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J.P. Coad, B. Farmery

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Redeposition Effects on the Target Plates of the JET Tokamak

J.P. Coad, B. Farmery[1]

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*University of Sussex, Brighton, UK.*

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ABSTRACT

Complete tiles from the X-point target region of the JET tokamak can be analysed by ion beam techniques in a special chamber equipped to handle beryllium and tritium - contaminated samples. From the amounts of deuterium co-deposited during plasma operations, and the pattern of beryllium deposits remaining from regular Be-evaporation in the torus, erosion and redeposition effects at the target area can be determined. The largest amounts of net redeposition occur in the "private zone" and near the inner separatrix. There appears to be a net transfer of material from the outer to the inner strike zone: the data are compared with models for divertor transport.

1. INTRODUCTION

The Joint European Torus (JET) is the world's largest fusion device. The toroidal vacuum vessel (which has a volume of about $200m^3$) is used to contain plasmas with temperatures of up to 200MK, densities of the order of $10^{20}m^{-3}$ and input powers up to 40MW. The next step in the development towards a fusion power reactor will be the International Thermonuclear Experimental Reactor (ITER), wherein the volume and power levels will be about an order of magnitude greater than in JET. There is inevitably some interaction between the plasma and the surrounding vessel, and the principal contact occurs in target areas which for the likely configuration for ITER (the magnetic field forming an X-point within the vessel, and particles being exhausted into a divertor region) are the divertor strike zones. One of the major developments necessary for the ITER design is a satisfactory way of handling the power flux to these divertor plates ($\sim 30MWm^{-2}$ [1]). In particular, erosion (a combination of sputtering by incident particles and thermal effects such as sublimation or evaporation) at the target surface may be intolerable unless local redeposition greatly reduces the net loss [2]. JET can be operated in an X-point configuration, using either the top of the vessel or the bottom of the vessel as a divertor target. Figure 1 shows the cross-section of the vessel with the X-point target regions indicated, and a typical plasma shape for the upper X-point configuration. During the 1991 - 1992 operations the top was covered with carbon tiles whilst the bottom was protected by beryllium tiles so that comparative measurements could be made. Detailed measurements have been made of the erosion and redeposition occurring in the upper region as a result of this mode of operation, using ion beam analysis of the retained deuterium, beryllium and impurity elements. The results give interesting, and sometimes unexpected, insights into the transport mechanisms and even though the JET divertor operates in a lower density regime, are of some relevance to future divertor designs.

2. EXPERIMENTAL

The upper X-point target region of the JET vessel was covered with eight toroidal rings of carbon tiles (each typically 120 x 100mm) throughout the June 1991 to February 1992 campaign. Initially each of the tiles was made of graphite and had a flat surface. However, toroidally the target is supported on 40 separate plates, and slight movements (~1mm) between plates due to pumpdown and heating to the operational temperature of 300°C and magnetic forces acting on local currents flowing in the tiles result in excessive fluxes (incident at 1°-2° to horizontal) to the edges of the tiles next to the joint. This severely limited the conducted power to the target that could be handled to ~4MJ per pulse before impurities severely affected the plasma (for plasma input powers in the range 12-16 MW) [3]. In September 1991 the four innermost rings of tiles which are intersected by the inner and outer magnetic separatrix and bear the greatest power loadings were replaced with special shaped tiles made from a carbon fibre composite material. The new tile shapes ensured that each joint was in the shadow of thicker tiles within the adjacent sectors. An impression of the appearance of one sector of tiles is given in Figure 2, whilst cross-sections of these tiles will be seen (schematically) in the Results section.

Due to the shaping of the tiles, the greatest power loading is taken by small areas of tiles with greater angles of inclination to the incident field lines (which are at 1°-2° to horizontal), the so-called "ski-slopes" indicated in Figure 2. Because field lines are incident at a glancing angle of typically 5° instead of 1°, the power loading will be about 5 times greater than at flat areas at the same toroidal radius. For upper X-point plasmas in JET, the magnetic X-point is formed inboard of the tiles LS11 - LS15 in Figure 2, and the greatest scrape-off-layer (SOL) flux is incident on the adjacent rows of tiles. Figure 3 shows the plasma configuration, viewed in an approximately toroidal direction (as if from the right-hand side of Figure 2). Thus the areas of greatest incident flux for the usual directions of magnetic field and field gradient in JET are the ski-slopes of LS28 (and the adjacent area of LS27) (outer strike zone) and LS19 (inner strike zone): these areas can reach over 2000K during a discharge, so that the observed erosion may include a contribution from sublimation.

