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Journal of Nuclear Materials 266–269 (1999) 604–610

journal of nuclear materials

Wall erosion and material transport to the Mark I carbon divertor of JET

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Abstract

Erosion and deposition at the vessel walls of the main chamber of JET were measured with long term samples during the whole operation period of the Mark I carbon divertor from April 1994 until March 1995. Assuming toroidal symmetry, about 70 g Ni + Cr + Fe was found to be eroded from the inner torus wall and about 55 g Be from the outer torus wall due to sputtering by energetic charge-exchange neutrals. Deposition has been measured on a poloidal section of the Mark I C divertor and on tiles from the inner and outer wall limiters. Eroded material is redeposited in the divertor and in the main chamber where it is found predominantly at the sides of the poloidal limiters and at the outer vessel wall. At these deposition-dominated areas in total about 25 g Ni + Cr + Fe, 28 g Be and 370 g C are found. The carbon originates mostly from the carbon limiters; additionally some may be originating from the divertor plates.

Keywords: Beryllium; Carbon; JET; Redeposition; Sputtering

1. Introduction

For a magnetically confined diverted plasma the ions diffusing out of the central plasma impinge at wall structures intersected by magnetic field lines such as divertor plates and protection limiters. In addition, all areas of the vessel walls are bombarded with energetic neutral atoms created predominantly in charge-exchange (CX) collisions [1–3]. Sputtering by these energetic neutral atoms at the main chamber walls is an important source of impurities [2–6], in addition to ion sputtering at limiters and divertor plates. This was already evident in the steel-walled ASDEX experiment, where the Fe, Cr, Ni concentration in the central plasma was greatly reduced after carbonisation of the main chamber walls [6,7].

At all areas of the vessel walls both erosion and redeposition are observed with net erosion and net deposition-dominated areas. Three different areas of the vessel walls have to be distinguished:

(1) *The divertor:* The divertor is the major area of interaction between first-wall material and the plasma. The particle flux to the target plates is high, up to about 10^{22}–10^{24} ions/m^2 s, while the plasma temperature in fornt of the target plates is low, only a few eV for detached plasma operation. For carbon the major erosion mechanism is chemical sputtering by formation of hydrocarbon molecules [8,9]. Eroded atoms from the target plates may be promptly redeposited on divertor tiles [10–12]. Due to divertor retention only a small fraction of the eroded atoms is able to penetrate as impurities into the core plasma [13].

(2) *The walls of the main chamber:* These areas are hit predominantly by energetic neutral particles [3,14]. The energy distribution of neutrals is broad, ranging from a few eV up to the several keV region. The flux density is of the order of 10^{18}–10^{20} atoms/m^2 s. This bombardment causes an erosion of the plasma facing first wall [2–4,15]. The flux density of the energetic neutrals to the wall is several orders of magnitude lower than the ion flux

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0022-3115/99/$ – see front matter
PII: S0022-3115(98)00834-4

density at the divertor target, though in compensation the area of the main chamber wall is about two orders of magnitude larger.

(3) *Limiters in the main chamber:* Limiters are hit both by ions and energetic neutral particles. The incident ion flux to limiters may be high, i.e. in the 10^{20}–10^{22} m^{-2} s^{-1} range. The plasma temperature in front of the limiters is also relatively high, i.e. about 50–200 eV. For carbon limiters both physical and chemical sputtering contribute to the erosion.

The aim of the present work is to get a quantitative description of the production of impurities and their redeposition at the different areas of the vessel walls for the carbon phase of the Mark I divertor [16] of JET.

2. Experimental

2.1. The JET vessel

(1) During the Mark I (carbon phase) the divertor plates consisted of carbon tiles with an area of about 25 cm^2 each. The tile bulk temperature was typically 320 K, which increased to about 370–470 K during a discharge. Surface temperatures vary greatly, and may exceed 1300 K. The total divertor area was 26.6 m^2, of which 21 m^2 were tile surfaces and 5.6 m^2 were gaps between tiles. The tiles surfaces were inclined at 4° to the horizontal producing a shadowed area extending over 25–50% of the surface area of the adjacent tile [17].

