EROSION AND DEPOSITION OF METALS AND CARBON IN THE DIII-D DIVERTOR

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ABSTRACT

Net erosion rates at the outer strike point of the DIII-D divertor plasma were measured for several materials during quiescent H-mode operation with deuterium plasmas. Materials examined include graphite, beryllium, tungsten, vanadium and molybdenum. For graphite, net erosion rates up to 4 nm/sec were found. Erosion rates for the metals were much smaller than for carbon. Ion fluxes from Langmuir probe measurements were used to predict gross erosion by sputtering. Measured net erosion was much smaller than predicted gross erosion. Transport of metal atoms by the plasma across the divertor surface was also examined. Light atoms were transported farther than heavy atoms as predicted by impurity transport models.

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1. Introduction

Erosion by the plasma may limit the lifetime of a fusion reactor divertor. Removal, transport and redeposition of material by the plasma results in net erosion in some regions and net deposition in other regions. These complex processes are coupled with the plasma boundary conditions, making prediction of net erosion rates and hence component lifetimes, difficult and uncertain. Measurements of net erosion are therefore necessary to test theoretical models and to guide material selection and design for fusion reactors.

We have used the Divertor Materials Evaluation System (DiMES) \([1]\) to measure the rates of erosion and deposition of carbon and several metals in the divertor of the DIII-D tokamak. The DiMES mechanism allows samples to be inserted into the floor of the DIII-D divertor, exposed to the plasma, and then retracted and removed for analysis. In previous experiments \([2]\) graphite samples, one of which had a thin tungsten film on the plasma-facing surface, were exposed to the outer strike point plasma. The resulting erosion and deposition of tungsten and graphite by the plasma were determined by ion-beam analysis of the samples before and after exposure to the plasma. Here we describe two additional experiments to measure erosion of metals and graphite at the divertor strike point. The first experiment used a graphite sample with molybdenum and vanadium films, and the second used a graphite sample with beryllium and tungsten films. These experiments show how erosion rates depend on the atomic mass of the material for low (Be, C), medium (V, Mo) and high (W) atomic mass materials for similar plasma exposures. Retention of deuterium in the above materials, which affects fuel recycling, was also measured. The spatial dependence of metal deposition onto neighboring carbon surfaces was also examined. This data provides a sensitive test of the accuracy of computer simulations of erosion/deposition. Various plasma diagnostics provided detailed characterization of plasma conditions at the strike point so that the measured erosion could be related to known plasma exposure conditions.

2. Experimental Procedure

2.1 Plasma Exposures

The DiMES mechanism \([1]\) consists of a hydraulically actuated shaft, which transports samples from a vacuum transfer chamber under the tokamak, to the divertor floor. Inserted
samples are positioned so that their flat plasma facing surface is coplanar with the surrounding flat graphite divertor tiles, at a radial distance of 148.5 cm from the centerline of the machine. The plasmas were single null deuterium plasmas with a plasma current of 1.5 MA and a toroidal field of 2.1 T. Quiescent H-mode conditions were achieved for two one second intervals during each shot with 2.5 MW of neutral beam heating. The plasma conditions were reproducible from shot to shot. During non-H-mode intervals the X-point was positioned such that DiMES was in the private flux region between the inner and outer strike points. The samples were exposed by moving the outer strike point onto the DiMES sample during the quiescent H-mode intervals. Plasma conditions at the outer strike point were mapped by sweeping the strike point across Langmuir probes in the divertor floor. The Langmuir probe measurements gave electron temperatures and densities of 70 eV and 4x10^{13}/cm^3 respectively, peaking near the separatrix. The heat flux at the strike point was mapped by an infrared camera. The heat flux (shown in figs. 1 and 2) peaked at about 70 W/cm^2 about 1 cm outboard of the separatrix. Ion fluxes (shown in figs. 1 and 2) were also determined from the Langmuir probe measurements peaked at about 10^{20} cm^2/s near the separatrix. CCD cameras with interference filters were used to map the brightness of emission lines from carbon and metals. The radius of the outer separatrix (R_{sep}) was determined to within 1 cm by magnetic field mapping. The peak erosion is close to the location of the separatrix and the peak in the ion flux, but is offset slightly from the peak in the heat flux. This offset may be partly due to the uncertainty in the position for the heat flux measurements which is ± 1 cm. The angle between the magnetic field direction and the plane of the DiMES sample surface was about 1.6 degrees.

