JET-R(94)11

An Appraisal of Deuterium Retention in JET and the Implications for Tritium Retention in ITER

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November 1994

ABSTRACT

The amounts of deuterium retained within the JET vessel after campaigns in the years 1985-9 have been re-evaluated and shown to indicate that codeposition of D and wall material is the principal retention mechanism. The amount retained per pulse (~4x10exp20 D atoms per pulse on average) is shown to fit well with a model wherein the amount of carbon (or other wall material) passing through the plasma during the discharge determines the maximum retention (which can only be realised if first wall temperatures do not exceed 270 C). Such a model can then be used to predict hydrogen isotope retention in other large machines such as ITER. For ITER if a global impurity level in the plasma of 1% is used, the maximum retention (wall temperature <270 C) of tritium would be 500g in 10exp6 secs.

INTRODUCTION

More detailed analytical surveys of the amount of deuterium retained on First Wall surfaces and measurements of the gas balance have been carried out at JET than on any other tokamak. Over a period of several years the measurements have followed the gradual development of the "all-carbon" machine, the introduction of beryllium gettering and the use of a mixture of Be and C first-wall components. This report summarises the JET data and develops some deuterium retention scenarios that can be extrapolated to ITER.

MEASUREMENTS OF DEUTERIUM RETENTION IN JET

(i) Gas Balance

(a) "All-Carbon" Machine

When JET first operated in 1983 the interior of the torus was bare inconel walls with 8 discrete limiters distributed around the outer midplane, of which four were nickel and four were graphite (though the nickel were always at larger radius than the graphite, so never actually used as limiters). Over the subsequent five years the inner surfaces were lined with an increasing number of graphite tiles (1). Firstly the inner wall was covered to protect it from erosion, and secondly poloidal rings of tiles were added in increasing numbers to reduce nickel atoms from the wall reaching the plasma (though nickel still entered the plasma at times from the RF antennae at the outer midplane) and to allow the X-point plasma configuration to be tested using the top of the torus as the target. Finally, in 1987 the discrete limiters were replaced with two toroidal belt limiters, so that by 1988 55% of the inner surfaces of the torus were covered with graphite tiles, and no ion from the plasma could impinge on any surface that was not carbon (an "all-carbon" machine). (Note, however, that for fast **neutrals** able to move in any direction almost half the inconel wall is still visible). In December 1987 a gas-handling manifold was

installed on the outlet line from the torus vacuum pumps so that the amount of gas exhausted could be measured and compared with the (known) gas input for each pulse (2).

The mean fuelling efficiency (ratio of plasma content to gas input to the vessel) for discharges in the "all-carbon" machine was 30% - 40% and the mean amount of deuterium recovered was ~60% of the input, in each case as an average over a day of plasma operations (2). (Note, the figures for individual discharges vary considerably with plasma density, power and particularly for discharges ending in a disruption). Thus the amount of deuterium **retained** was approximately equal to the integrated plasma contents for the day. It should also be noted that much of the release is quite slow - within 600secs after a pulse the release is more typically 20% (eg ~1x10exp21 from an input of ~5x10exp21) (Figure 1).

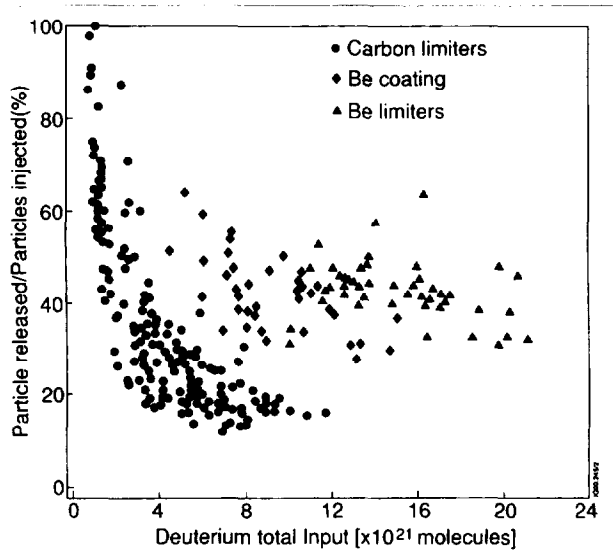

Figure 1. The fraction of gas released within 600 secs after a discharge as a function of the total input (for pulses fuelled with deuterium - disruptions not included).

(B) After the Introduction of Beryllium

In 1989 Be was introduced into the JET machine in two stages. Firstly Be was evaporated over the inner wall from four evaporator heads spaced around the outer wall of the vessel (just below the midplane). Typically a thin layer was evaporated each night in readiness for the following day's operations. After a few months the graphite tiles on the belt limiters were replaced with beryllium tiles, so that beryllium became the predominant plasma impurity during limiter discharges: beryllium evaporation was still employed on a regular basis.

Following the introduction of Be the control of the plasma density was much easier, for example uncontrolled release of gas at the start of pulses was reduced, and pulses tended to end with a MARFE rather than a disruption (3). The fraction of deuterium released after a pulse increased, initially to over 80% (2), and later including overnight collection to just over 90%. However, the fuelling efficiency fell following Be introduction initially to ~15% and subsequently averaged about 10%. **Thus with Be in the machine the mean amount of deuterium retained long-term within the torus is, as in the "all-carbon" machine, approximately equal to the mean plasma content, as the smaller percentage of gas retention is completely offset by the larger gas input.**

(ii) Analysis of First-Wall Components

(a) Limiter Tiles

After every operating phase of JET, first wall components have been removed for analysis. In particular the Ion Beam Analysis (IBA) technique Nuclear Reaction Analysis (NRA) has been used to give a quantitative analysis of the surfaces of first-wall components (to a depth of ~0.5 microns) for deuterium. It was already clear from the large concentrations of deuterium found at areas of the discrete limiters following the first use of D in JET for a few weeks in 1984 (~10exp18 cm-2) that deuterium must be trapped by codeposition with carbon and could not result from ion implantation alone (4). On the other hand, the levels at the vessel wall (measured using small long-term samples (LTS) bolted to the inner surface of the vessel) were <10exp16 cm-2 (5), which could result from either ion implantation or a small amount of codeposition. The pattern of the D distribution at the limiters shows a minimum at the region of maximum power deposition, passing through a maximum ~2-3 cm into the scrape-off layer (SOL) and then decreasing exponentially deeper into the SOL. (Figure 2, from ref. 4). The maximum energy flux occurs at the Last Closed Flux Surface (LCFS), which by definition is the tangency point for the central limiter tile, but here the surface is parallel to the direction of flow so there is theoretically no power deposition. The maximum power fluence to the surface occurs to either side of the tangency point where high fluxes combine with some projected angle. This can also be seen after the more extensive 1985 (Fig 2) and 1986 operations in D.