(2) The vessel walls of the main chamber, consisting of Inconel 600 (75% Ni, 15.5% Cr, 8% Fe), have areas of about 15 m^2 for the inner wall and 130 m^2 for the outer wall, excluding the limiters. For wall conditioning Be was routinely evaporated, resulting in a coverage of the outer wall with Be up to several μm [15]. Some areas at the outer wall were shadowed from the evaporators [4,15] by limiters, antennas, etc., and in these regions the Inconel wall remains visible.

(3) The inner poloidal protection limiters, made of carbon fibre composite, have an area of about 10 m^2. The outer poloidal limiters, made of fine grain graphite, have an area of about 11 m^2.

2.2. Plasma operation and wall analysis

JET was operated with the Mark I carbon divertor from April 1994 until March 1995 for about 3500 plasma pulses, each lasting about 25 s, resulting in about 24.2 discharge hours. A JET discharge normally starts as a circular plasma attached at the inner wall limiters for about 10 s. After this time the plasma is changed to the divertor configuration for about 10–15 s, while in the ramp-down phase the plasma usually again reverts to a circular plasma limited by the inner wall limiters.

After the Mark I carbon divertor was replaced by the Mark I beryllium divertor, samples were cut from the carbon tiles from a poloidal divertor section for analysis. 2.5-MeV proton backscattering at an angle of 165° was used for measuring D, Be, C, N and O; a spectrum is shown in Fig. 1. The measured spectra were analysed with the simulation program SIMNRA [18], which is able to deal also with non-Rutherford scattering cross sections [19–22]. The analysed depth for Be, C, N, O and metals is >15 μm, but only about 2 μm for D. H cannot be measured. The near surface H/D ratio was determined with heavy ion ERDA using 35-MeV Cl ions and was about H/D = 0.5. For the quantitative determination of Ni, Cr and Fe, particle induced X-ray emission (PIXE) with 1.5-MeV incident protons was used. The depth analysed with PIXE is about 25 μm.

For the walls of the main chamber erosion/deposition had been investigated with long term samples (LTS), mounted at the vessel walls between the limiters at a distance between 150 and 500 mm from the last closed magnetic flux surface [4,15]. Three sets of LTS were used during the different Mark I divertor phases: the first set was installed from April 1994 until September 1994, the second from October 1994 until March 1995 (both during Mark I carbon divertor phases), whilst the third set was used during the Mark I beryllium divertor phase from April until June 1995.

The LTS were made of fine grain graphite and partly coated with 500–800 nm Al or Ni, or implanted with a molybdenum marker to a depth of 380 nm into C. Detailed surface layer analysis with MeV ion beams, before and after installation in JET, allowed erosion and redeposition to be measured directly [4,15].

The carbon limiter tiles were installed in 1994 and were in operation during the whole Mark I carbon and beryllium divertor phases. They were removed from the

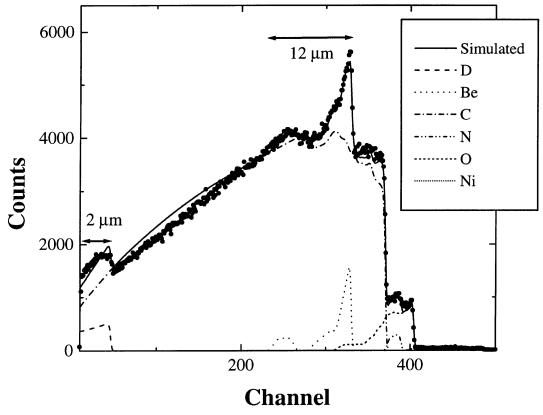

Fig. 1. Measured proton backscattering spectrum (dots) and computer simulation (lines) of the spectrum. Tile: 4; incident proton energy: 2.5 MeV; scattering angle: 165°.

inner and outer wall near the midplane position after the Mark I Be divertor campaign and analysed with 2.5 MeV ^{4}He backscattering at a scattering angle of 150°. The maximum analysable depth of this method for metals (Ni, Cr, Fe) is only about 3 μm.