Here we describe two new experiments. In the first experiment, a sample with Mo and V metal films (sample 70) was exposed for 14 seconds with the strike point at R_{sep} = 147.8, close to the center of the DiMES sample. This exposure is similar to that of DiMES sample 8 discussed in reference 2. In the second experiment, a sample with Be and W metal films (sample 71) was exposed for 4 seconds with the strike point at R_{sep} = 145.7 cm near the inboard edge of the sample.
2.2 Sample Preparation and Analysis

The DiMES samples were cylinders of ATJ graphite [2] 4.8 cm in diameter. The flat plasma-facing surfaces were mechanically polished to a 0.25 μm finish, cleaned, outgassed, and then implanted with 200 keV $^{29}$Si to a fluence of $1 \times 10^{16}$ Si/cm$^2$ to provide a depth marker 300 nm beneath the surface. Metal films were then deposited onto the surface of each sample over four square regions 0.75 x 0.75 cm. Sample 70 had two spots each of Mo and V deposited as illustrated in fig. 1, and sample 71 had two spots each of Be and W deposited as illustrated in fig. 2. Here we refer to the metal spots by the numbers 1 through 4 numbered from the inboard to outboard sides. The nominal thickness of the metal films was 100 nm.

Ion-beam analysis was done on both samples before and after the plasma exposures. Net erosion or deposition of carbon was determined from the shift in depth of the Si marker as measured by Rutherford backscattering spectroscopy (RBS) with an analysis beam of 2 MeV $^4$He. RBS was also used to measure the change in thickness of the Mo, V and W metal films, to map the distribution of Mo, V and W deposited on the carbon surface adjacent to the metal films, and to measure the thickness of carbon deposited on top of the metal films. The thickness of the Be films and the distribution of Be transported onto adjacent carbon surfaces by the plasma were measured using the $^9$Be(p,d)$^6$Be and $^9$Be(p,α)$^6$Li nuclear reactions with an analysis beam of 350 keV protons. The sensitivity for detection of Be was greatly enhanced by placing a 3.5 μm mylar range foil in front of the detector which stops protons elastically scattered from the target but still transmits the more energetic d and α particles from nuclear reactions with Be. Finally, retention of deuterium in the samples was mapped by counting protons from the d($^3$He,p)α nuclear reaction with a 700 keV $^3$He analysis beam, also using a range foil to stop scattered $^3$He ions. This $^3$He nuclear reaction analysis (NRA) gives the areal density of deuterium within about 1 μm of the surface, which is much larger than both the metal film thickness and the implantation depth of D from the plasma. The beam spot size for the RBS and NRA was 1 x 1 mm.

3. Experimental Results

3.1 Carbon Erosion

Figure 1 shows the net erosion of carbon on sample 70 measured along two lines in the radial direction from inboard to outboard sides and offset 1.2 cm from the center along the toroidal
direction on either side of the metal spots, as illustrated in the diagram. The peak carbon erosion is about 50 nm at a position about 1 cm inboard of the center of the sample. The erosion is slightly higher on the downfield side than on the upfield side over most of the sample except near the inboard edge. The erosion rate at the peak is $3.6 \pm 0.7 \text{ nm/s}$ which agrees with carbon erosion rates observed in previous similar experiments [2]. The location of the separatrix, the distribution of heat flux to the sample, determined from the infrared camera, and the ion flux determined from Langmuir probe measurements, are also shown in figure 1.

Figure 2 shows the net erosion of carbon on sample 71 measured along two lines in the radial direction from inboard to outboard sides and offset 0.7 cm from the center along the toroidal direction on either side of the metal spots, as illustrated in the diagram. The measurements show small negative values for erosion, i.e. a small net deposition, with mean values of $\sim 5$ and 9 nm for the downfield and upfield scans respectively. With peak carbon erosion rates of $\sim 4 \text{ nm/s}$ observed in similar experiments with longer exposures, we might have predicted a peak carbon erosion of about 16 nm for sample 71. In view of the $\pm 10 \text{ nm}$ uncertainty of this measurement technique, the small difference between the measured and predicted carbon erosion for sample 71 may be of marginal significance.