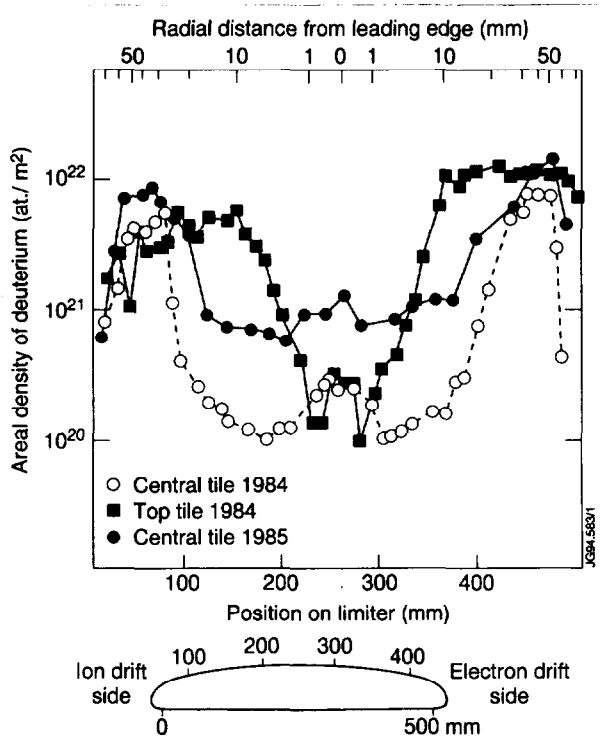

Figure 2. The lateral distribution of deuterium on three different limiter tiles. The two minima on each of the central tiles correspond to the regions of maximum heat load.

In the analyses of the limiters after each of the three years, the maximum D level in the NRA data is ~10exp18 cm-2. Since the depth analysed by NRA is ~0.5 microns, and the saturation level for H+D in C is given by (H+D)=0.4C (6), the maximum H+D that can be present in the layer analysed is ~2×10exp18 cm-2, so since H is also present in the film the level seen is merely the saturation level for the technique: if the film is, say, 10 microns thick the D content may be 20 times greater. Limiters removed from JET after the 1986 operations

were sectioned and the films in the SOL region were found to be up to 130 microns thick, whilst in the plasma contact area up to 200 microns had been eroded (Figure 3, taken from ref. 7). Clearly the deuterium content of these thick layers is important, since for one metre square the NRA saturation level gives an inventory of 2×10exp22 deuterons (assuming no H) but if the layer is saturated throughout the 130 microns the inventory is 5×10exp24 deuterons. One technique that was used to check the compositional uniformity through the film was Secondary Ion Mass Spectroscopy (SIMS). In SIMS an ion beam etches a pit into the surface, whilst ions sputtered from the surface are analysed in a mass spectrometer. Thus the relative intensity of each ion species detected with time gives the depth distribution of the element through the film. The resulting profile from a point on a 1986 limiter tile where the redeposited film was 24 microns thick is shown in Figure 4, also taken from ref. 7. The metallic impurity elements such as the nickel show considerable variation in concentration within the film, probably reflecting different phases of the campaign such as periods with extensive use of RF heating. It is clear that depths within the film correspond to different time-slices when one looks at an optical micrograph of a section from a nearby tile (Figure 5). Each of the multitude of layers clearly results from a specific period of operation, preserved as in a geological section. Care must be taken with SIMS data, however. The elemental profiles may be distorted by differential sputtering effects (when one element is sputtered more easily than another), surface roughness effects (either from the initial surface or due to differential sputtering), knock-on effects (profiles extended because atoms of the element are being knocked deeper into the surface by the incident beam) and matrix effects (the apparent concentration of an element can vary by an order of magnitude depending on how it is bound in

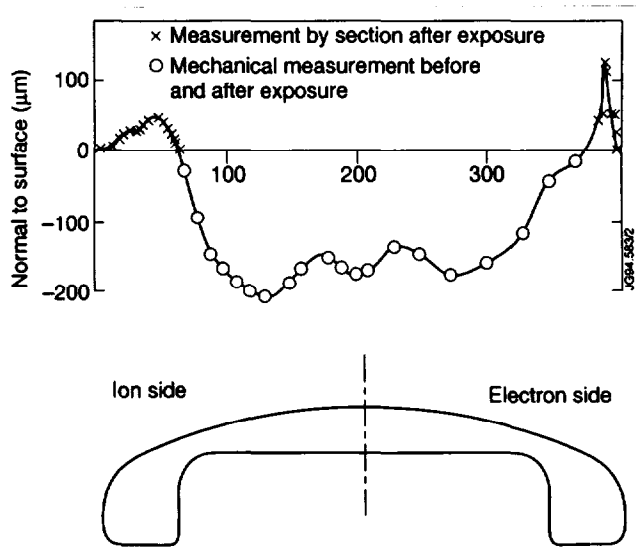

Figure 3. Experimental measurements of erosion and redeposition of carbon on a central JET limiter tile exposed in 1986.

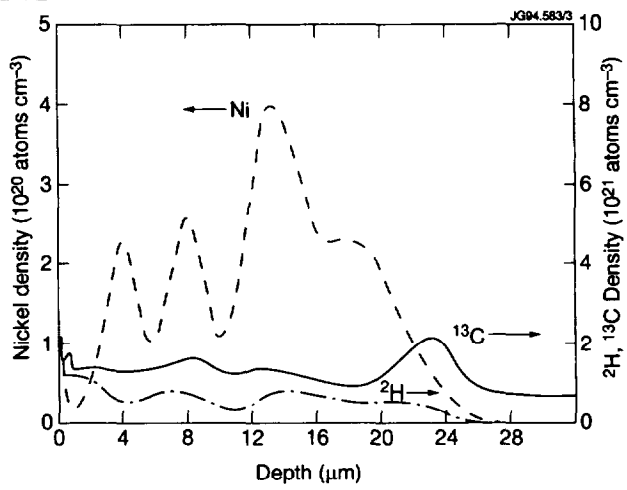

Figure 4. SIMS depth profiles of nickel and hydrogen in a 24 micron thick layer of redeposited carbon from the ion side of the same tile as used for the measurements reported in Figure 3.

the matrix). The H and D levels in the film appear to start high at the surface, but then fall to much lower values. This has a very significant effect on the retained D inventory of the film (possibly reducing it by an order of magnitude), but it must be stressed that the possible errors in SIMS measurements apply particularly to hydrogenic species, so the data can only serve as a stimulus for further quantitative analysis.