3. Results

3.1. Mark I carbon divertor

The total deposition of Be, C, N + O and Fe + Cr + Ni at a poloidal section of the Mark I divertor is shown in Fig. 2. The signals of N and O overlap and cannot be separated, see Fig. 1. However, due to the comparable proton backscattering cross sections of both elements [21,22] this introduces only a small error in spectra evaluation. N may be present due to nitrogen seeding of the discharges. The relative concentrations Ni:Cr:Fe were about 0.6:0.2:0.2, which is close to the composition of Inconel, but with some excess of Fe. For the determination of the carbon deposition on the carbon substrate, Be was taken as a marker element: throughout the depth where Be is visible it is assumed that the material has been deposited. This assumption may slightly overestimate the total amount of deposited carbon. As can be seen in Fig. 2 the major deposition is carbon.

The largest deposits are generally observed near the divertor corners. Due to the toroidally stepped divertor geometry, the deposition pattern on the tiles shown in Fig. 2 is not homogeneous in toroidal direction, as has been shown previously for the distribution of D [17]. The largest deposits are observed in the regions toroidally shadowed by neighbouring tiles, the smallest deposits are observed on the non-shadowed plasma exposed surfaces. The difference in net deposition between the plasma exposed surface and the shadow region can be up to a factor of 10. Fig. 2 shows the mean deposition averaged toroidally over plasma-exposed and shadowed regions. It should be noted that erosion cannot be determined by the analysis methods employed here, but may well be present in the plasma-exposed strike point regions, where actually small minima are measured.

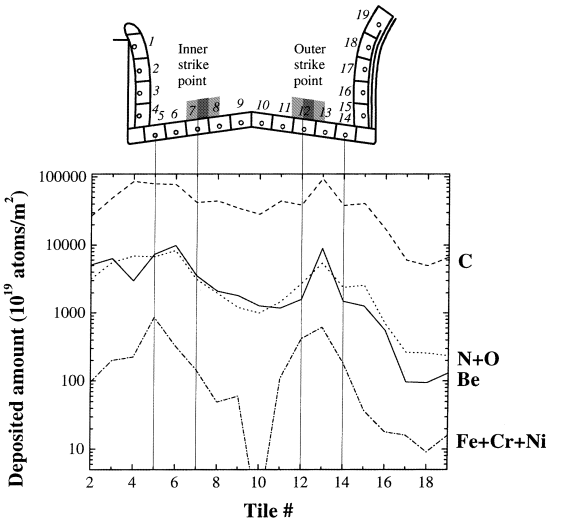

Fig. 2. Poloidal distribution of the deposition of Be, C, N + O and metals (Fe + Cr + Ni) in the Mark I C divertor.

The total deposition of Be, C and metals observed in the divertor is summarised in Table 1. Additionally some material is deposited in the gaps between the tiles at the tile sides, which have not been investigated.

3.2. Walls of the main chamber

At the outer wall, the carbon LTS from areas with line-of-sight to a Be evaporator were covered with Be to thicknesses up to several μm [15,23]. These Be layers contained H, D, C, O, Fe, Cr, Ni and other elements in varying composition [23].

At the inner wall, the LTS were found to be eroded, and no or only minor Be deposits were measured [15]. The LTS give average values for erosion and deposition during different discharge periods and over the limiter and divertor phases of each discharge (Table 2) [4]. In addition, traces of evaporated Be must have been deposited and subsequently sputtered from the samples after each evaporation. For the erosion at the outer wall, only samples which were shadowed from the Be evaporations are taken into account.

The measured erosion at the LTS was used to get an estimate of the average particle fluxes of energetic neutrals to the vessel walls. During the limiter phase the particle flux can be expected to be comparable to, or higher than, that during the divertor phase. The average flux thus determined for the inner wall midplane is about 10^{20} atoms/m^2 s [4]. This value is in good agreement with spectroscopic measurements at the inner wall midplane which yield a particle flux of about 2×10^{20} atoms/m^2 s [24]. Computer simulations for the divertor phase with the EDGE2D/U code yield a flux typically in the range 10^{19}–10^{20} atoms/m^2 s to the inner wall midplane [25,26]. According to these computer simulations the flux of energetic neutrals to the outer wall midplane is a factor of 2–3 times lower than to the inner wall [25,26]. This is in good agreement with the observed lower erosion of Al and Ni on LTS mounted at the outer wall in positions shadowed from the Be evaporators, as shown in Table 2.