3.2 Metal Erosion and Deposition

Erosion of Mo, V, and W metal films was measured by RBS. RBS spectra were recorded for each metal spot before and after the plasma exposures. The thickness of the films were determined from the energy loss of the $^4$He ions produced by the metal films [3]. The changes in thickness of the Mo, V and W films were smaller than the limit of detection by this method, i.e. the erosion was less than 5 nm for the Mo and V films on sample 70 and less than 2 nm for the W films on sample 71. Erosion of Be on sample 71 was determined from NRA measurements at the center of each Be metal spot taken before and after the plasma exposure. The change in thickness of the Be film was determined from the change in yield of energetic d, $\alpha$ and $^6$Li normalized to the yield of protons scattered from the carbon substrate. Be erosion determined by this method was $5 \pm 2 \text{ nm}$ on the Be spot (1) near the inboard edge and $6 \pm 2 \text{ nm}$ on the Be spot (3) just outboard of the center of the sample.
Metal atoms eroded from the films by the plasma are redeposited on the DiMES samples and neighboring divertor tiles. We have mapped the distribution of metal atoms on the DiMES samples after exposure to the plasma using RBS and NRA. The distributions of Mo and V on sample 70 and of Be and W on sample 71 are shown in figures 3 and 4 respectively. The scans are taken along lines in the toroidal direction through the centers of the metal spots. The metal distributions can be approximated by an exponential function

\[ n(r) = n_0 \exp(-r/\lambda) \]  

where \( n(r) \) is the metal areal density at a distance \( r \) from the center of the metal spot and \( \lambda \) and \( n_0 \) are the e-folding length and coverage at \( r = 0 \). Table 1 gives values of \( \lambda \) and \( n_0 \) obtained from linear least squares fits of equation 1 to \( \log(n) \) versus \( r \), using the data shown in figures 3 and 4. It can be seen in figures 3 and 4 and table 1 that the e-folding lengths are larger (ie. metal atoms are transported farther) in the downfield direction than in the upfield direction, especially on sample 70. Also the e-folding lengths increase with decreasing atomic mass, ie. lighter atoms are transported farther than heavier atoms. This behavior is mainly because lighter atoms penetrate farther into the plasma before ionizing due to their higher velocities and smaller ionization cross sections. Since the plasma conditions are well characterized for these experiments, the observed metal deposition should provide a good test case for impurity transport simulations [4].

Erosion of the metal films can be evaluated from the observed number of metal atoms deposited on the surrounding carbon. Such an evaluation assumes that all eroded metal atoms are redeposited, and requires estimation of metal coverage on regions not analysed. The following estimate is based on the approximation that the metal coverage \( n \) is radially symmetric and decreases exponentially with distance from the metal spots. The total number of metal atoms \( N \) on the carbon is then given by

\[ N = 2\pi \int_a^{\infty} r n(r) \, dr. \]  

\( N \) was evaluated using the above equations with \( a = 0.5 \) cm and values for \( n_0 \) and \( \lambda \) given in table 1. Total metal coverage was estimated by taking an average of values calculated using parameters from deposition on the upfield and downfield sides,

\[ N = (N_{\text{upfield}} + N_{\text{downfield}})/2. \]  

The metal erosion in units of length is given by
where \(A=0.56 \text{ cm}^2\) is the area of the metal spots and \(\rho\) is the metal atomic density. Table 1 gives the values obtained for the erosion and erosion rates by this method. These values agree fairly well with the RBS measurements of the change in metal film thickness.

Much of the carbon which is eroded from the surface is redeposited. Since some of this carbon may be deposited on the metal films we have used RBS to examine the thickness of carbon on the metal. A carbon layer on the metal films is likely to remain very thin when the neighboring carbon surfaces are undergoing net erosion. However, even thin carbon layers may reduce the metal erosion rate. Conclusions from the RBS analysis are: 1) the carbon layers on all four metal films on sample 70 were thinner than 5 nm, 2) on sample 71 the surface carbon layer was less than 2 nm thick on both W spots, 2±1 nm on Be spot 1 and 4±1 nm on Be spot 2.