The picture that emerges from the analysis of the discrete limiters is that the power flux to surfaces at or near the LCFS causes net erosion in these areas, with a small D inventory due probably to implantation and ion mixing ahead of the erosion wavefront. Deeper into the SOL the lower ion energies mean less efficient sputtering, and there is net deposition by codeposition of D and carbon. The observed data were modelled by McCracken et al (7), and similar results have been observed on probes exposed to single plasma pulses (8). The same scenario applied to the JET belt limiters in use from 1987 to 1992 (9), although the interpretation of the data was complicated by the redeposition of material subliming (graphite) or evaporating (beryllium) from prominent tile edges. The black streaks of redeposited material starting at each erosion site and angled along the field line direction show this to be a rapid process, with a mean free path before ionisation and re-entrainment for return to the surface characteristic of sublimation (evaporation) rather than sputtering: entrainment and redeposition of molten Be particles could also be seen on video films of the limiters.

Figure 5. An optical micrograph of a section through a thick redeposited layer on the side of a 1986 JET limiter. Layers deposited in each period of the operations can still be distinguished.

(b) X-Point Tiles

From 1987 increasing use was made of the 40 poloidal rings of tiles at the top of the vessel as the plasma contact point for so-called "X-point" discharges. The plasma geometry and the resulting strike zones on the poloidal rings of tiles are shown schematically in Figure 6 (from ref. 10). One of the poloidal rings of tiles was removed for analysis in August 1987 after ~32 pulses with ~4MW of coupled ICRH power. The analyses showed a region of extensive erosion at the outer strike point surrounded by areas of extensive deposition, with the retained D

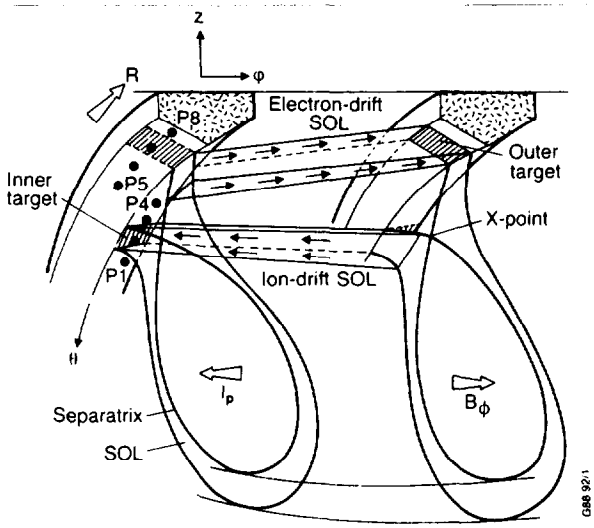

Figure 6. Geometry of the X-point divertor in JET.

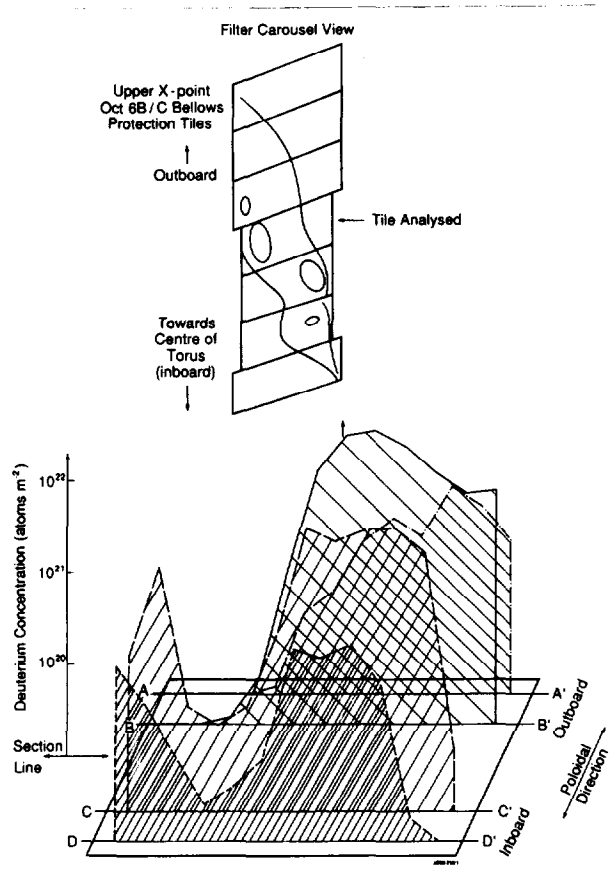

Figure 7. Deuterium profiles determined from tiles exposed in the upper X-point region of JET.

level up to 10exp18 cm-2 and considerable amounts of H also seen by SIMS (10), so the deposits may already have reached the maximum depth that can be analysed by NRA.

Further tiles were removed in May 1988 after ~2500 discharges, of which ~1000 were X-point discharges. Again a region of net erosion was clearly seen (with the polished appearance characteristic of such regions) wherein the D level was ~10exp17 cm-2 surrounded by redeposited material which sectioning showed to be up to 5 microns thick (11). Poloidal tiles were also examined in 1989 with similar results (Figure 7 from ref. 12). Since Be had now been introduced into the vessel, samples removed from the vessel had to be handled in glove boxes, so a special IBA analysis facility was built at the Sussex University Accelerator facility to handle Be-contaminated samples safely and also to cater for large samples such as X-point tiles without needing to cut them up.