At the end of the 1991 - 1992 period of operation, the target tiles were removed from the torus and individually sealed in two metallised plastic bags, one within the other. JET operates with some beryllium components and used small amounts of tritium, so that all material from within the machine is regarded as contaminated with Be and T: double bagging ensures safe containment of these species. Tiles from two sectors of X-point target in different octants of the machine have been analysed using Ion Beam Analysis (IBA) techniques. A special target chamber on one of the beam lines from the 3 MeV Van-de-Graaff accelerator at Sussex University allows two X-point tiles to be mounted in the vacuum system for analysis at a time, via a glove box with filtered air extract. The IBA technique used to measure D and Be on the carbon tiles was Nuclear Reaction Analysis (NRA), via the reactions ^{2}D (^{3}He, p) ^{4}He and ^{9}Be (^{3}He, p) ^{11}B respectively, using a 1mm diameter beam of ^{3}He ions at 2.5 MeV. Other impurity elements were measured using Particle Induced X-ray Emission (PIXE) and Rutherford Backscattering (RBS).

3. RESULTS

Figures 4 - 6 show the variation in deuterium concentrations found in the outer ~1μm of the target tile surfaces along poloidal lines in the sector. Figure 4 is the analysis along a line across all eight rings of tiles near the centre of the sector (where all tile surfaces are flat and parallel to the toroidal direction). Figures 5 and 6 are along the "ski-slopes" near either edge of the sector, plus the analysis across the poloidally adjacent fifth (flat) tile: the beryllium concentrations are included in these figures. The data in Figure 5 cross the inner strike zone on tile LS19 as indicated in Figure 2, whilst those of Figure 6 cross the outer strike zone on tile LS28.

The beryllium level found on the tiles is mostly the result of regular beryllium evaporations over the inner surfaces of the JET vessel, from which a uniform concentration over the X-point region may be expected: the Be will be mixed with carbon which has been redeposited during plasma pulses. Deuterium, which is the gas used to form most of the plasma discharges in JET, is bound within the surface layer. Important mechanisms for trapping the deuterium are co-deposition with carbon from the plasma [4,5], and ion implantation into the surface layers [6]. Thus the quantity of deuterium accumulated on a first-wall surface increases with the amount of redepositon that has occurred. Laboratory experiments on carbon-based materials show that hydrogen isotopes reach a saturation level in the near-surface region of 0.4 times the number of carbon atoms [7,8], a limit also found on surfaces in "all-carbon " tokamaks [5]: there are no clear data, however, on the effect of including Be in the surface layers. Since NRA analyses to a depth of ~1μm (ie 1-2 x 10^{19} atoms cm^{-2}), and there is also hydrogen present in the surface, deuterium concentrations of about 2 x 10^{18} atoms cm^{-2} are the maximum to be expected, and at these levels may merely be the outer part of a thicker deposit in that region.

In the regions of greatest power flux (the ski-slopes of tiles LS19 and LS28) both the D and Be levels drop significantly, the latter over a less extensive region. The outer strike zone shows the more dramatic changes. Although a low D level could be the result of heating a C : H deposit to ~1000K, the low beryllium level is only consistent with heating to much higher temperatures or erosion of the tile surface by the plasma, i.e. by sputtering and sublimation: the physical appearance of these regions is consistent with erosion having taken place. No point on the profile of Figure 4 has experienced a sufficiently high power loading to cause a significant temperature excursion during X-point discharges. Note however that there are large differences in the deuterium level observed, with a maximum on LS20 (near the inner separatrix) and a minimum on LS8 (in the outer SOL). Beryllium levels (not shown) are more uniform, reaching a maximum on LS40 (1.1 - 1.5 x 10^{19} atoms cm^{-2}) and a minimum on LS26 (1.3 - 3.0 x 10^{18} atoms cm^{-2}), so do not show a peak on LS20.