Sample 70 was examined by scanning Auger electron spectroscopy (AES). Metal atom coverage on the carbon surface was homogeneous over distances of hundreds of microns. The composition versus depth was examined at selected locations using AES with sputter profiling. The V and Mo films had much more carbon near the surface extending to greater depths (10 to 15 nm) after exposure in DIII-D than before exposure.

### 3.3 Deuterium retention

The retention of deuterium on samples 70 and 71 was measured by NRA along a line connecting the centers of the metal spots. The results are shown in figure 5. The D retention for the various materials is about 0.35×10^{17} \text{D/cm}^2 for W, 0.4 \times10^{17} \text{D/cm}^2 for Mo, 1\times10^{17} \text{D/cm}^2 for Be, 1.2\times10^{17} \text{D/cm}^2 for carbon, and 2\times10^{17} \text{D/cm}^2 for V. The areal density of D retained in carbon is nearly the same on samples 70 and 71 even though the exposure times differ by a factor of 3.5. This is because D retention saturates after a few milliseconds for the ion fluxes (see figs. 1 and 2) at the divertor strike point. For regions undergoing net erosion, the areal density of D in the saturated carbon depends on the thickness of the saturated layer which in turn depends on the energy and range of the impinging D ions. From the observed areal density of D retained on the carbon surfaces we estimate the energy of the impinging D to be about 300 eV, and the thickness of the D saturated carbon layer to be about 20 nm [5]. An energy of 300 eV is reasonable considering that most of the energy of ions impacting the surface probably comes from
acceleration through the sheath potential which is typically several times the electron temperature of the plasma.

On sample 71 the areal density of D in Be is only slightly smaller than in carbon. This is consistent with previous measurements of D retention in C [5] and Be [6]. The ion ranges in C and Be are similar [7] and the D concentration in the saturated layer is slightly larger for carbon than for Be; $n_{\text{sat}} = 0.44 \text{ D/C versus 0.31 D/Be}$ (for T<125°C).

The smaller D areal density in Mo and W is probably mainly due to the fast diffusion of D in body centered cubic metals above room temperature, so that the D can migrate to the external surface and leave. Furthermore the heat of solution of D in Mo and W is large and endothermic so that it is energetically favored for the D to leave the metal lattice [8,9].

The larger D retention in V is probably due to the exothermic heat of solution and the fast diffusion of D in V [10, 11] which would lead to a high D concentration throughout the film.

NRA gives the number of D atoms per unit area ($2 \times 10^{17}/\text{cm}^2$) and RBS gives the number of V atoms per unit area ($6.5 \times 10^{17}/\text{cm}^2$) so from these two measurements we obtain the atomic ratio of $0.31 \text{ D/V}$ for the V films on sample 70.

4. Discussion

4.1 Carbon erosion, gross and net

The gross erosion rate can be estimated assuming that the dominant mechanism is physical sputtering by the impinging energetic deuterium. The sputtering coefficient for 300 eV D at normal incidence on carbon is $S_c = 0.02$ [12]. Variations in the energy by factors of 2 have little effect on this value since this energy is near the peak in the sputtering yield curve. Also, the assumption of normal incidence should be good when most of the particle energy is due to acceleration through the sheath (ie. normal to the surface) and when the ion gyroradius is large compared to the Debye length which should be the case for the plasma densities and temperatures at the strike point. The outgoing sputtered atom flux, ie. the gross erosion rate is

$$\Phi_{\text{gross}} = S \Phi_D$$

(5)

From the incident D ion flux $\Phi_D$ shown in figs. 1 and 2 we find that the peak gross carbon erosion rate should be $\Phi_{C_{\text{gross}}} \sim 2 \times 10^{18} \text{ C/cm}^2\text{s}$. This corresponds to an erosion rate of 200 nm/s for a carbon density of 2 g/cm$^3$. The sputtered carbon atoms are ionized by the plasma and return to
the surface to be redeposited at some distance from their origin. Locally, the incident flux \( \Phi_{\text{cin}} \) of carbon may be higher or lower than the outgoing flux resulting in net deposition or erosion of material respectively. The measured or net erosion rate is the difference between outgoing and incoming carbon fluxes. The result that the net erosion rate is 50 times smaller than the predicted gross erosion rate leads to the conclusion that the incoming and outgoing fluxes of carbon atoms differ by only two percent.