The power handling capability of the poloidal rings of graphite tiles was limited, so in 1992 the top of the vessel was given a complete toroidal cover of tiles. During the period June to August 1992 JET operated with flat graphite tiles mounted side by side on backing plates, with 40 plates making up the complete toroidal cover. Included on one of these plates was a poloidal

set of three boron-carbide coated graphite tiles (Figure 8 from ref. 13). Due to slight misalignments in tiles and plates on mounting in JET, severe edge effects were seen during X-point discharges which limited the power handling capability to roughly that of the previous poloidal rings. Massive erosion from the prominent edges and the attendant redeposition downstream tended to obscure the erosion/redeposition picture, however some patterns did emerge. Firstly, there was a general polishing of the tiles in the vicinity of the outer strike point

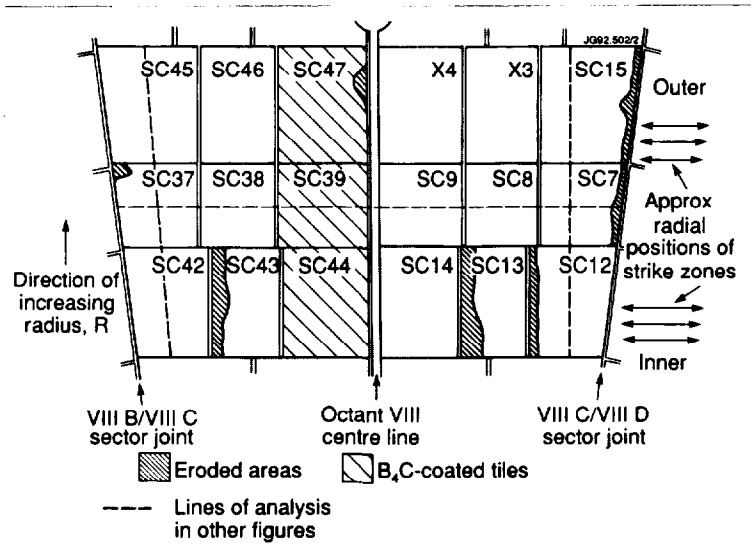

Figure 8. Plan view of a sector of graphite tiles at the upper X-point region of JET, showing the boron carbide-coated tile positions.

with generally low levels of D retention. Secondly, large concentrations of retained D were found inside this radius, that is on surfaces between the strike zones (the private flux region) and around the inner strike zone. The region **outside** the outer strike zone showed no evidence of codeposited layers, but rather D concentrations typical of anywhere in the vessel (a few 10exp17 cm-2).This is in marked contrast to the theoretical predictions (14) from the linked kinetic and Monte Carlo codes of Brooks (15) from which one expects that ions sputtered from the outer separatrix will be ionised and redeposited deeper into the SOL (ie to larger radius). Boron emanating from the coated tiles also provided valuable insights into particle transport. (Note that one of these tiles showed some edge erosion - Fig. 8). The amount of redeposited boron decreased exponentially with distance toroidally away from the coated tiles (Figure 9), whilst in the poloidal direction it was strongly peaked in the private region. Amounts of redeposited D reached 6×10exp18 cm^{-2} which implies a D:C ratio of more than 0.4:1. It may be that the presence of beryllium (and boron) can stabilise greater retained concentrations of hydrogenic species in carbon, as was postulated by Bergsaker, Coad et al (16)

In August 1992 shaped carbon fibre reinforced graphite tiles replaced the flat tiles in the target area. The tiles were carefully designed so that each tile provided a shadow region on the adjacent tiles so that no edge would be exposed if the tiles were slightly misaligned, particularly

at the plate joints, as shown schematically in Figure 10. These tiles behaved as predicted, with the power handling capability limited to about 4MJ per pulse by the flux to (and resulting temperature of) the "ski-slopes" which were angled at ~4 degrees to horizontal to give the required shadowing at the plate joints. (The field lines are incident typically at 1-2 degrees to horizontal, so flux to the "ski-slopes" is 3-5 times greater than elsewhere). The pattern of D retention on the flat sections of tiles was similar to that seen before - maximum redeposition around the inner strike zone and a minimum at the outer separatrix (Figure 11 from ref. 17). Along the "ski-slopes" the strike points were clearly visible

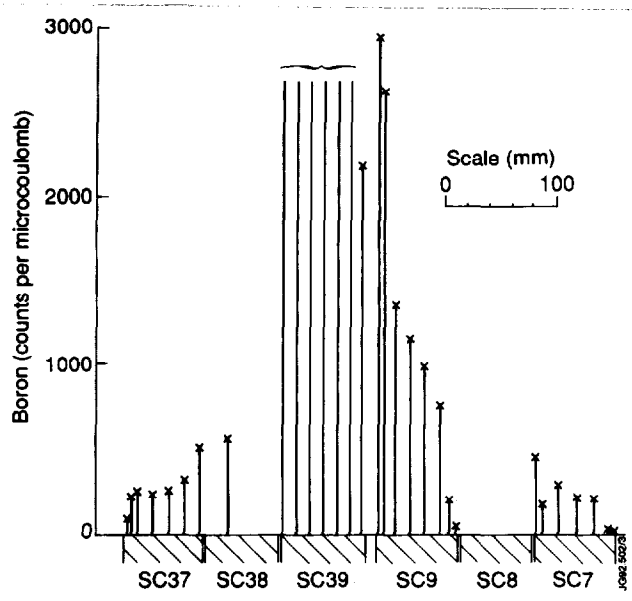

Figure 9. Boron concentrations (in arbitrary units) at points along a toroidal line across the X-point (the location of the line is shown in Figure 8).