Figures 7 and 8 show the D and Be analyses along toroidal lines across the sector at the outer and inner strike zones, respectively. The D and Be levels are greatly reduced on the ski-slopes where the flux is higher than elsewhere on the section. The D and Be levels also remain lower than average on the flat sections of LS27 and LS26 in Fig. 7, however at the inner strike zone the Be level immediately returns to 10^{19} atoms cm^{-2} on LS20 (Fig. 8) and the average deuterium level on LS20 is the highest found on any tile in the entire sector. Note that incident ion energies are constant for a given major vessel radius, so are identical along the exposed surfaces in Fig. 7 and similarly (at a different value) for Fig. 8: the minima on the ski-slopes can therefore only be due to the greater flux due to the angled surfaces and the higher associated heat flux. In the regions of the edge tiles LS28 (Fig. 7) and LS19 (Fig. 8) shadowed by tiles in the adjacent sector, the beryllium and deuterium levels recover, and then decrease close to the tile edge (deeper into the shadowed zone). The regions of reverse slope and the chamfered edges also receive no direct plasma flux. The D and Be analyses were omitted from these areas in Figures 7 and 8 because they clearly do not relate to the dependence of concentration on flux being depicted in the figures. However, the D and Be levels are almost invariably high ($\sim 10^{18}$ and $\sim 10^{19}$ atoms cm^{-2}, respectively), even when the surrounding area is an erosion zone (e.g. the average analyses for D and Be on the bolt slope and chamfered edge of LS28 are 1×10^{18} and 1.8×10^{19} atoms cm^{-2}, and 0.5×10^{18} and 1.7×10^{19} atoms cm^{-2}, respectively) suggesting local redeposition processes operating within the erosion zone.

Several other elements are found on the tiles by RBS and PIXE analyses. These include Ni, Cr and Fe, the main constituents of inconel, the structural material used for the vessel walls, internal pipes, bolts, brackets, etc. Although much of the vessel is covered with carbon (or beryllium) tiles, including all surfaces interacting with plasma ions, very low concentrations of these elements are invariably present in the plasma. They are probably sputtered from unprotected inconel components by charge-exchange neutrals, contaminate target surfaces and thence may enter the plasma: the presence of these elements on in-vessel surfaces is a good indication of the extent of redeposited films. Other impurity elements usually detectable were Al, K and Ca, and low levels of Cl. Cl had been a significant plasma-impurity in JET since Be was introduced, though was not a problem in 1991 - 1992. Oxygen was, of course, also present in all RBS spectra: its amount increased with the extent of the Be and other impurity concentrations and was peaked at the film surface. Much of the oxygen level may result from the period of exposure to air prior to analysis of the tiles.

4. DISCUSSION

Since impurities (principally carbon which is the usual target material) are invariably present in the plasma, there must be a continual process of erosion from areas of greatest incident power in the tokamak and redeposition elsewhere. The process was clearly demonstrated in campaigns involving the discrete limiters [9]. In more recent JET campaigns localised erosion at edges of tiles has been clearly visible on the belt limiters and X-point target tiles as well as more generalised erosion and redeposition effects [10, 11]. It is clear, therefore, that there must be erosion at the strike points on the target for the X- point discharges analysed here, and this is confirmed by the Be analysis in particular. The amount of erosion, and the process of redeposition of the eroded material is of immense practical importance to future fusion devices because they may pose intolerable limits on the lifetime of the target plates [1], unless prompt local redeposition greatly reduces the net erosion [2]. It is important, therefore, to assess the processes occurring in the JET X-point region, which, although operating at a lower density by about an order of magnitude, should evince the same erosion and redeposition processes.

The basis for the amelioration of erosion by redeposition [2] is that most material will be sputtered as atoms from the region of high power flux, will be ionised in the SOL and will return to the high flux region some distance away toroidally. Because the local magentic fields also have a small poloidal component away from the X-point (see Figure 3), the point of return to the strike zone following ionisation is also marginally deeper into the SOL. Thus, for a toroidally symmetric target there is little loss of material, except for a drift deeper into the SOL which would eventually allow particles to escape to a region of net deposition after several cycles. Of course, particles are sputtered with a cosine distribution about the surface normal, and cross-field diffusion of the ions also broadens the distribution of return sites from a sputtering source point, but neither effect alters the mean drift. (A small percentage of sputtered atoms may reach the confined plasma without ionisation, but these would also be most probably redeposited somewhere in the SOL). The first lesson from JET is that it is actually very difficult to achieve a toroidally symmetric divertor target. There are, in addition, several features of the redeposition in JET at variance with predictions.

