken to the melting temperature at the end of the Mk I divertor campaign to look for vapour shielding effects, yet quite high levels of D were found in some regions, the D being retained within the Be (from ~2 to >8 μm from the surface). It is believed that at high fluxes and high temperatures D diffuses into the Be surface [12,28]. The much greater D retention at the inner leg of the Mk I divertor is emphasised when analysis of the side wall (tiles 1-4) is included: for both carbon and Be sets, there is heavy deposition on these

inner side wall tiles, whilst the outer wall tiles appear pristine with only implantation levels of D.

The heavy deposition on the Be tiles is predominantly **carbon** and not beryllium, as was clear from $^{1}$H RBS analyses. For most of the discharges with the Be divertor, C was still the major plasma impurity [29]. The C (which must come from the walls of the main chamber) travels along the SOL to arrive on the plasma-facing parts of the divertor. From there it must be recycled in preference to the Be to deposit in the shadowed areas in conjunction with D. As the temperature is low (certainly <200°C) the D:C ratio is high (~0.5:1). The low level of deposited D in the outer leg of the Be divertor indicates that C does not deposit to the same extent in the outer leg, or is resputtered and transported out of the outer leg completely.

### 3.4. The JET Mk IIA divertor

A cross-section of the Mk IIA divertor that was installed in JET for operation from April 1996 to Feb 1998 is shown in Figure 1(b). The divertor is designed to be more closed in aspect, in order to be closer to ITER conditions. It has a smaller number of much larger tiles than the Mk I divertor, as seen in Figure 2, where the dashed outlines of Mk IIA tiles are superimposed on a plan of a section of the Mk I divertor floor; 4 Mk IIA tiles replace 64 Mk I tiles. A consequence is that whilst the Mk I divertor was ~15% transparent for pumping (through the gaps between tiles), in Mk IIA all pumping by the sub-divertor cryopump is through the gaps between floor and side wall modules at the inner and outer corners (the speed through each being roughly equal).

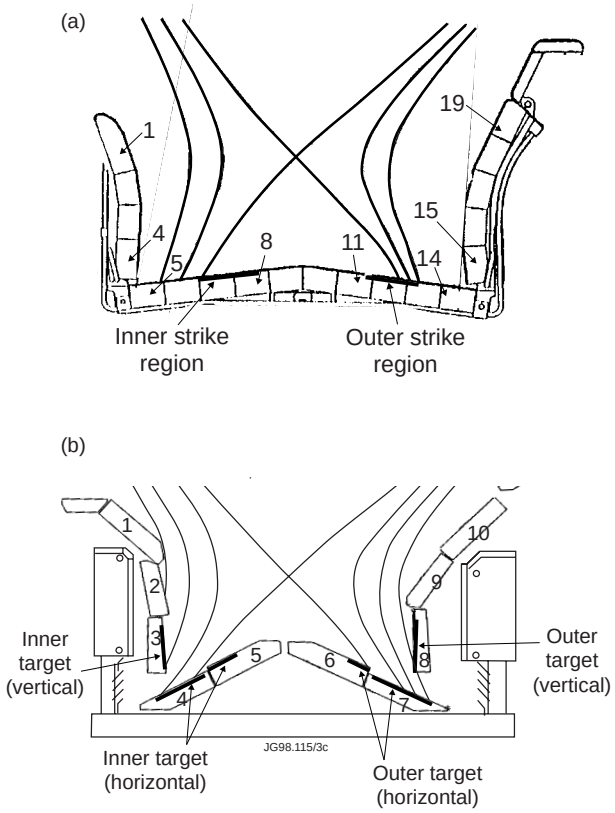


*Fig.1: Cross-sections of the JET divertors, showing some field lines for a typical plasma, and showing the numbering systems for the target tiles (a) the Mk I divertor, (b) the Mk IIA divertor.*