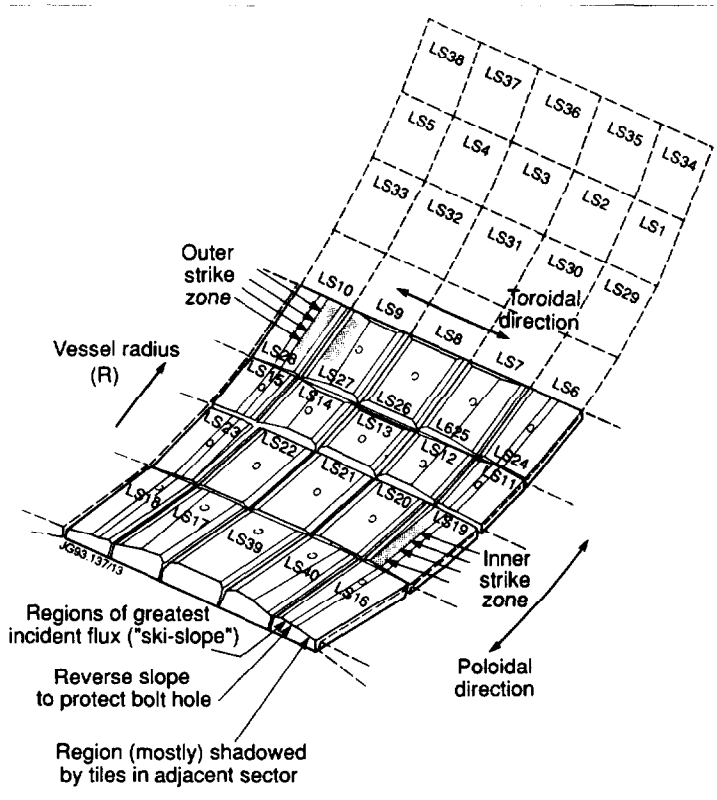

Figure 10. A schematic view of a section of X-point tiles: this set of numbered tiles is mounted on one support plate. The shaped CFC tiles are drawn with solid lines, whilst the flat graphite tiles are indicated with dashed outlines.

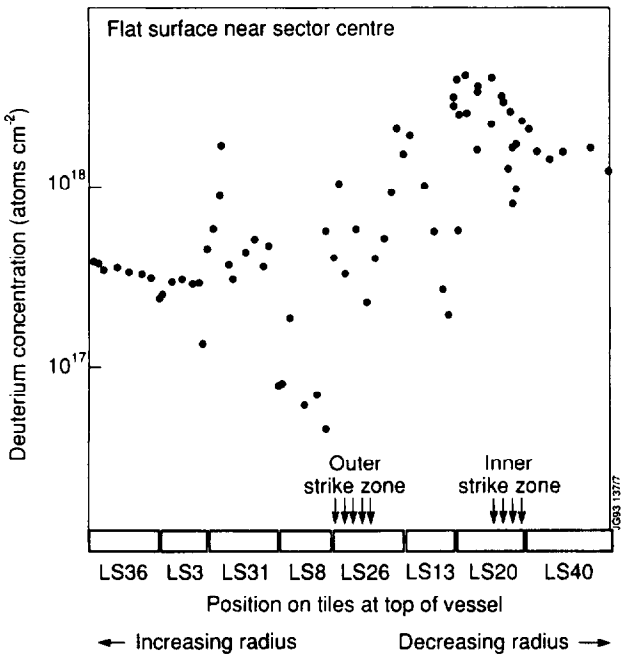

Figure 11. A plot of deuterium versus position on the target tiles, along a radial line across all eight rings of tiles at the centre of the sector (where the tiles are each flat).

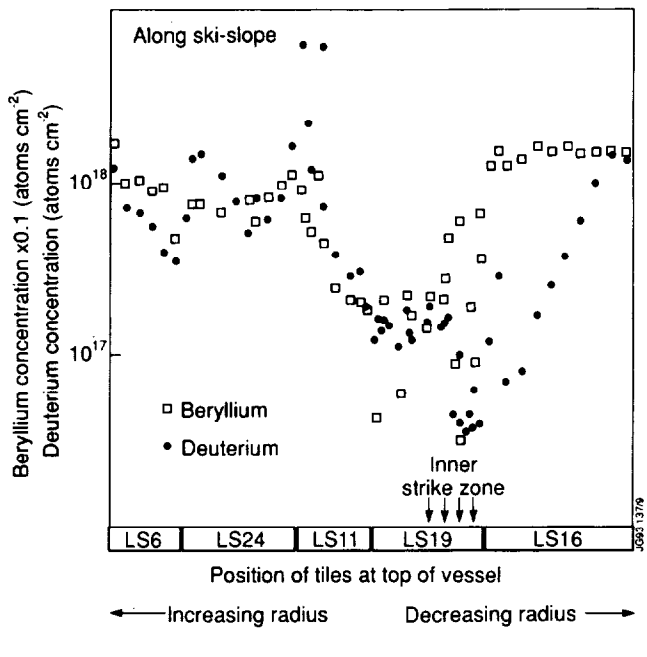

Figure 12. Beryllium and deuterium concentrations along the ski-slope on the right of the sector (as portrayed in Figure 10)

both by eye and from the D analyses which show very low retained D levels (~10exp16 cm-2), as seen in Figure 12 for a line along the "ski-slope" bearing the load at the inner separatrix. It is worth noting that all surfaces with reverse slopes (ie shadowed from direct plasma flux) show heavy deposition, even in the strike zones, showing that rapid local redeposition occurs.

(iii) Estimated Total Inventory in JET

A serious attempt was made by Coad et al (1) to derive figures for the total amounts of deuterium retained in the JET vessel after each operational campaign, based on the analysis of hundreds of pieces of graphite first wall tiles and LTS. The authors invented a special projection of the torus to show the areal density of deuterium at all points in the machine, which is reproduced in Figure 13 for the last exhaustive data set completed at that time (after the 1986 campaign). For each year the total in-vessel inventory was derived by mutiplying the surface area of each first wall component by the typical analysis for that item and summing over the entire inner surfaces. The resulting table, updated in a later publication (12), is given below in a re-written form as Table 1. In 1985 the vessel walls were coated with a thick layer of carbon by Glow Discharge Carbonisation (GDC) (18) using deuterated methane, which accounts for the majority of the D on the inner walls. If the same D wall loading as found after 1986 is used, the figures for % retention and average D atoms retained per pulse in 1985 become similar to those

Table 1: Amounts of Deuterium retained in the JET vessel after different campaigns

