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\* *See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",  
Fusion Energy 2000 (Proc. 18<sup>th</sup> Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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## **ABSTRACT**

Coated divertor and wall tiles exposed in JET for the 1999-2001 operations have been used to assess erosion/deposition. Deposited films of up to 90 microns thickness at the inner wall of the divertor tiles are, for the most part, enriched in beryllium and other metals, whilst carbon is probably chemically sputtered from these tiles and transported to shadowed regions of the inner divertor. However, from the composition at the surface of the tiles, it appears that the chemical erosion was "switched off" by reducing the JET vessel wall temperature for the last part of the operations to 200°C. Thick powdery deposits localised at the ion transport limit at each corner of the divertor may be due to physical sputtering. Erosion of the coatings is seen at the outer divertor wall, and on all the inner wall and outer limiter tiles.

## **1. INTRODUCTION**

Previous analyses of plasma-facing tiles removed from JET have shown that material flows round the SOL from outboard to inboard to be deposited in the inner divertor [1,2]. From there carbon is chemically sputtered leaving behind films rich in beryllium and other metals, and is transported to regions shadowed from the plasma, such as the inner louvres. Although it is known that material is eroded from the inner wall of the main chamber [3], it is not known how much material arrives at the inner divertor, and how much of it comes from parts of the main chamber and how much from the outer divertor. During the shutdown of JET in 1999, tiles coated with markers were installed at selected points at the Inner Wall Guard Limiter (IWGL) and Outer Poloidal Limiter (OPL), and as a complete poloidal set of divertor tiles. Following their removal in 2001, the tiles have been re-analysed to determine the erosion/deposition at the limiters in the main chamber and (particularly) in the divertor.

## **2. EXPERIMENTAL**

JET normally operated with a wall temperature of 320°C and deuterium fuelling. However, for the last twelve weeks the wall temperature was reduced to 200°C, and of this period three weeks (towards the end) were with helium fuelling. The divertor structure (including the louvres) was water-cooled, but the divertor tiles are not directly bolted to the structure, so were at intermediate temperatures (in the range 160-220°C with the wall at 320°C, and 80-140°C with the wall at 200°C).

The special marker coating consisted of two layers; firstly, a thin layer (~0.5mm) of rhenium (Re) that is easy to detect with the analysis techniques (see below) to mark the original surface, and secondly, a layer of a 90% carbon/10% boron mixture ~2.5µm thick. The C/B layer is designed to be similar in composition to the in-vessel tile surfaces so that there is minimal distortion of plasma transport processes, yet allows erosion of the layer to be assessed from the amount of boron detected. Amounts of deposition and (small amounts of) erosion are determined by comparing the position of the Re (and B) relative to the surface before and after exposure in JET.

If there is gross erosion, all trace of the markers may disappear. To cope with this possibility, a number of slots were milled in one poloidal edge of each divertor tile, to act as reference points. Distances

to the tile surface from these slots were measured with a micrometer before and after exposure.

Before mounting in JET in 1999, and again following their removal in 2001, the coated tiles were analysed using Ion Beam Analysis (IBA) techniques. The change in surface composition for each tile was determined; in some cases a thick layer had been deposited that obscured the Re and B signals, and in others a reduced Re and B level was observed (indicating some erosion).

The divertor tiles have also been analysed with Secondary Ion Mass Spectrometry (SIMS): the sample was bombarded with  $O_2^+$  ions, and the sputtered secondary ions were analysed with a mass spectrometer. Unlike the IBA system, the SIMS equipment can only handle samples of limited size. In preparation for analysis, a series of 17 mm diameter samples were cut from the divertor tiles using a coring technique [4].

### **3. RESULTS AND DISCUSSION**

#### ***3.1. MECHANICAL MEASUREMENTS***

The results of the micrometer measurements on the poloidal set of divertor tiles are shown in Figure 1. The numbering of the measurement points (1-24) is shown in the upper part of the Figure, as well as the tile numbers (1-8). The thickness of the deposit on the inner divertor wall increases towards the bottom, reaching a maximum of ~90 microns. Surprisingly, there are even thicker deposits on the small section of the floor that can be accessed by the plasma both at the inner and outer divertor legs (points 10 and 16, respectively). All other quoted values are an average of at least three measurements at that point, and repeatability was excellent. However, at these two points, each measurement gave a smaller value than the preceding one, so that after about 15 measurements the value had reduced by ~50% (grey shading on Figure). This suggests that the film is powdery in nature, and compresses with successive micrometer measurements. Only small amounts of erosion/deposition are found elsewhere in the outer divertor (of the order of the accuracy of the measurement, which is  $\pm 10\mu\text{m}$ ).

