EROSION AND REDEPOSITION OF METALS AND CARBON ON THE JET LIMITERS

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1. Introduction

It has been observed in JET and other tokamaks that the limiters become contaminated by material from the walls (1) (2) and in JET they are the main source of impurities in the plasma, although for current plasma discharges in JET the metals do not contribute significantly to the energy balance in the plasma centre. The analysis of the metal concentration on the limiter of JET gives indication on the erosion and redeposition processes for all impurities. These analyses have been carried out after the various periods of operation in 1983, 1984 and 1985 and have been described in detail elsewhere (3). The general features common to each period of operation are that the concentrations of metals have minima (~ 3×10^{20} atoms m^{-2}) near the centre and maxima (some 10^{21} atoms m^{-2}) near the edges. However the detailed distributions differ significantly for the three operating periods. In the present paper we discuss the possible mechanisms of contamination and some of the possible explanations for the observed spatial distributions.

2. Limiter Contamination and Cleaning Processes

The possible processes by which metals from the wall may be transferred to the limiter are: (a) Glow discharge cleaning (GDC). (b) Pulse discharge cleaning (PDC). (c) Disruptions or runaway electron interactions with the wall, leading to wall evaporation. (d) Arcing at the wall. (e) Charge exchange neutral sputtering of the wall. The contamination of the limiters by metals is clearly the integral effect of some or all of these processes. We have experimental evidence that all of these processes have occurred during the period of interest on JET.

Processes (a),(b) and (c) are expected to give a fairly uniform deposition flux onto the surface of the limiter. Process (c) may also result in discrete metal splashes and droplets on the limiter. Processes (d) and (e) would result in a deposition flux on the limiter peaked at the outside edge where material entering the scrape-off layer from the wall will be first ionized and swept along field lines onto the limiter.

However, the spatial distributions are modified by subsequent exposure of the limiter to tokamak discharges. Because of the limiter geometry in JET atoms sputtered from the limiter surface have a high probability of being ionized and entering the plasma. When these impurity ions subsequently diffuse out of the plasma they will be redeposited primarily on the limiter.

Direct experimental observations of impurity erosion from the limiter have been made spectroscopically. Early in the 1985 operating period one of the limiters was accidently contaminated by iron when a stainless steel probe was destroyed by a disruption. During the subsequent series of discharges the iron influx from this limiter was initially very high, but progressively fell to a negligable value after about 1 week. Similar results have been seen more recently when nickel and chromium deposited in discharges with r.f. heating have been removed in subsequent discharges without r.f.

3) Modelling of Erosion and Deposition Processes

In this section we examine in more detail the distribution of Ni on the limiter tiles from the 1983, 1984 and 1985 experimental period. Ni is chosen because it is the major wall (inconel 600) constituent. We first discuss empirical fits to the measured distributions and then propose a simple model which may explain some of the observed erosion and deposition phenomena.

Fig. 1 shows the Ni concentration per unit area of the limiter for the three limiter tiles of interest plotted as a function of the radial distance into the scrape-off layer X = r-a and divided by cos α to take into account the geometry of the limiter surface relative to the toroidal magnetic field lines. Where α is the angle between the surface normal and the toroidal magnetic field. We assume that the impurity distribution on the limiter is due to erosion and deposition and that this is composed of three terms:
(i) a uniform layer of metals C_o which represents the accumulated deposition due to glow and pulse discharge cleaning and to disruptions; (ii) an erosion fluence $C_e \exp(-x/\lambda_e) \cos\alpha$ which represents the removal of metals from the limiter during tokamak discharges (iii) a redeposition fluence $C_d \exp(-x/\lambda_d) \cos\alpha$ which represents the redeposition of metals from the plasma. Thus the resulting concentration on the limiter surface is

$$C(x) = C_o - C_e \exp(-x/\lambda_e) \cos\alpha + C_d \exp(-x/\lambda_d) \cos\alpha. \quad [1]$$

For simplication we will assume that $\lambda_e = \lambda_d$ and thus the difference $C_e - C_d$ represents the net erosion.
The date for the 1983 limiter is best fitted (figure 2) by $C_o = 2\ 10^{22}$ atoms m^{-2} and $C_e - C_d = 2.08\ 10^{22}$ atoms m^{-2}, ie. there is an initial uniform deposition consistent with the extensive glow clearing during this period of JET operations and a net erosion during subsequent tokamak discharges. It contrast the 1984 limiters is best fitted with a very small uniform deposit, Co = 0, and with net redeposition in tokamak discharges, $C_d - C_e = 1.07\ 10^{22}$ atoms m^{-2}. The difference between the 1983 and 1984 cases is not fully understood. There may have been a lower ratio of glow cleaning per tokamak discharge in 1984, particularly towards the end of the operating period resulting in the initial contamination being completely redeposited. It may also be significant that during this period of operation the limiter surface temperature was raised to around 1500°C compared to $\leq$ 700°C during earlier operation. A detailed surface analysis (4) suggests that diffusion of Ni into the bulk of the limiter to a depth of several μm took place due to the higher surface temperature. This would allow Ni to accumulate in the limiter at a depth where it would be protected against erosion but subsequently measured by the PIXE analysis technique which measures to a depth of several μm. Using the alternative technique of Rutherford backscattering with which a surface layer of about 10nm can be analysed, the concentrations on the actual surface have been found to have a distribution similar to that found on the 1983 limiter.