	1985	1986	Estimate for August 1987 (f)	May '88	October '88	(g) Estimate after 1989 (all phases)
Number of pulses in deuterium	~1800	~2800	~250	~2500	~4000	~1700
D gas input		~8.8×10^{24}	~8.1×10^{23}	~6.1×10^{24}	10.6×10^{24}	
Amounts retained: Inner wall	1.3×10^{23}	1.5×10^{23}	2.5×10^{23}	2.5×10^{23}	5.7×10^{23}	1.7×10^{23}
Limiters	~0.1×10^{23}	~10^{23}	~1.6×10^{23}	~2.5×10^{23}	3.1×10^{23}	(d) 1.6×10^{23} (e) 0.5×10^{23}
Rf Antennae			0.8×10^{23}	~0.6×10^{23}	0.4×10^{23}	~0.6×10^{23}
Poloidal tiles	–	0.6×10^{23}	(c)~2×10^{23}	4.5×10^{23}	6.3×10^{23}	2.1×10^{23}
Vessel wall	4.5×10^{23}	1.0×10^{23}	0.4×10^{23}	0.7×10^{23}	~0.8×10^{23}	0.9×10^{23}
Total	~5.9×10^{23} (~2.4×10^{23}) (a)	~3.5×10^{23}	(b) ~7.3×10^{23}	10.8×10^{23}	16.3×10^{23}	7.4×10^{23}
% gas retained	~16 (~4) (a)	~4	(b) ~90	16.9	15.5	
Atoms retained per pulse	(~1.3×10^{20}) (a)	~1.3×10^{20}	(b) ~3×10^{21}	~5×10^{20}	4.1×10^{20}	4.4×10^{20}

Notes

(a) Brackets denote figures disregarding D from carbonisation of walls.

(b) Small number of samples, so large errors. Also contributions from previous campaign due to re-use of some components.

(c) Based on average for X-point region – amounts elsewhere may be less

(d) Be evaporation phase.

(e) Be limiter phase.

(f) Small number of samples.

(g) Small number of samples due to Be-contamination restrictions.

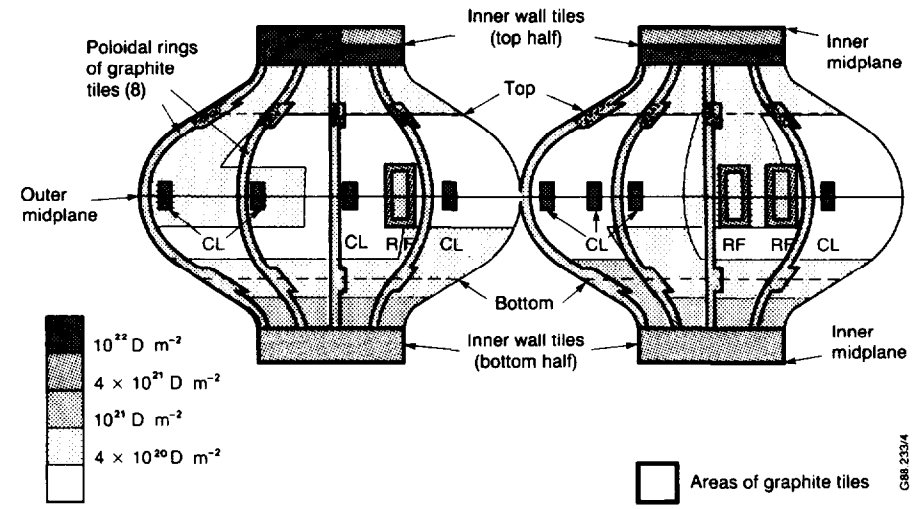

Figure 13. Distribution of deuterium retained in JET as determined from samples removed after the 1986 campaign.

for 1986 (4 and ~1.3x10exp20, respectively). By 1988 these figures had risen to ~16% retained and 4-5x10exp20 atoms per pulse. These figures probably reflect two developments. Firstly, the area of graphite tiles within the vessel increased significantly in 1986 with the introduction of the belt limiters and extra poloidal rings. Secondly, a lot more carbon was eroded from surfaces in contact with the plasma due to edge effects on the belt limiters and the inner wall than ever occurred with the discrete limiter operation.

The figure of 16% for the retained deuterium after the campaign as a whole is to be compared with the figure of 40% for the amount of gas input remaining in the vessel at the end of the day (see the section on gas balance above). There are several factors which are likely to result in the post-mortem analysis figure being genuinely lower, including some associated with venting the machine and restarting operations which occurred on a number of occasions. Firstly, on venting all the in-vessel surfaces are exposed to air (and in particular water vapour) and deuterium is released by isotope exchange. This phenomenon has been studied in detail by the author, by measuring release directly and by inference from T release (19,20). These measurements show that on average about 1.3x10exp23 D atoms are released on venting: since JET was vented six times in the 1987-1988 campaign this means ~8x10exp23 atoms were lost. Secondly, on restarting after venting the vessel was "conditioned" using several tens of hours glow discharge cleaning. Part of this was normally in D which will add to the inventory, but much was in H and the final 10-20 hours were normally in He so a net **loss** of inventory is to be expected. Thirdly, during operations in the "all-carbon" vessel it was necessary to run a series of conditioning discharges in helium on a regular basis to avoid uncontrolled gas release during the start-up of D-fuelled pulses. Finally, there are two systematic errors associated with the analysis which may give a low D level: the D content of thick layers near strike points is

underestimated due to the 0.5 micron analysis depth (see above) and there is presumably a progressive loss of D due to long-term air exposure of the samples (maybe evidenced by the large H content observed). Thus the 16.3×10exp23 atoms of the Oct 1988 inventory might well have been more than 30×10exp23 atoms retention were it not for the various losses mentioned above. This would represent at least 30% of the gas input, in good agreement with the gas balance data. As a footnote to the 1987-1988 data, they do suggest a reduced rate of D build-up with length of campaign: one would expect an anomalous rate of D accumulation initially due to saturation of the surfaces of new first wall components by D gas absorption/isotope exchange and ion implantation.

Table 1 also lists an inventory after the introduction of Be into the machine (1989). A smaller number of samples were analysed than after 1988 because each sample had to be handled with gloves and in a controlled air enclosure due to the dangers from inhaling beryllium oxide dust. (This is no longer such a limitation since JET has now set up the special IBA facility with integral glove-box). Although this inventory may not be as accurate as that after 1988, it gives a similar value for the amount of D retained per pulse (~4x10exp20 atoms). Thus the analysis of first wall components gives an independent confirmation of the gas balance result that **the amount of D retained per pulse is the same for the mixed C-Be first wall as it was for the "all-carbon" machine.**