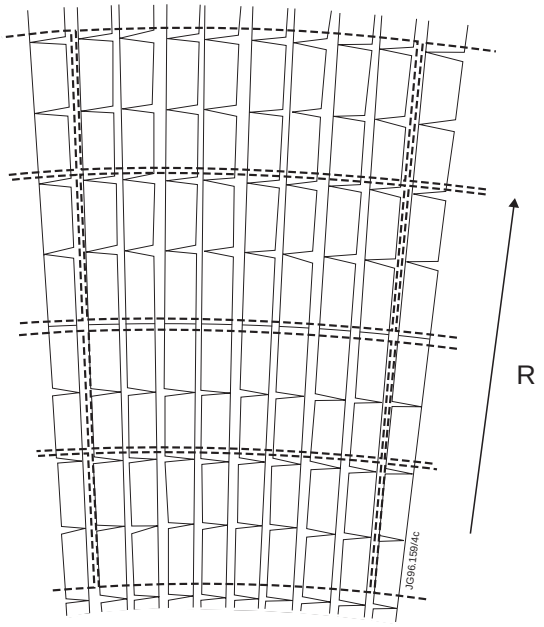


*Fig.2: Schematic of a sector of the floor of the Mk I divertor (target tiles outlined with solid lines), with the dashed outlines of Mk IIA divertor floor tiles superimposed.*

Figure 3 shows the D analysis by NRA over a set of Mk IIA floor tiles removed in October 1996 after ~ 2000 pulses. The D level is seen to be quite uniform toroidally (the only variation being a slightly higher level in the part of tile 5 shadowed by the adjacent tile to the right). A variety of strike point positions were employed using both floor and side wall tiles, however the most common positions for the outer and inner strike points were the centre of tile 7 and the outer half of tile 4, respectively. The ends of tile 7 (where the D analysis is < $10^{22}$ atoms $m^{-2}$) and tile 4 (D >3 x $10^{23}$ atoms $m^{-2}$) are shadowed by the side wall tiles 8 and 3, respectively. In fact these analyses do not do justice to the disparity in D retention between the inner and outer corners. There was also heavy deposition on the water-cooled louvres beyond the inner corner, and on the bottom end of tile 3 (i.e. facing the end of tile 4).

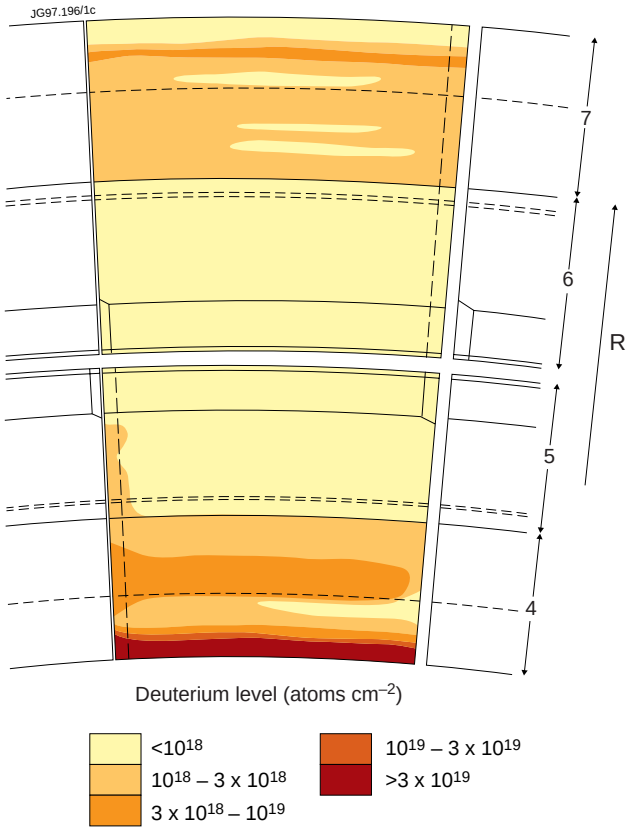


*Fig.3: A map of the D concentration on the surfaces of a sector of Mk IIA divertor floor tiles.*

Some of the film spalled off the louvres (probably following venting to air) and lay as flakes on the structure below. From flakes retrieved from this region, and sections cut from the end of tile 3, the films were measured to be 40 μm thick [30]. In total contrast the tile and louvre surfaces beyond the outer corner appear pristine. The outer side wall tiles also appear clean, with D levels of ~3 x $10^{21}$ atoms $m^{-2}$, compared with an order of magnitude more on the inner side wall.

During the period April-October 1996 the total gas input to the torus was 9 x $10^{25}$ D atoms. The D retained on the plasma-facing parts of the divertor (i.e. not including the heavy deposit on the inner edge of tile 4) from the NRA analysis of the tiles removed in Oct 1996 was ~3 x $10^{23}$ atoms. In Oct 1996 only the sides of the louvres facing radially outwards could be seen, however when the Mk IIA divertor was removed in Spring 1998, the heavy deposition was seen to extend over about half of the back surfaces. Assuming the deposited film beyond the inner corner of the divertor was carbon (saturated with D) and everywhere 40 μm thick, and a D:C ratio of 0.5:1, the retention for the period April-Oct 1996 in these deposits alone amounts to ~5 x $10^{24}$ atoms, or ~6 % of the gas input. Indications from RBS measurements are that the D:C ratio may be as high as 0.8:1, in which case the deposits account for nearer 10% of the gas input; gas balance measurements (which were not as accurate as for pre-divertor phases) indicated ~10-15 % long-term D retention.