The greatest erosion occurs at the outer strike zone (which agrees with camera observations of the target region), so one might expect the greatest deposition deeper into the outer SOL. This is not the case, indeed deeper into the SOL (tile LS8 in Figure 4) there appears to be a minimum in the deuterium level (and, by implication, in the deposited film thickness). On the contrary, the maximum deposition inferred from the deuterium is within the region of very low flux between the strike zones (the so-called "private region") and around the inner separatrix. The JET data also casts doubt on the assumption that the dominant erosion mechanism at the target is sputtering. Atoms sputtered at the JET target will have a mean-free-path of the order of a centimetre before being ionised, entrained and subsequently redeposited at the intersection of the flux line with the target. However, we find that wherever there is a surface which is **not** connected to a flux line (chamfer around the edges of tiles, reverse protective slopes, shadowed regions) there is above average deposition. We believe this is due to erosion by **sublimation** resulting in very low energy emitted particles and hence short mean-free-paths further diminished by local pressure gradients.

Maximum deposition within the private region, and localised redeposition were also found in experiments using boron from a boron carbide source within the JET X-point region as a tracer [11]. Sublimation may be avoided if the power loading can be more evenly distributed than in JET and the target is actively cooled. However, the power flux in ITER (up to 30 MW m^{-2}) will be greater than even on the JET ski-slopes (~10 MWm^{-2} at maximum), so it is unlikely that sublimation will be avoided completely.

The deposition maximum inboard from the source may be explained by reference to Figure 3. As stated previously, the flux surfaces have a small poloidal component away from the X-point, and in poloidal section (Figure 3) the envelope of the flux surfaces at the separatrix makes an angle of about 45° at the target. For atoms emitted from the outer separatrix by the cosine law there is 15% probability of particles entering the private region. If the particle is ionised within the private region (where λ is large due to the low density) then it will be deposited therein with a sticking coefficient of unity: if it approaches the inner separatrix the increased flux density will ensure redeposition close to the intersection of the separatrix with the target. This steady loss channel becomes much more significant when one recalls that although the majority of particles are redeposited within the SOL, they may be recycled many times before eventually finding an alternative loss channel (e.g. migration into a region of net deposition), so the private zone can statistically be the region of greatest deposition. In a future device such as ITER the target may be angled to give a low angle of incidence of plasma particles at the target so that the solid angle for emission into the private zone is negligible, however this means that there is then rapid transport outwards into the SOL so the assumption of multiple redeposition events per particle within the high flux region is not justified.

Greater D and Be levels are found in the inner SOL than in the outer SOL. During 1991-2 JET generally operated with greater particle densities at the inner strike zone, but greater ion temperatures at the outer zone. This results in a greater power loading on the outer strike zones and greater particle fluxes to the inner zone. It may also result in more sputtering in the outer SOL if the increased sputtering efficiency with energy (for energies < 100 eV) is more important than the greater fluence in the inner SOL. Since entrained ions may travel in either direction in the SOL, it is thus possible that there is a net transfer of material from the outer to inner target regions, which is certainly in agreement with the analytical data of Figure 4.

CONCLUSIONS

Complete tiles from the JET X-point region, which are contaminated with beryllium, can be mounted and analysed in an IBA facility equipped with a glove box at Sussex University.

Surveys of D and Be levels over large areas of the X-point region clearly identify the areas of net erosion at the inner and outer strike zones. The pattern of redeposition shows a maximum within the "private region" and around the intersection of the inner separatrix with the target. Localised redeposition in shadowed areas suggests sublimation is an important erosion mechanism. Both these observations have implications for future higher power fusion devices.

The ion temperature and power loading at the outer strike zone of the upper X-point at JET were usually higher than on the inner strike zone due to the gradients in the normal magnetic field configurations employed. A consequence of this appears to be greater erosion at the outer strike zone and a net transfer of material from the outer to the inner strike zone.

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REFERENCES

1. M F A Harrison and E S Hotston, J Nuclear Materials, 176-177 (1990) 256.
2. J Brooks, J Nuclear Materials, 170 (1990) 164.
3. C G Lowry, W N Ady, D J Campbell et al, J Nuclear Materials, 196-198 (1992) 7356.
4. R Behrisch, J Ehrenberg, M Wielunski et al, J Nuclear Materials, 145-147 (1987) 723.
5. J P Coad, R Behrisch, H Bergsåker et al, J Nuclear Materials, 162-164 (1989) 533.