DISCUSSION

Before assessing the implications that the data on D retention in JET have for ITER, it is first necessary to discuss which mechanisms are responsible for the retention. There are three principal mechanisms to consider. Firstly, D may be trapped by codeposition with C and other impurity elements at up to 0.4 times the number of C atoms in the film (possibly more in the presence of Be) and up to the thickness of the deposited film (films of over 100 microns have been seen in JET). Secondly, D may be implanted into any first wall surface as ions or fast neutrals. Charge Exchange Neutrals (CXN) travel in all directions out from the confined plasma and are the main flux to the parts of the vessel wall and other components that cannot be reached by the ions travelling along field-lines (which are intercepted by the various rings of tiles). The vast majority of CXN have energies <<1KeV and a typical D analysis for LTS in JET in 1987-8 is ~5x10exp16 cm-2: this may represent the saturation level for the mix of CXN energies in JET since rapid exchange of atoms between this reservoir and the plasma has been observed (21,22). Thirdly, every in-vessel surface is regularly exposed to D gas, which may absorb/isotope exchange and remain trapped. Apart from a small initial uptake when new components are installed, and some uptake after Be evaporation (~10exp16 cm-2 - ref 23) this process is likely to be negligible: 100% of gas fed into the torus is re-emitted after a "dry run" (a pulse without plasma). For all these mechanisms, the influence of diffusion towards the surface

or into the bulk over long periods of time must be considered. Diffusion depends critically on temperature, so it should be pointed out that for the great majority of the time **JET has operated with the first wall at 250-300 C**. Mobility is very low at these temperatures, but diffusion effects may be expected at strike points where temperatures will rise locally during power loading, and in ITER if the machine is run with ~600 C wall temperature.

Codeposition clearly occurs where the SOL intersects first wall components, eg on the sides of limiters and on X-point tiles, because there is far too much D retention for any other mechanism to be possible. The critical aspect of codeposition is the steady build-up of carbon and/or other elements on a surface. In such areas there is a far greater flux of D ions through the SOL than necessary to saturate the growing film. The density of CXNs is also a maximum near the contact points. The exact origin of the D atoms is immaterial, however, since the inventory for such areas depends only on the D saturation level in the film together with the thermal history of the region. The CXN mechanism sets a minimum to the inventory in parts of the vessel further from the LCFS and areas shielded from ions following field-lines. If we assume a level of 5x10exp16 D atoms cm-2 due to saturation by CXNs over the whole 200 m2 JET wall, their contribution to the inventory is 10exp23 D atoms, which could be ~10-15% of the total. For larger tokamaks, and for longer periods of operation the contribution from implantation becomes insignificant.

The configuration for 1987-8 was referred to above as the "all-carbon" vessel. In practical terms, however, there was little difference to the situation in 1986 when the inconel walls were also well screened from ions by poloidal rings of tiles and by the inner wall tiles, whilst the small discrete limiters defined the LCFS well away from the outer wall just as effectively as the much larger belt limiters did in subsequent years. Reference to Table 1 shows, however, that the retained inventory increased from 4% in 1986 to 16% in 1988. From the discussion above one would not expect the increase in the mass of graphite in the vessel to make a significant contribution to this increase, which should be dominated by codeposition. Reference to the literature of this period suggests the explanation. JET operations in 1987-9 were plagued with sudden and large influxes of carbon (and beryllium in 1989) into the plasma during pulses with additional heating, especially at low densities (24). These influxes, referred to as "carbon (or beryllium) blooms" could result in plasma impurity contents of 5x10exp20 atoms m-3 (in effect a C or Be plasma) and terminated the plasma with a disruption. The large influxes were attributed to localised heating at tile edges to temperatures high enough for radiation-enhanced sputtering or sublimation to occur on carbon tiles or for evaporation at Be tiles. Evidence of such heating effects was seen at the graphite X-point tiles (the influx commencing at 1850 C and "blooming" at 2400 C, ref 25), the belt limiters (both with C and with Be tiles, ref 26), the inner wall (temperatures up to 2800 C, with "blooming" from 2200 C, ref 24) and RF antenna protection tiles (either C or Be, ref 24). Clearly, then, there were a large proportion of pulses when large amounts of carbon (and/or Be) were redeposited, which may be expected to lead to

increased trapping of D by codeposition, in line with the analytical data. The interior of the JET vessel has now been re-configured to include a divertor (which in 1994 is fitted with carbon tiles) and carbon poloidal limiters. Close attention has been paid to the design of the divertor target tiles, to ensure there are no exposed edges, so as a result C influxes (and hence D retention) should be lower than in the 1987-9 period: detailed measurements to confirm this have yet to be made.

A MODEL FOR HYDROGEN RETENTION IN LARGE TOKAMAKS

The thickest deposits in JET are clearly codeposited films in the SOL but close to the LCFS. However the surface area of these regions is relatively small, so their contribution to the total inventory is comparable to that of the inner wall and of the other poloidal tiles. The inner wall and poloidal tiles are also in the SOL and during each pulse there are periods when the LCFS is close to such surfaces. As examples, for many periods of operation it has been standard practice to start the plasma in contact with the inner wall, and the earliest collector probe results at JET (27) showed that in the rampdown phase of the discharge the flux of carbon was almost constant throughout the SOL. The excess of the D concentration over possible ion implantation levels can reasonably be ascribed to small amounts of codeposition.

In order to estimate the likely codeposition in ITER, it is first necessary to relate the amount in JET to some parameters which can be extrapolated to ITER. In the gas balance section, the amount retained was shown to be equal to the sum of the plasma contents for the day's pulses. There is no mechanistic justification for this fact, however, and it is probably just a coincidence. Since the **extra** retention each pulse is determined by the amount of redeposited impurities per pulse (assuming walls are already saturated by implantation, absorption, etc), let us estimate this quantity. Assume for simplicity that the first wall is carbon. To the first approximation, **the amount of wall material redeposited is the amount that has been in the plasma.** For JET a typical plasma density is 3x10exp19 m-3, the plasma volume is ~100 m3, the C impurity level is ~5%, and the containment time for impurities is ~0.3 secs. The amount of carbon in the plasma at any moment is therefore given by

$$\text{Carbon in plasma} = \text{Density} \times \text{Volume} \times \text{Impurity fraction} \qquad (1)$$

$$= 3\text{x}10\text{exp}19 \times 100 \times 0.05 = 15\text{x}10\text{exp}19$$

and the amount of redeposited carbon per 10 second pulse is given by

$$\text{Redeposited carbon} = \text{carbon in plasma} \times \text{pulse length} / \text{impurity containment time} \qquad (2)$$