4.2 Dilution model for reduction of metal erosion by carbon

Gross erosion rates for pure metal surfaces are also given by equation 5. For 300 eV D the sputtering coefficients for the metals are: \( S_{\text{Be}} = 0.04 \), \( S_{\text{V}} = 0.02 \), \( S_{\text{Mo}} = 0.002 \) and \( S_{\text{W}} = 0.0002 \) [12]. The sputtering yield for V was estimated from yields for other elements with similar atomic masses. The dependence \( S \) on D energy near 300 eV is weak for the low \( Z \) elements, but strong for high \( Z \) elements, especially for W. Predicted peak gross erosion rates (\( \Phi_{\text{Mgross}} \)) for the metals based on the above values of \( S \) and \( \Phi_{D} = 10^{20} \text{D/cm}^2\text{s} \) are 320 nm/s for Be, 280 nm/s for V, 30 nm/s for Mo and 3 nm/s for W. All of these values are all much larger than the experimentally determined metal erosion rates given in table 1. In the following discussion we examine whether the difference can be understood in terms of the influence on the metal erosion rates of the incoming flux of carbon atoms.

Energetic carbon ions from the plasma will be implanted into the metal surface producing a thin surface layer consisting of a mixture of carbon and metal atoms. The impinging D from the plasma will sputter both carbon and metal atoms from this mixed layer according to eq. 5. The sputtering yield of the mixed layer is approximated here by

\[
S = f_{C} S_{C} + f_{M} S_{M}
\]

with

\[
f_{C} + f_{M} = 1,
\]

where \( S_{C} \) and \( S_{M} \) are the sputtering yields for pure carbon and pure metal respectively and \( f_{C} \) and \( f_{M} \) are the atomic fractions of carbon and metal in the mixed layer. Sputtering by impinging carbon is neglected. If the metal is in a location where the adjacent carbon is undergoing net erosion, the carbon deposition on the metal will not continue indefinitely, but will rapidly establish a steady state coverage at which the incoming and outgoing fluxes of carbon are equal,
For a steady state carbon coverage less than a few nm thick the time to reach steady state coverage should be a few milliseconds for the estimated carbon fluxes at the DIII-D divertor.

If the metal spot is small compared to the mean distance the carbon is transported between erosion and redeposition, then the flux of carbon atoms onto the metal surface will be the same as the flux of carbon atoms onto adjacent carbon surfaces. If the mean distance the metal atoms are transported between erosion and redeposition is large compared to the extent of the metal spot, then the incoming flux of metal atoms onto the metal region will be much less than the outgoing flux of metal atoms. In this case the net metal erosion rate is given by

$$\Phi_{M_{\text{net}}} = \Phi_{B}, f_M S_M.$$  \hspace{1cm} (8)

The above approximations lead to the following relations for the net metal erosion rate. The net metal erosion rate is equal to the net erosion rate of the adjacent carbon times the ratio of the sputtering yield of the pure metal to the sputtering yield of pure carbon,

$$\Phi_{M_{\text{net}}}/\Phi_{C_{\text{net}}} = S_M/S_C.$$  \hspace{1cm} (9)

Also, the ratio between the net and gross erosion rates is the same for metal as for carbon, and is equal to the atomic fraction of metal at the surface,

$$\Phi_{M_{\text{net}}}/\Phi_{M_{\text{gross}}} = \Phi_{C_{\text{net}}}/\Phi_{C_{\text{gross}}} = f_M.$$  \hspace{1cm} (10)