#### ***3.2. SIMS MEASUREMENTS OF THE TILES AT THE INNER WALL OF THE DIVERTOR***

SIMS measurements have been made on a number of samples from each coated divertor tile. Since the surface topography of the Carbon-Fibre-Composite (CFC) tiles varies, SIMS measurements are repeated at several points on each sample, covering an area larger than the fibre plane separation. Typical SIMS depth profiles from five tile samples are shown in Figure 2. The samples are indexed according to the equivalent poloidal micrometer position, although the SIMS measurements were made near the centre (in the toroidal direction) of each tile, whereas the micrometer data (Fig. 1) are taken at the edge.

The SIMS depth profiles are plotted as the number of counts in the appropriate mass channel at each sampling time, against the depth in microns. The sensitivity for each element depends on the sputtering coefficient for  $O_2$  ions, which varies by several orders of magnitude over the periodic table, and is also matrix dependent. Thus the amounts cannot be readily quantified, except by cross-calibration with IBA analyses of similar films, and at this stage are used to indicate trends

within the films. The depth calibration results from a large number of measurements of crater depth using a stylus technique. Note, however, that the sputtering rate depends on the precise composition at that point, and varies considerably.

For each of the profiles (except Fig. 2(e)), the Re and B-containing layers are clearly visible at the interface between a deposited film and the CFC substrate. The depth profiles in Figs 2(a) and (b) are from the inner wall of the divertor (tiles 1 and 3, respectively). They show that the majority of the films (from 4 - 12 $\mu$ m at point 4 and 13 - 32 $\mu$ m at point 7) are very rich in beryllium, and nickel also peaks in this region. The Ni is indicative of the constituents of inconel, which is used as the JET vessel wall and for internal metal fittings, bolts etc; the other constituents such as iron, chromium behave similarly. Layers rich in metals, and depleted in carbon, have been found at the inner divertor wall previously [1.2]. The mechanism proposed is that much more carbon arrives along the SOL from the main chamber, but that chemical sputtering by deuterium ions and neutrals causes the majority to migrate into shadowed areas.

The surface compositions of the samples from poloidal positions 4 and 7 are quite different to the composition deeper into the deposit, being mostly C and Be (with some Ni), and with a higher deuterium content. This surface composition is similar to that found in deposits at the sides of limiters in the main chamber, and presumably to that arriving at the inner divertor along the SOL. It thus appears that during the last part of the campaign, the carbon was no longer being chemically sputtered from the films. For the last 3 months of operations prior to the 2001 shutdown, the vessel wall temperature was reduced from the 320°C normally used in JET to 200°C. This reduces the average bulk temperatures of tiles 1 and 3 during a day of pulsing from 190°C to 120°C, respectively. Infra-red cameras show that, although the surface temperature at the strike point may reach much higher temperatures (1000°C or more [5]), the strike zone is narrow and more than 50mm from the strike point there is no resolvable temperature change from the bulk value. It is known that the C<sub>2</sub>H<sub>X</sub> formation rate by chemical sputtering is a strong function of temperature [6], for example, and it may be that this reduction in tile temperature effectively "switches off" the secondary process of C removal by chemical sputtering.

During the divertor phase of the last thirteen pulses prior to the shutdown, <sup>13</sup>CH<sub>4</sub> was puffed from the top of the vessel. It is interesting that the <sup>13</sup>C is seen right at the surface of samples from the inner divertor wall (maximum concentration equal to the <sup>12</sup>C value), but much smaller amounts are seen at the surface of the sample from poloidal position 9 (in the region shadowed from the plasma by tile 3). If most of the carbon were transported to shadowed regions, as occurs for operations at 320°C wall temperature, the reverse might be expected. More details of the puffing experiments will be given elsewhere [7].

### **3.3. SIMS ANALYSES OF THE DIVERTOR FLOOR**

The film in the shadowed region on tile 4 (point 9, Fig. 2(c)) is relatively pure carbon, with a very high D content, and with a well-marked interface to the CFC substrate. The film is ~85 $\mu$ m thick, with a similar composition to that previously found for the flaking deposits at the inner louvres [2].

Deposits on the part of tile 4 shadowed by the septum are somewhat thinner ( $\sim 20\mu\text{m}$ ), and do not have quite as high deuterium content, again as seen before [2]. Deposited films were found covering all parts of the divertor support structure on the inner divertor side, and on the fins of the inner carrier (behind tile 3). It also appeared that there had been some spalling of deposits at the inner louvres, as first observed with the Mk IIA divertor in 1996 [8]. This deposition could not be quantified, but metallic clips were fitted to both inner and outer louvres so that a measurement may be possible following the planned 2001-2004 operational campaigns.