$$= 15\text{x}10\text{exp}19 \times 10 / 0.3 = 5\text{x}10\text{exp}21$$

If this redeposited carbon is saturated with D, **the amount trapped would be 2x10exp21 atoms per pulse**. This figure is similar to that from gas balance measurements quoted earlier (long-term retention of ~40% of an input which is typically ~5×10exp21 deuterons). This then provides a physically realistic explanation for the amount retained, and the number of impurity confinement times per pulse happens to give the retention of approximately one plasma content per pulse in JET. Over a JET campaign of ~40,000 secs as in 1987-8 the estimated retention would then be ~80×10exp23 atoms. As shown above about half of the inventory may be lost through ventings, He conditioning discharges and GDC, so the probable long-term retention would be ~40×10 exp 23 atoms. Futhermore, analyses suggest there is as much H in the first wall samples as D (at least, there is by the time they are analysed). Thus for the 1987-8 JET campaign the H+D inventory was likely to have been ~2×16.3×10exp23, i.e. ~33×10exp23 atoms. Since there are estimates and averages over widely varying functions in each derivation, this can be seen as excellent agreement. The theory might be checked by doing detailed comparative gas measurements between a day (at least) of discharges producing little carbon sputtering and one with long pulses with more impurity production, for example.

IMPLICATIONS FOR THE TRITIUM INVENTORY IN ITER

In order to draw some parallels between T retention in JET and ITER we must assume similarities in the some of the operating variables. One of these assumptions is that the wall temperatures are similar: ITER may operate with much hotter walls and this would seriously affect the predictions - the likely effect is mentioned later.

For CXNs JET and ITER can be regarded as similar, since the CXN energy distributions in the two machines will not be sufficiently different to make a significant difference to the saturation level. Thus, by analogy the resulting D+T inventory in ITER from this source is 10exp24 atoms, assuming a surface area ten times greater than JET: we will see below that this is insignificant.

The model for H isotope retention in codeposited layers outlined above can now be applied to ITER. For ITER we can take a plasma density of 10exp20 m-3, a volume of 500 m3, 1% of plasma impurities, an impurity confinement time of 1 sec and a campaign time of 10exp6 secs. The amount of redeposited impurities is then given by

$$\text{Redeposited impurities} = 10^{20} \times 500 \times 0.01 \times 10^{6} / 1.0 \qquad (3)$$

$$= 5 \times 10^{26} \text{ atoms}$$

Assuming this to be carbon saturated with equal fractions of D and T, **the retained tritium would be 10exp26 atoms (500g).** This figure has been derived by analogy with JET, and as such it applies to a machine with walls at 250-300 C (or cooler). The wall

temperatures in the ITER device may be much higher than in JET, and peak temperatures in some areas may be in the range 1000 to 1900 C (28). At temperatures above 300 C the amount of H isotopes that can be retained starts to decrease (29), and by 1000 C are greatly reduced. From this viewpoint the inventory estimated above must be considered an **upper limit**. For components reaching temperatures of the order of 1000 C or above, the bulk diffusion of T probably becomes the dominant factor controlling the inventory.

Much larger values for the possible retained H isotope inventory for ITER can be obtained if the D+T flux to the target is simply converted to a sputtered carbon yield and multiplied by 0.4 (0.2 for T). However, as was discussed by Brooks the vast majority (>>90%) is promptly redeposited in the strike zone whence it may be resputtered. The cycle may be repeated many times before the atom of target material finally escapes to a region of net deposition. It is patently obvious that there is no H isotope retention associated with the local recycling - the strike zone is an area of net erosion and at most can have a dynamic inventory of the ion implantation saturation level. The concept of retention being associated only with atoms entering the plasma (and hence being redeposited largely outside the strike zone) avoids this overestimate. Carbon eroded from the target which may provide an **extra** inventory is carbon sublimed from points on the target and redeposited nearby in cooler areas without entering the plasma. This has happened in JET, for example, in gaps and reverse slope regions on shaped X-point tiles. The design of the ITER target will be required to avoid such problems.

The latest ITER designs incorporate a gaseous divertor, wherein the plasma is cooled in the divertor channel to temperatures too low to sputter from the target, or flow is halted before reaching the target. In these designs the power flux into the divertor is distributed over a large area of the side walls. These concepts are still under development and as yet it is unclear how much erosion and redeposition will occur locally within the divertor channel. Estimates (for example based on Monte-Carlo calculations) will eventually be necessary of the redeposition expected, so that the T inventory can be estimated using the same data on saturation levels as functions of temperature as used in the past.

CONCLUSIONS

The amount of long-term D retention (ie after many hours) in JET was measured by detailed gas balance experiments in 1987-9 to be ~2x10exp21 atoms per pulse (with a very large scatter due to the wide variety of plasma parameters). The amounts retained in the "all-carbon" machine (that is, a machine with enough carbon tiles to screen all other parts of the vessel from significant ion fluxes) and in the vessel after replacing some of the graphite tiles with beryllium tiles and using regular Be-evaporation were the same.

During the course of a campaign perhaps up to half of this amount may be lost /removed by conditioning pulses and GDC in helium, isotope exchange on venting and other release

mechanisms. The analysis of first wall components gave a total estimated retained inventory for the vessel after the 1987-8 campaign ("all-carbon") of 16.3x10exp23 deuterium atoms, which represents ~4x10exp20 atoms per pulse. After the Be-phases in 1989 the retention was again equivalent to 4-5x10exp20 atoms per pulse. First wall samples also appeared to contain as much H as D (some of which may result from isotope exchange of initially higher D levels).

Although ion/CXN implantation may give a significant contribution to the inventory in JET, the dominant mechanism for D trapping and long-term retention is codeposition. For a larger machine such as ITER, codeposition would be the totally dominant retention mechanism if component temperatures were low (eg <300 C as in JET). Good agreement with the measured JET inventory is obtained if all the impurity elements entering the plasma eventually trap D in codeposited layers. On the same basis the tritium retained after 10exp6 seconds of operation in ITER would be 10exp26 atoms (500g) if a global impurity level of 1% is assumed. local recycling within the divertor channel may add to the inventory and needs to be modelled for the various divertor concepts currently being considered.

The retained inventory in ITER would be considerably altered if wall temperatures were much higher than in JET. Retention by codeposition reduces with temperature, and by 1000C the significant mechanism influencing retention would be bulk diffusion.

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