The erosion of Ni measured on the LTS at the inner wall during the Mark I Be divertor operation was found to be about 0.8×10^{19} atoms/m^2 per JET discharge (Table 2). During this operation phase the average Al erosion per discharge is lower by a factor of about 1.7

Table 1
Net erosion and deposition of Be, C and metals at different areas of the JET vessel wall during the Mark I carbon divertor phase, April 1994 – March 1995

	Erosion (g)			Deposition (g)		
	Be	C	Ni, Cr, Fe	Be	C	Ni, Cr, Fe
Inner Wall (15 m^2)	≈0	0[a]	70	0	0	0
Outer Wall (130 m^2)	55	0[a]	n.d.	n.d.	46[b]	15
Limiters (inner 10 m^2, outer 11 m^2)	0[a]	60[c]	0[a]	20[d]	160[d]	6[d]
Mark I C divertor (21 m^2)	0[a]	n.d.	0[a]	8	160	4

Inner wall and outer wall are the wall areas between the poloidal limiters, n.d. means not determined.
[a] Initially not present at that area.
[b] may be due to gettering by Be.
[c] Calculated, CX flux only, ions are not considered.
[d] Analysed after the Mark I Be divertor campaign.

compared to the Mark I C divertor phase (Table 2). Taking this into account in the extrapolation of the measured Ni erosion to the Mark I C divertor operation phase, gives a mean erosion of 1.4×10^{19} Ni-atoms/m^2 per JET discharge. The sputtering yield of Inconel is nearly the same as the sputtering yield of Ni [27]. Taking the inner wall area as 15 m^2, and assuming toroidal symmetry this gives a total erosion of 70 g Ni + Cr + Fe during the whole Mark I C divertor operation phase (Table 1). Additionally some Ni + Cr + Fe is likely to be eroded from areas at the outer wall which are shadowed from the Be evaporators, but CX fluxes to the outer wall would be small during phases when the plasma is limited at the inner wall. Despite the larger area of Inconel at the outer wall, the lower average fluences and the fact that a significant fraction is covered with Be suggest that the contribution from this region is likely to be much less than from the inner wall.

At the evaporated Be layers on the outer wall the erosion cannot be measured. It was estimated by taking a flux of 3×10^{19} D^0 atoms/m^2 s and assuming the same energy distribution at the inner and outer wall [27], i.e. the same effective sputtering yield of 1.3×10^{-2} Be/D^0 atom [4,14]. This gave an erosion of about 0.8×10^{19} Be-atoms/m^2 per discharge. The total surface area of the outer wall is about 130 m^2, which, if it were all Be, would give a total Be erosion of 55 g during the Mark I C divertor campaign (Table 1). In fact some of the outer wall is shadowed from the evaporation, but on the other hand Be evaporated onto other surfaces in the vessel such as the inner wall limiters is also being sputtered, so the overall estimate for Be erosion should be of the right order.

Finally, at the outer walls some deposited C and Ni + Cr + Fe were also measured in the evaporated Be layers. The total deposited amount of Fe + Cr + Ni is deduced to be about 15 g, while the deposited C is about 46 g. The evaporated layer of Be acts as a strong getter for oxygen and carbon, so some of the carbon seen may result from gettering.