The outer parts of the thick, powdery deposits on tiles 4 and 6 (points 10 and 16 in Fig. 1, respectively) contain mostly C, with negligible amounts of metallic impurities, and a very low D content (apart from right at the surface). This is shown in the SIMS depth profile in Fig. 2(d) (sample from point 16). Between this region and the substrate is a zone with quite high Be and Ni content. These deposits are located at the extreme corner of the plasma-accessible region, i.e. the end points for transport as ions, for example by successive sputtering, ionisation and re-deposition sequences. It may be that, although chemical sputtering at the inner divertor dominates, these deposits show the ion induced physical sputtering process also occurs in each leg of the divertor. Part of the deposition may have occurred during the three weeks operation with He fuelling; more experiments are required.

Apart from the localised area accessible by the plasma (including point 16), SIMS analyses of samples from the outer divertor base tile 6 show a film typically  $3\mu\text{m}$  thick on the Re interlayer. Since a  $\sim 2\mu\text{m}$  C/B film was deposited on the tiles prior to exposure, there is negligible deposition (or erosion) in the shadowed regions of tile 6.

### ***3.4. SIMS MEASUREMENTS OF TILES AT THE OUTER WALL OF THE DIVERTOR.***

SIMS analyses of tiles 7 and 8 from the outer divertor wall show implanted H-isotopes at the surface of an eroded CFC tile. In some areas there are no remaining signs of the Re and B markers, suggesting several microns erosion (at least) in these regions, whilst at some other points reduced quantities of B and Re (relative to the composition prior to exposure) were still present. A typical example of the former is shown in Figure 2(e) from point 20 on tile 7.

### ***3.5. ANALYSIS OF MARKER TILES FROM OTHER REGIONS***

Since there is less erosion than deposition in the divertor, there must be net erosion in the main chamber; the surfaces closest to the plasma boundary are the IWGL and OPL. The special OPL and IWGL tiles have been analysed by IBA, and figure 3 shows the amount of rhenium from the marker layer remaining on three OPL tiles after their removal in 2001. An OPL is a band of 92 tiles each 26mm wide, extending from 1.1m below to 1.3m above the outer midplane. Toroidally, each tile is  $\sim 350\text{mm}$  wide, and is slightly curved so that the central portion is tangential to the field lines, whilst the ends of the tile are deeper into the SOL. Re levels prior to exposure were typically 140-180 a.u. over the central part of each tile, so the reduced Re (and also B) signals seen in Fig. 3 from almost all OPL tile areas indicate widespread erosion, though the largest erosion is clearly seen on Tile C. The ICRF antenna screens are aligned parallel to the OPL, and during ICRF heating



experiments the separatrix is close to the OPL. Strong plasma interaction with the mid-plane sections of the OPL is frequently observed with the JET wide-angle viewing cameras, due to high energy particles generated in the SOL.

IBA analyses also show widespread, but limited, erosion from the IWGL tiles, together with some local areas of deposition. Erosion by CXN from tiles at the inner wall of the vessel has been demonstrated previously [4], and, although a full analysis is still in progress, was again apparent following the 1999-2001 campaign, as a series of thin metallic markers were no longer visible.

#### 4. CONCLUSIONS

Special marker tiles exposed in JET from 1999-2001 confirm deposition of many tens of microns at the inner divertor, with erosion evident over large areas of the main chamber.

SIMS profiles show that for most of the exposure period, C is probably chemically sputtered from the deposits at the inner divertor, leaving films rich in beryllium and other metals. Almost pure carbon films (with high deuterium content) are deposited in shadowed regions, as previously demonstrated [2].

The composition of the surface region of the deposits on tiles 1 and 3 is closer to that of deposits in the main chamber. It is believed that the secondary process of C removal by chemical sputtering was effectively "switched off" by reducing the vessel wall temperature from the 320°C normally used in JET to 200°C for 3 months at the end of the campaign.

Powdery deposits, with thickness up to 200µm, were found at the extreme corners (both inner and outer) of the divertor accessible to the plasma. It is believed that these deposits largely result from physical sputtering and re-deposition in the divertor; any influence from three weeks with helium fuelling has not yet been assessed.