6. P Andrew, J P Coad, J Ehrenberg et al, to be published in Nuclear Fusion.
7. G Staudenmaier, J Roth, R Behrisch et al, J Nuclear Materials, 84 (1979) 149.
8. W Möller, J Nuclear Materials, 162-164 (1989) 138.
9. J P Coad, R Behrisch, J Roth et al, Proceedings of the 14th European Conf. on Controlled Fusion and Plasma Physics, Madrid, June 1987, p 744.
10. G M McCracken, R Behrisch, J P Coad et al, Proceedings of the 16th European Conf. on Controlled Fusion and Plasma Physics, Venice, March 1989.
11. J P Coad and B Farmery, J Nuclear Materials (in press) (1993).

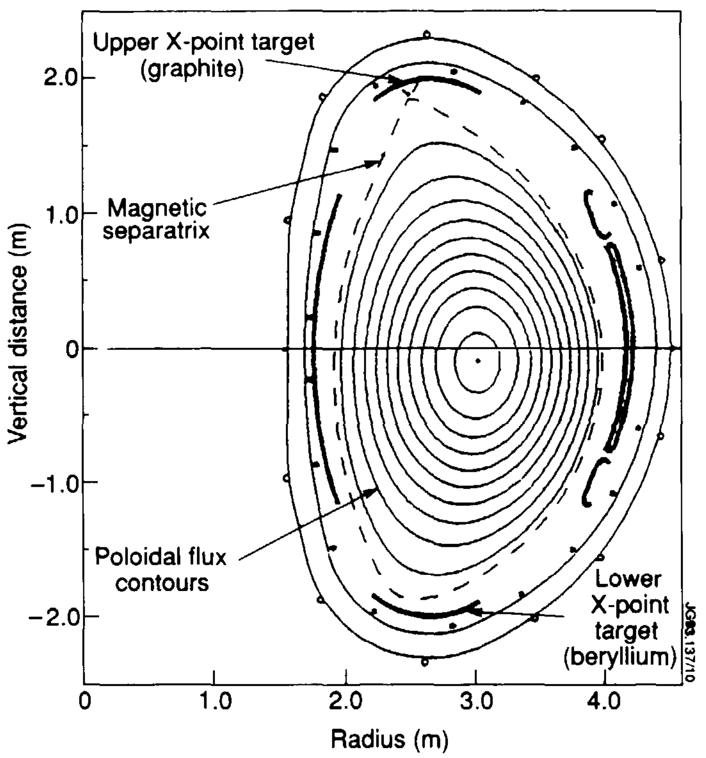

Figure 1: Cross-section of the JET vessel showing the principal first-wall components and a typical plasma shape for the upper X-point configuration.