3.3. Poloidal limiters in the main chamber

For the limiters two different regions can be distinguished:

(1) The plasma exposed limiter faces show only minor deposits. These areas are erosion-dominated zones; however, the erosion of C could not be measured. For an estimate we will assume that all the C which was found as deposits (about 370 g) was eroded from the erosion-dominated area of the limiters, which is approximately two-thirds of the area (i.e. 14 m^2). Assuming toroidal symmetry this gives an average erosion of 3.9×10^{20} C/m^2 per JET discharge, or for uniform dis-

Table 2
Measured mean erosion of Al, Ni and C at the inner and outer walls of the main chamber near the torus midplane during the different operation phases of the Mark I divertor

	Inner wall			Outer wall			No. of discharges
	Al	Ni	C	Al	Ni	C	
Mark I C divertor campaign							
April–September 1994	1.8×10^{19}	1.4×10^{19}[a]	–	0.6×10^{19}	–	–	1785
October 1994–March 1995	1.6×10^{19}	–	–	–	–	–	1741
Mark I Be divertor campaign							
April–June 1995	1×10^{19}	0.8×10^{19}	$>3.6 \times 10^{19}$	0.4×10^{19}	–	2.2×10^{19}	1070

All numbers are given in atoms/m^2 per JET discharge.
[a] Calculated for the time April 1994 to March 1995 from measurement with Mark I Be divertor.

tribution a total erosion of about 13 μm. For the assumption of chemical sputtering this needs a D flux of about 6×10^{20} D/m^2 s, which is an order of magnitude larger than the neutral flux to the vessel walls.

(2) At the sides of the limiters thick deposits are found with layer thickness $>3 \times 10^{23}$ atoms/m^2 (about 3 μm) (i.e. greater than the maximum depth of analysis). The area of the deposition zone is about one-third of the total limiter area, i.e. about 7 m^2.

The deposited layers consist mainly of carbon with some Be. Furthermore some Ni + Cr + Fe is uniformly distributed in the deposited layers at a concentration of about 0.5–2 at.%. For an estimate of the total deposition at the limiter sides we assume a layer thickness of about 10 μm. This gives a total deposition of 180 g Be + C and 6 g Ni + Cr + Fe. The uncertainty of these numbers is a factor of about 3 due to the unknown total layer thickness. Additionally these limiters have also been in use during the Mark I Be divertor campaign. The number of discharges during this campaign was only about one-third of the number of discharges during the Mark I carbon divertor campaign (Table 2).

It is important to note the visual appearance of the poloidal limiters after the operational campaign. It might be expected that the inner limiters near the midplane which act as plasma limiters during start-up and ramp-down would display the tell-tale ''footprints'' of erosion at the front face and deposition on the flanks seen in tokamaks with limiters (e.g. JET prior to 1993). However what is interesting is that the full toroidal arcs of inner and outer poloidal limiters display similar characteristics, implying that during a large proportion of divertor discharges there is sufficient plasma interaction with the front surfaces of the limiters for them to be areas of net erosion (despite being many centimeters from the LCFS).

4. Discussion

From the viewpoint of erosion and redeposition of wall material the operation in the limiter phase (about 10 s), in the following divertor phase (about 10–15 s) and the ramp-down in the limiter phase have to be taken into account. Additionally material may be eroded during glow discharge cleaning (GDC). GDC in He or D is employed for wall conditioning at the start of the campaign, and also occasionally during the campaign. However the measured erosions for the different materials scale well with the respective effective sputtering yields by the energetic neutral D atoms and not with the effective sputtering yields for He ion bombardment [4].

During the limiter phase the plasma is in direct contact with the inner wall carbon limiters. The plasma temperature in front of the limiters is of the order of 50–100 eV. The incident high ion fluxes result in a high flux of recycling D^0 atoms inducing a large flux of energetic CX neutrals. Both the ions and the energetic neutrals cause erosion at the limiter faces. This is confirmed by the very small amounts of deposited Be, Ni, Cr and Fe in these areas and the large C deposition at the sides of the limiters. At the limiters of all tokamaks and stellerators, including JET during the initial operation phases [28] and TEXTOR [29,30], major erosion is observed at the plasma exposed faces of limiters, and deposition at the sides. The amount of erosion has not been determined experimentally; however from the total deposition and the assumption of uniform erosion we estimate a total erosion of about 13 μm.