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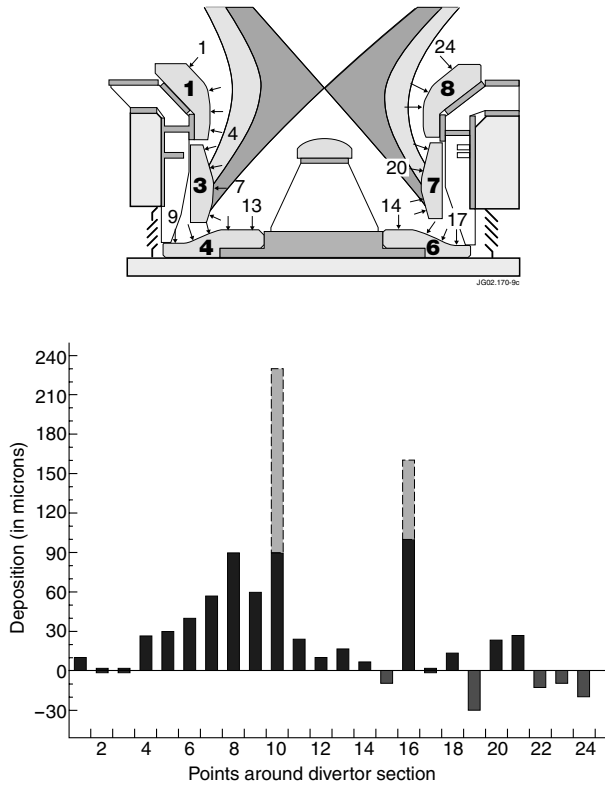


Figure 1: Erosion/deposition in the period 1999-2001 as measured by micrometer. (Grey bars denote the decrease in apparent thickness during many repeat measurements.)

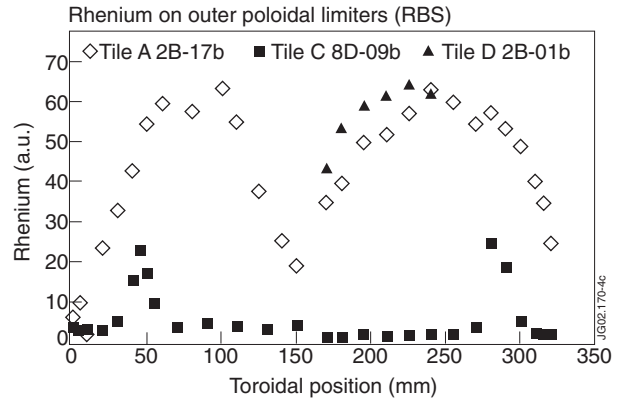


Figure 3: Comparison of RBS analysis of Re on three OPL tiles after exposure (tiles A, C and D, from the bottom, middle and top of the limiters, respectively). The surface of each tile is tangential to the plasma at its midpoint, and the tile is curved so that the surface is deeper into the SOL towards each end. Note, the original coating was thinner towards each end of the tile.

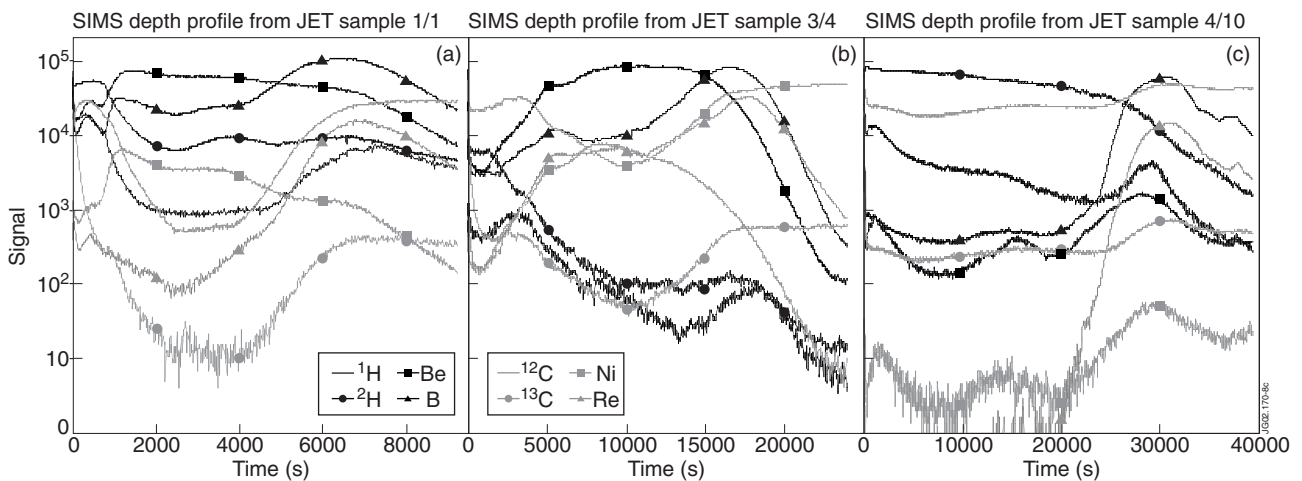


Figure 2: (a) to (e) Depth profiles by SIMS at the equivalent poloidal positions to micrometer points 4 (bottom of tile 1), 7 (centre of tile 3), 9 (shadowed region on tile 4), 16 (powdery deposit on tile 7) and 20 (centre of tile 7), respectively.