The 1985 data (figure 1) has a distribution similar to that for 1983 near to the centre, but increases sharply at x ~ 20nm and is much higher on the outer part of the limiter. The step coincides with the radius of the leading edge of the carbon shield surrounding the RF antenna which had been installed at the start of 1985. It seems resonable that the carbon shields which also act as limiters affect the scrape off layer and reduce the net erosion on the outer part of the limiter.

To examine these processes further we have developed a more detailed model of erosion and redposition in the scrape-off layer of a tokamak discharge.

The model is presented in more detail elsewhere (5) and we only give here a brief summary. We assume that the Ni distribution on the limiter is eroded by sputtering due to deuterons, light impurities (carbon) and self sputtering during plasma discharges. We also assume that the eroded flux of Ni enters the confined plasma and is then redeposited on the limiter by diffusion perpendicular to the magnetic flux surfaces. We assume further that the sputtering coefficients are energy dependent and therefore decrease with increasing radial distance from the leading edge of the limiter. By using measured data for the relative particle fluxes, the relative coverage of the limiter surface with metal (described by the factor f in figure 3) the scrape-off layer decay lengths and the plasma temperature at the limiter we get the erosion and deposition rates as indicated in fig. 3.

One result is that the limiter is split into an erosion and deposition zone the formation of which depends on the plasma boundary parameters. In our example this deposition zones is at $x \geq 15$mm for kT=100eV.

Another result is that erosion rates on the limiter surface are about 10^{20}atoms/m^2.s at $x \approx 10$mm. Thus an initial thin film surface coverage of 10^{21}atoms/m^2 would be eroded off in 10s. This is consistent with spectroscopic observation of the rate of which a limiter appears to clean up following contamination.

Erosion of droplets, however, which have been detected with diameter of up to 100 µm on the limiter will take much longer to erode. They may represent a more persistent source of Ni.

In view of this model we suggest that the surface concentration on the limiter does not reach steady state, as long as processes are present which contaminate the limiter in its erosion zone. This may occur in processes as mentioned under (a) - (c) in section (2).

4) Conclusions

A more detailed analysis of the metal distribution found on the JET limiters from three different operational periods indicates that the final distribution is largely affected by erosion and deposition processes caused by the plasma. Contamination of the limiter surface is probably due to tokamak operational processes as GDC and PDC as well as transfer of metal from the walls to the limiter in disruptive discharges. For a complete description the results suggest that the limiter surface conditions (temperature) and the positioning of the limiter in the torus relative to other structures (r.f. antenna) have to be taken into account. A theoretical model describing the 1983 limiter erosion and deposition processes gives results which are qualitatively in agreement with experimental observations during discharges.

References

(1) G M McCracken et al. J.Nucl.Mat. 111 & 112 (1982) 159.
(2) R Behrisch et al., J.Nucl.Mat. 128 & 129 (1984) 470.
(3) J Ehrenberg et al., 12th Europ.Conf.Fus.Plasma Phys. Budapest 2-6 September 1985.
(4) J Ehrenberg and P Borgesen, Proceed.7th Int.Conf. Ion Beam Analysis Berlin 7-12 July 1985.
(5) G M McCracken et al Proceed. 7th Int. Conf. Plasma Surface Interactions, Princeton N.J. USA 5-9 May 1986.

Fig. 1 Ni concentration distributions on JET carbon limiters from three experimental periods.

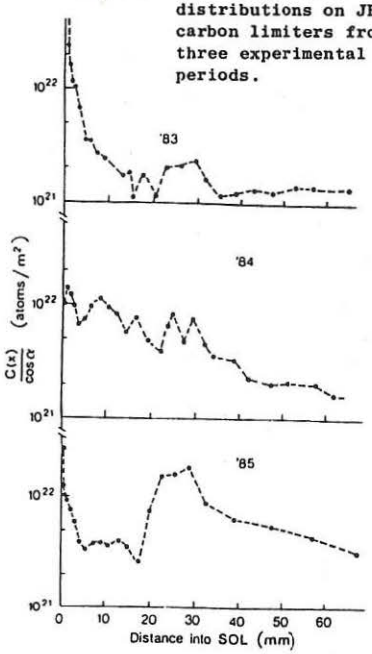
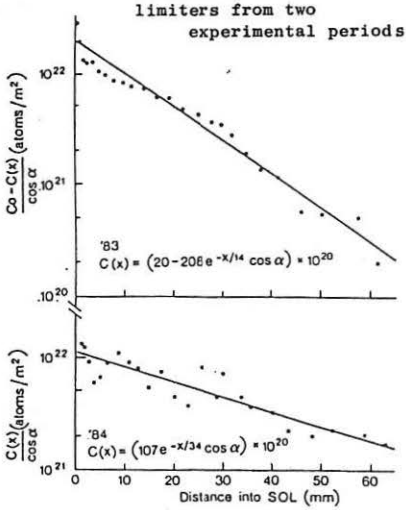


Fig. 2 Empirical fits to the Ni concentration distributions on JET limiters from two experimental periods



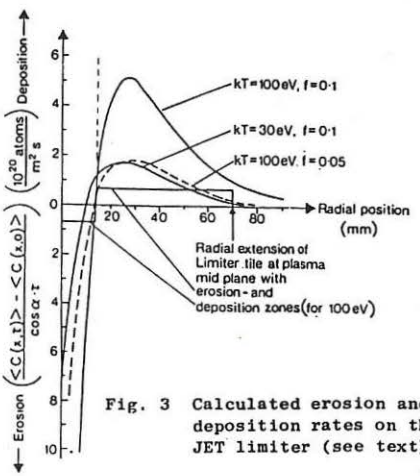


Fig. 3 Calculated erosion and deposition rates on the JET limiter (see text)