### 3.5. The JET DTE1 campaign

In the period May to November 1997 JET conducted a series of experiments using deuterium-tritium fuelling mixtures known as the “DTE1 campaign”. During the campaign the T gas entering and recovered from the vessel was accurately measured [15]. The quantities of D entering and leaving the vessel were also measured. In total 35g T entered the vessel, and after the last T-fuelled pulse 11.5g still remained in the vessel. Following 3 months of cleanup experiments, mostly using deuterium (and some hydrogen) pulses the T still trapped in the vessel was 6g [15]. The figure of 11.5g retention represents ~30 % of the T input, and the final retention is still ~17 % of the input, compared to the percentage of D retention seen in previous Mk IIA phases of ~10-15 %. However, the gas balance measurements during DTE1 show that D is released during T fuelling, and vice versa, and that the mean **total** hydrogenic gas retention was still ~10-15 %, as seen in Figure 4, so the additional T retention may result from isotopic exchange with D in pre-existing retention sites.

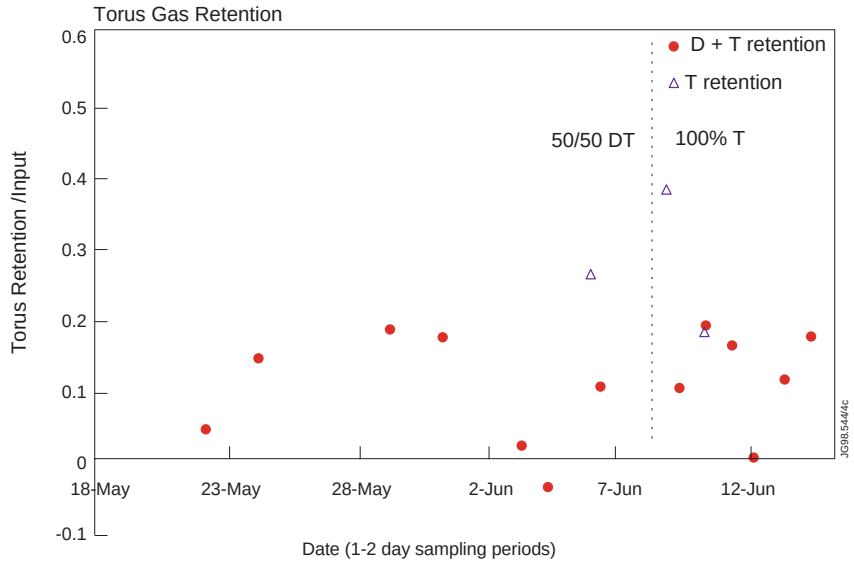


*Fig.4: The fraction of gas retained in the torus over 1-2 day sampling periods during the 1997 JET DTE1 campaign, plotted against the date.*

From the gas balance and previous analyses, a large part of the trapped T may be assumed to be in the deposits beyond the inner corner of the divertor. There is additional evidence to demonstrate this hypothesis. Firstly, the results from the Preliminary Tritium Experiment (PTE) in 1991 [14] were scaled up by the amount of T fuelling to predict the retention and the plasma tritium fraction during DTE1. The tritium fraction is accurately predicted, both for the D-T fuelled pulses and the subsequent clean-up programme [15]. However, the retention prediction is that only ~2g should finally remain in the vessel. During the PTE all surfaces likely to retain T were accessible by ions or neutrals from the plasma, however as seen in the previous section this is not true for the sink of material at the inner divertor corner. As seen in Figure 5 the discrepancy in the prediction of retention for DTE1 from the PTE is removed if ~14% of the T

fuelling is assumed to go into deposits which cannot be accessed. Further evidence comes from the T outgassing behaviour of the torus. The outgassing rate on exposure to air is ~20 times that predicted from the PTE, and removal of all the divertor tiles and fittings from the vessel still left more than half of the activity within the vessel. Removal of the tile carriers allowed access to the deposits on the inner louvres, and most was captured by brushing and vacuuming: the deposits will be thoroughly analysed for H,D,T,C and other elements, though their extremely high activity of ~5 $TBqg^{-1}$ means very stringent safety measures must be employed.