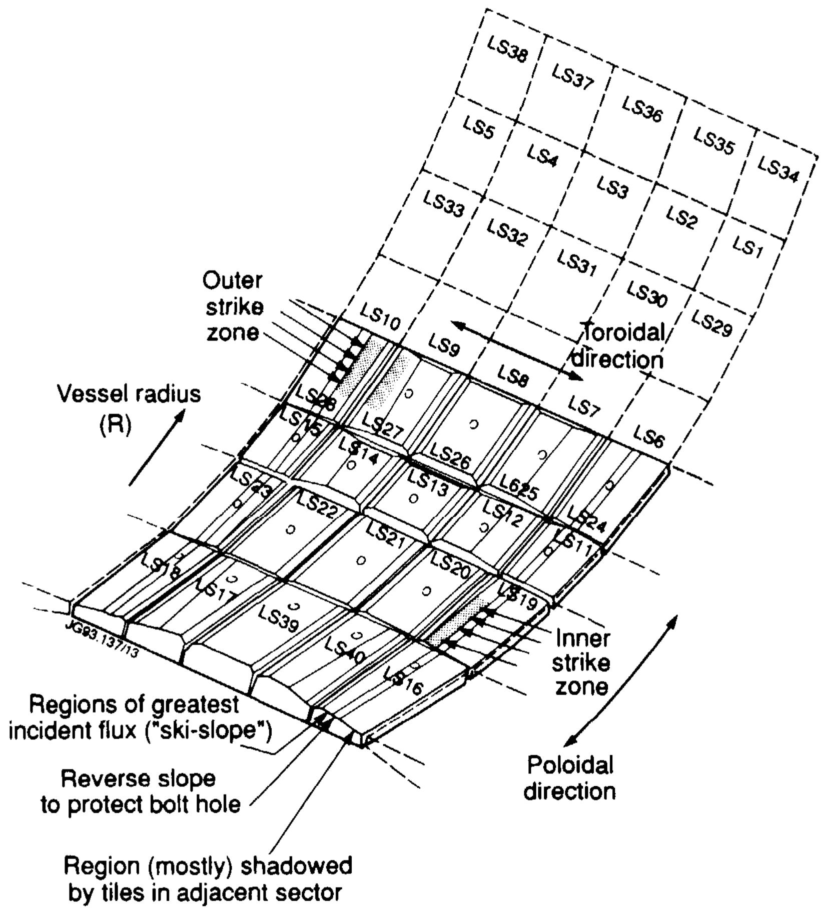

Figure 2: A schematic view of a section of X-point target tiles: this set of numbered tiles is mounted on one support plate. The shaped CFC tiles are drawn with solid lines, whilst the flat graphite tiles are indicated with dashed outlines.

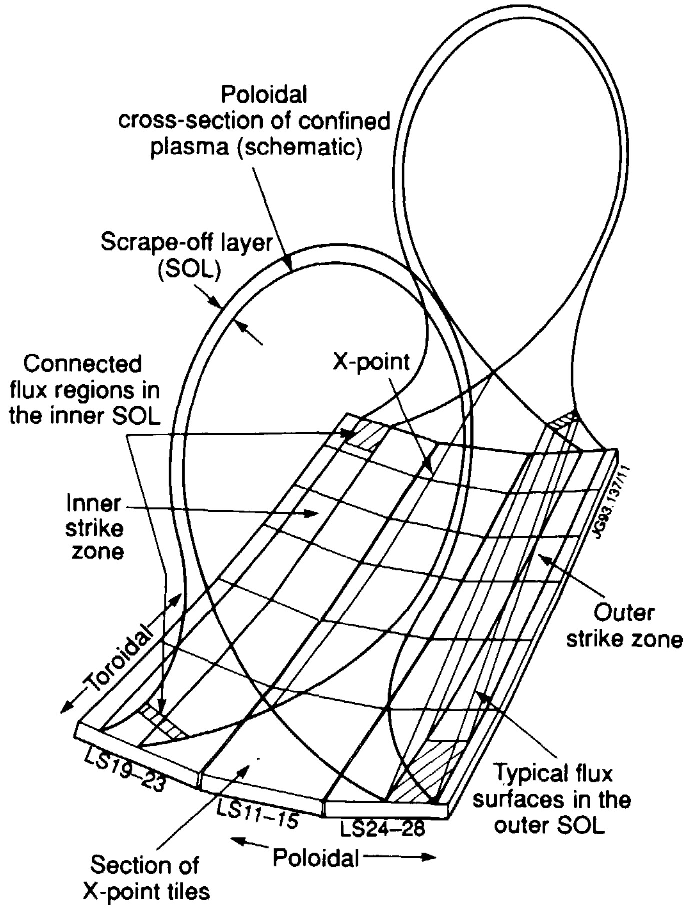

Figure 3: An (approximately) toroidal view of the interaction between the plasma and X-point tiles, defining the relative positions of the X-point and the interaction zones.