At the walls of the main chamber the bombardment with the energetic neutrals results in erosion of Ni + Cr + Fe at the inner wall and of evaporated Be at the outer wall. Only the erosion of Al was determined during the whole Mark I campaign and was found at the inner wall midplane tobe 1×10^{19}–1.8×10^{19} atoms/m^2 per JET discharge, see Table 2. The erosion is ascribed to sputtering by energetic neutral hydrogen atoms [4]. Carbon is eroded from the poloidal limiters especially during the limiter phase, but also during the divertor phases. Sputtering of carbon from the limiters during the divertor phase is additionally confirmed by the observation of carbon deposits on the Be divertor tiles with a thickness of several μm during the Mark I Be divertor operation [17].

Eroded wall atoms moving toward the central plasma are liable to be ionised in the scrape-off layer. They then travel along field lines to be deposited at the sides of limiters or divertor plates. However, a small proportion of eroded particles may enter the central plasma as impurities. For impurities diffusing out of the central plasma the concentration outside the LCFS decays exponentially with a decay length of about 1–2 cm [31]. These impurities are then also deposited predominantly at the side faces of the poloidal limiters or at the divertor plates, and contribute to the build up of the thick deposits which are observed at these areas; see Section 3.2 and Table 1.

In the divertor the first areas of plasma bombardment are the plasma exposed divertor tile areas where the separatrix intersects. However, these are normally areas of net erosion. Thus the material deposited in this first step must be further eroded and redeposited until it ends up in regions shadowed by neighbouring tiles or deep in the SOL where deposition dominates, see Fig. 2. In JET much more deposition is found in the inner than in the outer divertor corner. The total amount of deposited carbon is about 370 g (Table 1).

Both in the limiter and the divertor phases the inner wall is a source of Ni + Cr + Fe, the outer wall is a source of Be and the limiters are a source of carbon. During the whole Mark I carbon divertor campaign between April 1994 and March 1995 about 70 g

Fe + Cr + Ni was estimated to be eroded from the inner vessel wall. About 25 g Fe + Cr + Ni can be found at deposition dominated areas, see Table 1. About 55 g Be was eroded from the outer wall, of which about 28 g is found in deposition zones. The total amount of eroded carbon could not be measured, but about 370 g was found to be deposited at the sides of the limiters and on the divertor tiles. For Ni, Cr, Fe and Be the determined total amount of eroded material was larger than the total amount of material found to be deposited. This may be due to further sinks for material, such as the gaps between the divertor tiles, which were not analysed. Furthermore, the amounts of eroded and redeposited material determined are only accurate within a factor of about 2.

5. Conclusions

The vessel walls of the main chamber at JET are sources of Ni + Cr + Fe and Be due to sputtering by energetic charge exchange neutrals. Of the material eroded at these areas roughly half is found at deposition-dominated regions at the sides of the poloidal limiters and in the divertor. About 370 g C is found in redeposits. Most of the carbon is believed to be eroded from the poloidal limiters, but the carbon redeposited in the divertor must include some eroded at the divertor strike points and redeposited in shadowed areas or the corners of the divertor.

By operating in the detached plasma regime the energy of the plasma ions reaching the divertor plates can be reduced. At low plasma temperatures the divertor surfaces, except for the intersection area at the separatrix, are deposition dominated, i.e. a surface film is built up of material eroded from other wall areas. The vessel walls are always sources for impurities due to bombardment by energetic neutrals, which are difficult to control. To reduce the flux of fast neutrals created by charge exchange the neutral density in the plasma boundary has to be reduced. Fast neutral production in the plasma centre cannot be reduced.

ITER will have a total main vessel wall area of >1000 m^2. The CX fluxes to the vessel walls of ITER are predicted to be lower by a factor of about 10 than the CX flux measured at JET, but may be as high as observed at JET. The measured erosion rate at the vessel walls of JET may be therefore taken as an upper limit for the impurity production at the vessel walls of ITER, but has to be scaled with the larger wall area. The complex structure of the main chamber wall of JET, and the visual appearance of the poloidal limiters, demonstrates that the impurity transport behaviour at JET is very complex. The pattern of erosion and redeposition in ITER may thus be significantly different than in JET.

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