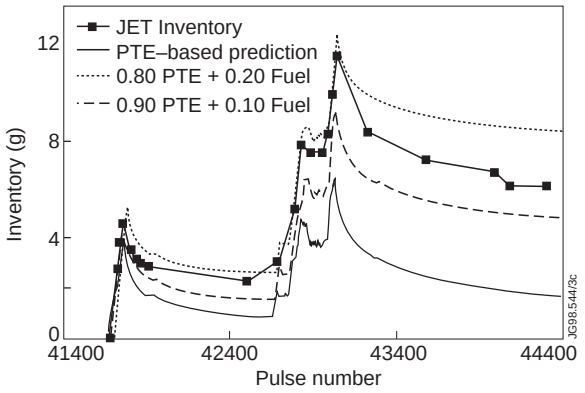


*Fig.5: The tritium inventory in the JET vessel (measured as the difference between the tritium fuelling and the amount recovered from the vessel) plotted against pulse number for the 1997 DTE1 campaign. Also plotted are predictions of the inventory based on the behaviour during the PTE campaign of 1991, made by (i) merely scaling up the amount of T fuelling, (ii) adding an extra retention equal to 10% of the fuelling, and (iii) adding an extra retention equal to 20% of the fuelling.*

## 4. DISCUSSION

Accurate estimates of the amounts of hydrogenic species retained in a tokamak, measured either by gas balance or post-mortem analysis, are notoriously difficult to obtain. The former are bedevilled by problems such as gauge calibration, impurity production, branching ratios to various pumps, etc, whilst for the latter the techniques cover only limited depth, a minute proportion of the first wall surface area is analysed, surfaces may be modified by exposure to air, etc. One of these points merits a special comment: analyses of surfaces removed from tokamaks invariably show comparable hydrogen levels to the deuterium levels, despite almost exclusive operation in deuterium [3,4,20]. The H appears to be localised to the deposited films (or to the surface layers where there is no extra deposit on the component). Although one belief is that the H comes from isotopic exchange in air with the D, the distribution of H into the film may be quite different to the D [20]. The H may arise from absorption from the air throughout the porous tokamak deposits, though the most reactive species is water (and there is negligible associated O). Analysis of hydrogen in surfaces is difficult, but further work is clearly indicated, such as whether there are independent saturation levels for H and D, or instead a limit to (H+D).

Despite the difficulties, reasonable agreement between post-mortem analyses and gas balance measurements has been obtained consistently at JET. Furthermore, the trends and changes in the retained inventory clearly demonstrate the influence on the inventory of materials, operation modes, etc, and indicate important lessons for consideration in the design of future devices. Firstly, the amount of gas retained in JET clearly increased with the amount of carbon used as protective cladding for the inner wall and to act as targets. It is important to point out that the JET measurements of retention for the “all-carbon” limiter machine are totally compatible with studies on TFTR [26]. Secondly, the presence of relatively small amounts of Be in the vessel had

a profound effect on fuelling parameters. The amount of D retained per pulse did not change significantly, but the amount of gas required to fuel the plasma increased by about a factor of 5, and the stability of the D within the first wall surfaces greatly increased, so that the frequent He GDC to prevent uncontrolled density rises in the “all-carbon” machine was unnecessary.

Another important step in JET towards the current designs for future machines was the installation of a divertor (together with an internal cryopump). Although there was a further increase in the mean fuelling per discharge, the amount of D retention in the Mk I was comparable to previous phases. One significant change made when installing the divertor was to introduce water-cooled surfaces within the vessel, whereas previously all in-vessel surfaces were held at 300°C. The majority of the deposition in the Mk I divertor was in shadowed areas on tiles attached to water-cooled supports; as a consequence the permissible D:C saturation level is higher, and the retention in these areas correspondingly increased.

Two issues concerning the pattern of deposition in the Mk I divertor are important for our understanding of the processes involved (and hence our confidence in predicted retention in future machines such as ITER). Firstly, there is an asymmetry in deposition between the inner and outer divertor legs: about an order of magnitude more carbon deposition occurs at the inner divertor leg than at the outer leg. The integrated ion fluence to each leg is virtually identical [31], and although a slightly lower ion energy on average may be expected at the inner leg, the plasma normally remains attached in JET. Theoretical modelling has not so far provided a satisfactory explanation of the strong asymmetry. Secondly, the classical picture for impurity recycling is sputtering of neutrals from a surface, ionisation in the SOL, and transport along field lines to another point on a surface intersecting the SOL. This does not explain local deposition in shadowed regions as seen in the Mk I divertor [12]. Both the asymmetry and deposition in shadowed regions were also noted on the upper X-point targets used in 1991-2 [32].