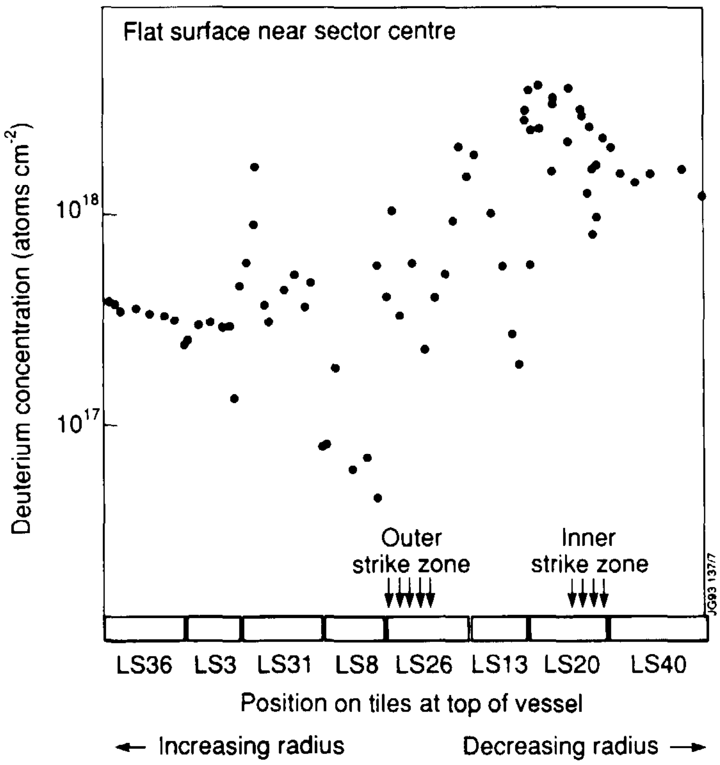

Figure 4: A plot of deuterium versus position on the target tiles, along a radial line across all eight rings of tiles at the centre of the sector (where the tiles are each flat).

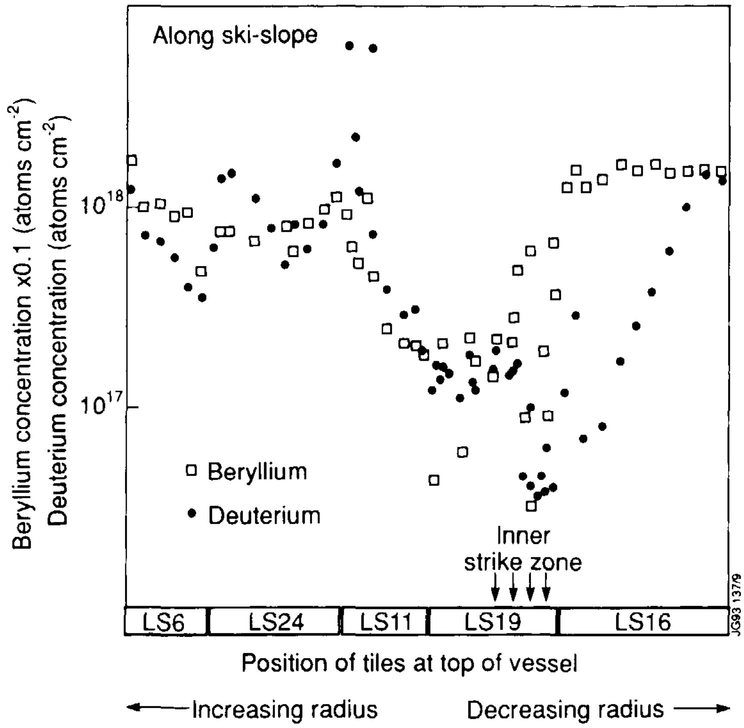

Figure 5: Beryllium and deuterium concentrations along the ski-slope on the right of the sector (as portrayed in figure 2).