Using the measured value of 3.6 nm/sec for the peak net carbon erosion rate from sample 70 and sputtering yields for the pure metals given above, eq. 10 gives the following predicted values for the peak net metal erosion rates, 6 nm/s for Be, 5 nm/s for V, 0.5 nm/s for Mo and 0.05 nm/s for W. Comparing the model with the experimental metal erosion rates given in table 1 we find the agreement is fairly good for Mo and W but for V and Be the experimental values are smaller than those predicted by the model. However, the agreement between the model and experiment is reasonably good considering the approximations involved in the method used to determine the metal erosion, and the approximations used by the model. The main conclusion from this discussion is that dilution of the metal atom concentration at the surface by recycling fluxes of carbon can greatly reduce erosion of higher Z materials. Similar effects may be expected if Be is used in place of carbon. This effect might allow the use of medium or high Z materials in the divertor of a machine such as ITER.
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References


Table 1. Metal Erosion

Parameters describing the distribution of metal atoms from fits of equation 1 to the data shown in figures 3 and 4. The metal erosion estimated from the measured metal deposition, and the corresponding metal erosion rates are also given.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Metal</th>
<th>$\lambda$ (cm) (upfield, downfield)</th>
<th>$n_0$ (at/nm$^2$) (upfield, downfield)</th>
<th>Erosion (nm)</th>
<th>Erosion Rate (nm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71-1</td>
<td>Be</td>
<td>0.71, 1.18</td>
<td>45, 31</td>
<td>2.7</td>
<td>0.68</td>
</tr>
<tr>
<td>71-2</td>
<td>W</td>
<td>0.31, 0.40</td>
<td>34, 24</td>
<td>0.37</td>
<td>0.09</td>
</tr>
<tr>
<td>71-3</td>
<td>Be</td>
<td>1.38, 1.46</td>
<td>20, 24</td>
<td>3.8</td>
<td>0.95</td>
</tr>
<tr>
<td>71-4</td>
<td>W</td>
<td>0.29, 0.33</td>
<td>46, 46</td>
<td>0.41</td>
<td>0.10</td>
</tr>
<tr>
<td>70-1</td>
<td>Mo</td>
<td>0.27, 0.70</td>
<td>52, 18</td>
<td>0.8</td>
<td>0.06</td>
</tr>
<tr>
<td>70-2</td>
<td>V</td>
<td>0.41, 0.88</td>
<td>141, 135</td>
<td>4.9</td>
<td>0.36</td>
</tr>
<tr>
<td>70-3</td>
<td>Mo</td>
<td>0.39, 0.85</td>
<td>95, 62</td>
<td>4.4</td>
<td>0.32</td>
</tr>
<tr>
<td>70-4</td>
<td>V</td>
<td>0.64, 0.75</td>
<td>84, 141</td>
<td>7.8</td>
<td>0.56</td>
</tr>
<tr>
<td>8</td>
<td>W</td>
<td>0.18, 0.24</td>
<td>664, 353</td>
<td>0.77</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Figure Captions

1. Measured erosion of carbon on sample 70 versus position along the two lines indicated in the diagram. The ±10 nm uncertainty and 1 mm spatial resolution of the erosion measurements are indicated by the error bars. The heat flux, ion flux and location of the separatrix are also shown.

2. Measured erosion of carbon on sample 71 versus position along the two lines indicated in the diagram. The ±10 nm uncertainty and 1 mm spatial resolution of the erosion measurements are indicated by the error bars. The heat flux, ion flux and location of the separatrix are also shown.

3. Metal atom coverage on sample 70 versus position along lines through the metal spots in the toroidal direction.

4. Metal atom coverage on sample 71 versus position along lines through the metal spots in the toroidal direction.

5. Deuterium coverage on samples 70 and 71 versus position along lines through the centers of the metal spots. The location of the metal spots is shown by the horizontal bars. The regions between the metal spots are graphite.
The graph shows the relationship between radial position (cm) and carbon erosion (nm) in the context of magnetic field effects. The lines represent different conditions: Downfield, Upfield, Heat Flux, and Ion Flux.

Key points:
- **Carbon Erosion (nm)**: The y-axis plots the carbon erosion in nanometers.
- **Radial Position (cm)**: The x-axis represents the radial position in centimeters.
- **Heat Flux (W/cm²)**: The right y-axis shows the heat flux in watts per square centimeter.
- **IONS (10^{18}/cm² s)**: The top y-axis indicates the ion current density in ions per square centimeter per second.

The graph includes a separatrix and areas labeled as Outboard and Inboard.