An issue of basic importance for divertor studies is understanding the source of impurities. Although the regions of high incident ion flux are the divertor target tiles, these areas do not necessarily provide the plasma impurities. Operating the JET Mk I divertor with Be tiles demonstrated that carbon was still the principal plasma impurity for most discharges [29], so that under these conditions most impurities must originate at the walls of the main chamber. Furthermore, the post-mortem analyses showed that deposition and retention in the divertor was dominated by carbon arriving in the divertor from the main chamber and recycling locally in preference to the Be substrate material (perhaps due to chemical sputtering). The ITER divertor conditions will be more favourable for efficient screening of impurities than any existing divertor. However, the problem is to first quantitatively account for the sources of plasma impurities in present-day tokamaks so that the relative contributions of the divertor and the first wall can be ascertained, and to then extrapolate from these to ITER. ITER assumes a negligible influx of impurities from the first wall into the plasma, and this is a long way from the situation in present-day machines.

Retention in the Mk IIA divertor is dominated by the codeposition beyond the inner corner of the divertor on the louvres and the tile surfaces adjacent to the pumping gap. The deposition in this region is **in addition** to the deposition seen in JET prior to the divertor installation. For the first time material is being deposited many centimetres into a shadowed area without attenuation, by what appears from shadowing on the support structure to be line-of-sight transport. Deposition seen on the back of the louvres appears to show that there is a reasonable probability of reflection from the first impact (at the face of the louvre above) , and the quality of the deposits also indicates energetic particle impingement. There is a sight line to the surface of tile 4 (an area that frequently acts as the inner strike zone), however the amount of carbon deposited is ~4% of the total ion fluence to the inner target (~3 x $10^{26}$ ions) [15] (which will include fluence to areas without a line-of-sight to the deposition area). It is difficult to see how such a large sputtering coefficient (coupled with a suitable transport mechanism) can be explained. It is possible that large quantities of carbon may be eroded from tile 4 during ELMs, but there is no obvious difference in gas balance results between periods with mostly ELMy discharges and periods with fewer ELMy pulses. It is important to discover if certain modes of divertor operation produce less deposition (and hence less gas retention), and dedicated experiments are planned.

Since the Mk IIA divertor is the only JET configuration in which such large deposits have occurred, it is difficult to predict what will happen in future machines such as ITER. Further experiments to show how divertor plasma conditions affect the extent of deposition are necessary. However, it is clear that if all the surfaces where deposition occurs are held at high temperature, then the codeposited hydrogen isotope concentration can be greatly reduced.

JET has now installed the Mk IIGB divertor, which provides an even more closed aspect, includes a central septum, and allows separate fuelling into the inner and outer divertor legs. It is hoped that a series of careful experiments with additional diagnostics may help to elucidate the mechanisms controlling retention in divertors.

## 5. CONCLUSIONS

The fraction of deuterium fuelling retained in the JET vessel following plasma pulses increased with the proportion of carbon cladding installed on the interior surfaces of the torus, reaching ~40% of the input for the “all-carbon” machine in 1988. About one-half of this retained D was probably released during ventings to air, periods of He GDC, etc, before a detailed analysis survey of first wall components was made.

The introduction of Be into JET by regular Be evaporations and the use of some Be components did not significantly affect the amount of D retained per pulse. However, the amount of D gas required to fuel the plasma rose sharply, by about a factor of five. The presence of Be greatly reduced the level of oxygen in the plasma, and improved the control of the plasma density by preventing uncontrolled release of gas from the walls.

X-point and Mk I divertor operation in JET have shown that there is a marked asymmetry

in the deposition of impurities (and the associated codeposition of D); about an order of magnitude more D is retained in the region of the inner strike zone than in the outer strike zone. Operation of the Mk I divertor with Be tiles showed that for most discharges carbon from the first wall was the principal plasma impurity, and that the retention of D in the divertor was associated with carbon (which is presumably transported to the divertor along the SOL). Higher concentrations of D are found in deposits formed in regions held at <200°C, with D:C ratios of at least 0.5:1.