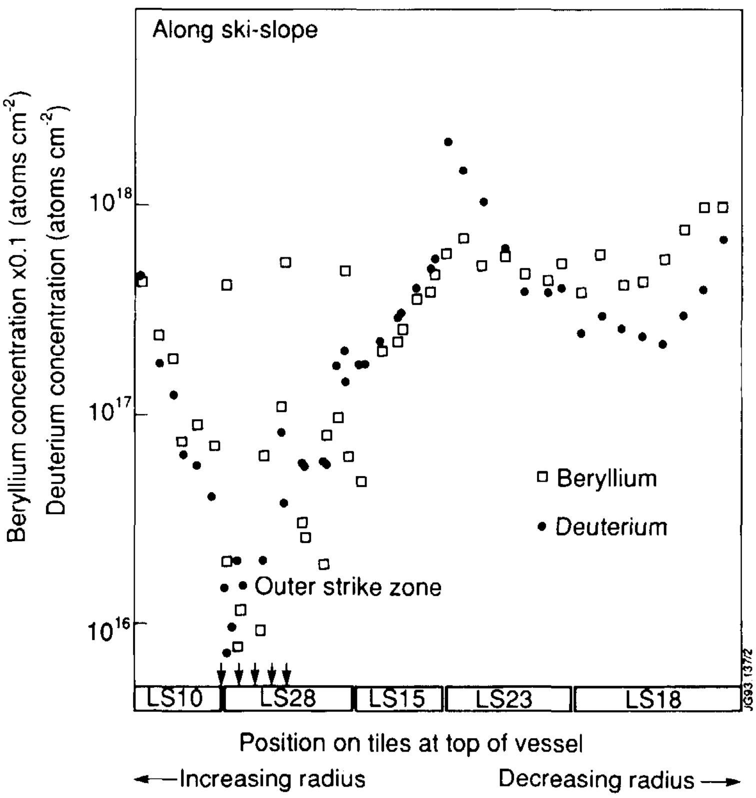

Figure 6: Beryllium and deuterium concentrations along the ski-slope on the left of the sector (as portrayed in figure 2).

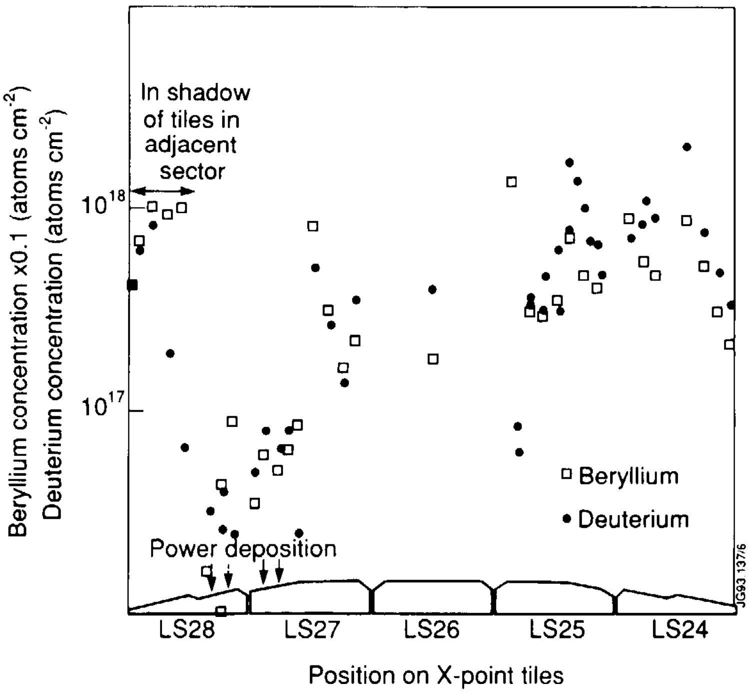

Figure 7: Beryllium and deuterium concentrations across the sector at the radius of the outer strike zone.

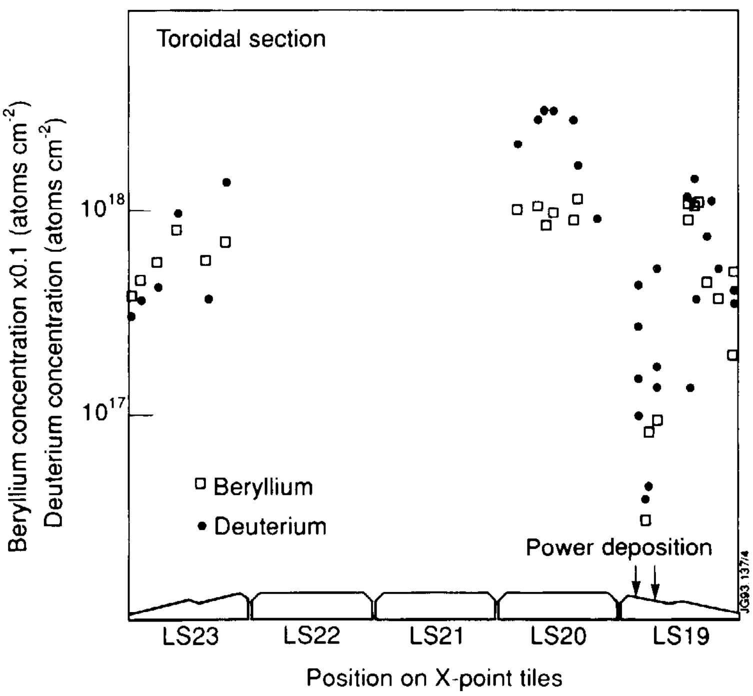

Figure 8: Beryllium and deuterium concentrations across the sector at the radius of the inner strike zone.