Following the first 6 months of operation with the JET Mk II divertor in 1996, heavy carbon-based deposition was found on water-cooled louvres and other cool surfaces several centimetres beyond the inner corner of the divertor. The deposits were dense films with high D:C ratio (at least 0.5:1), and resulted in additional retention during this phase of at least 6% of the gas fuelling. Much of the T retained in JET following the DTE1 campaign in 1997 was also trapped in deposits in this region, resulting in an activity of ~5TBqg$^{-1}$ for this material. The mechanisms controlling the film formation are not understood, and further experiments are planned to ascertain which divertor plasma parameters (or phenomena such as ELMs) are important, so that such films may be minimised in future machines such as ITER.

**REFERENCES**


[1] Ehrenberg, J.K. *et al.*, Proc. of the 14th European Conf. on Controlled Fusion and Plasma Physics, Budapest, September 1985 (European Conf. Abs. 9F Part II, 575 (1987))

[2] Coad, J.P. *et al.*, *ibid* p571.

[3] Behrisch, R. *et al.*, J. Nuclear Materials, 145-147, 723 (1987)

[4] Bergsaker, H. *et al.*, *ibid* p727

[5] Coad, J.P. *et al.*, Proc. of the 14th European Conf. on Controlled Fusion and Plasma Physics, Madrid, June. 1987

[6] Harbour, P. *et al.*, J. Nuclear Materials, 162-164, 236 (1989)

[7] McCracken. G.M., Goodall, D.H.J., Stangeby, P.C., Coad, J.P. and Roth, J., *ibid* p356

[8] Coad, J.P. *et al.*, *ibid* p533

[9] McCracken, G.M. *et al.*, Proc. of the 16th European Conf. on Controlled Fusion and Plasma Physics, Venice, March 1989

[10] Peacock, A.T. *et al.*, J. Nuclear Materials, 176-177 326 (1990)

[11] Coad, J.P., J. Nuclear Materials, 226, 156 (1995)

[12] Coad, J.P., Rubel, M. and Wu, C.H., J. Nuclear Materials, 241-243 408 (1997)

[13] Peacock, A.T., Coad, J.P., Dietz, K.J. and Knight, A.P., Proc. of the 17th Symposium on Fusion Technology, Rome, Sept. 1992

[14] Andrew, P.L. *et al.*, Nuclear Fusion, 33 1389 (1993)

[15] Andrew, P.L. *et al.*, Proc. of the 13th Conf. on Plasma-Surface Interactions, San Diego, May 1998

[16] Bertolini, E. *et al.*, Proc. of the 15th Symposium on Fusion Engineering, Hyannis, Mass., October 1993
[17] Federici, G. *et al.*, Proc. of the 13th Conf. on Plasma-Surface Interactions, San Diego, May 1998
[18] Coad, J.P., Simpson, J.C.B. and Neill, G.F., Surface and Interface Analysis, 14 543 (1989)
[19] Coad, J.P. *et al.*, J. Nuclear Materials, 176-177 145 (1990)
[20] Coad, J.P., Skorodumov, B.G., Ulanov, V.G. and Wu, C.H., Vacuum, 47 985 (1996)
[21] Coad, J.P. *et al.*, Proc. of the 12th European Conf. on Controlled Fusion and Plasma Physics, Budapest, Sept. 1985 (European Conf. Abs. 9F Part II, 571 (1985)).
[22] Roth, J., Ehrenberg, J.K., Wittmaack, K., Coad, J.P. and Roberto, J.B., J. Nuclear Materials, 145-147 383 (1987)
[23] Coad, J.P., Davies, B.J., Edge, G.J., McCracken, G.M. and von Seggern, J., *ibid* p736
[24] Sartori, R. *et al.*, J. Nuclear Materials, 176-177 624 (1990)
[25] Coad, J.P., Orchard, J. and Monahan, J., J. Nuclear Materials, 160 95 (1988)
[26] Wampler, W.R., IEA Workshop on: Tritium Experience in Large Tokamaks; Application to ITER, Princeton, March 1998
[27] Pasini, D. *et al.*, J. Nuclear Materials, 176-177 186 (1990)
[28] Macaulay-Newcombe, R. G., Thompson, D. A. and Coad, J. P., Proc. of ICFRM-8, Sendai, Japan, October 1997
[29] Thomas, P. and the JET Team, J. Nuclear Materials, 176-177 3 (1990)
[30] Peacock, A.T. *et al.*, Proc. of the 13th Conf. on Plasma-Surface Interactions, San Diego, May 1998
[31] Monk, R.D., Ph.D. Thesis, University of London, 1996
[32] Coad, J.P. and Farmery, B., Vacuum 45 435 (1994)