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IN-SITU SPECTROSCOPIC MEASUREMENTS OF EROSION BEHAVIOR OF TFTR-REDEPOSITED CARBON MATERIALS UNDER HIGH-FLUX PLASMA BOMBARDMENT IN PISCES-A

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**In-situ Spectroscopic Measurements of
Erosion Behavior of TFTR-Redeposited Carbon Materials
under High-Flux Plasma Bombardment in PISCES-A**

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ABSTRACT

The chemical erosion behavior of graphite materials pre-exposed in Tokamak Fusion Test Reactor (TFTR) as the bumper limiter has been investigated spectroscopically under deuterium plasma bombardment in the PISCES-A facility. The deuterium plasma bombardment conditions are: ion bombarding energy of 300 eV; ion flux of 1.7×10^{18} ions $s^{-1} cm^{-2}$; plasma density of $1.4 \times 10^{12} cm^{-3}$; electron temperature of 11 eV; and neutral pressure of 3×10^{-4} torr. The chemical erosion yield is measured with CD-band spectroscopy during the temperature ramp from 100 to 900 °C at an average rate of about 5 degrees/s. The materials used include virgin POCO AFX-5Q graphite, graphite tile pieces from the redeposition-dominated and erosion-dominated areas of the bumper limiter in TFTR. It has been found in common for these graphite materials that the chemical erosion yield maximizes at a temperature around 550 °C. However, graphite from the redeposited area has shown a somewhat higher maximum erosion yield and significantly steeper temperature dependence. In addition, the removability of the redeposited materials by helium plasma bombardment has been studied. The removal rate is found to be similar to the physical sputtering yield of carbon by helium. The surface morphology and surface composition has been analyzed with SEM and EMPA in parallel with these erosion behavior measurements.

I. INTRODUCTION

It has been observed in many tokamaks that materials once eroded from the plasma interactive surfaces are redeposited elsewhere due to toroidal and/or poloidal plasma transport effects. In some cases, redeposited materials are identified as "droplets", indicative of localized melting [1]. It is also true that repeated redeposition over an extended period of routine plasma operations can form rather thick films with archaeological layers such as those found in the T-10 tokamak [2] and in TFTR [3,4] recently. Due to codeposition, the resultant redeposited layers are likely to be incorporated with plasma fuel particles (hydrogen isotopes) as well as other elements eroded from various in-vessel components [3,4,5]. It is important to mention here that material transport associated with erosion and redeposition can be strongly affected by plasma operational scenarios such as whether limiter or divertor discharges are employed. Along with changes in the plasma environment, the surfaces once redeposited may act then as those to be eroded in a yet-to-be explored manner. From an impurity control viewpoint, therefore, it is of significant importance to understand the re-sputter (secondary) erosion behavior of tokamak-redeposited materials, which are referred to as "tokamakium" in the fusion community. In the INTOR design study [6], the need for data on sputtering of tokamakium was first addressed as one of the crucial issues in parallel with the effect of redeposition on the net materials erosion yield.

Unfortunately, however, there has been only limited amount of experimental data on the sputtering yields of tokamakium or equivalent materials to date although several theoretical predictions can be found [7]. One of the few studies which fall into this category is the secondary physical erosion yield measurements of sputter-deposited copper [8]. In this work, reduction in the erosion yield was observed. This reduced erosion yield was attributed to the incorporated oxygen during the initial sputter-deposition process because usually oxide formation increases the surface binding energy. As such, impurities incorporated during deposition can play an important role in determining the secondary erosion behavior of the resultant deposits. On the other hand, the chemical sputtering behavior of carbonaceous films produced by plasma-chemical deposition processes has been reported by several groups [9-11]. It is still controversial whether the incorporated hydrogen or modified structure in these deposits alter the re-sputtering behavior.

In the present work, the erosion behavior of graphite materials pre-exposed in TFTR as the bumper limiter has been investigated spectroscopically using the PISCES-A facility [12]. Particular emphasis is placed on understanding the chemical erosion behavior of TFTR-redeposits as an example of tokamakium.

II. EXPERIMENTAL

The graphite tile materials obtained from TFTR were first machined into disks with a diameter of about 3 cm and a thickness of 0.6 cm. The graphite disk specimen was set on an air-cooled sample probe and was placed in steady state deuterium or helium plasmas in the PISCES-A facility. The plasma diameter was set at 4 cm with a magnetic field of 1kG. The temperature of the graphite during plasma bombardment was measured by a thermocouple pressed against the side not facing the plasma. The plasma density and electron temperature were measured using a Langmuir probe positioned in front of the target. A monochromator with an optical multi-channel analyzer (OMA) was set in such a way that radiations of excited impurities such as hydrocarbons from the surface could be monitored *in-situ*. Details of the *in-situ* spectroscopic measurements will be described in the next section. The side wall of the disk target was shielded from plasma bombardment with a tantalum jacket in order to ensure that impurities measured spectroscopically are emitted from the front surface. Here, tantalum is little sputtered by deuterium bombardment under conditions to be described below because of its high sputtering threshold energy (305.3 eV for D⁺ [13]). More information about the PISCES-A facility and materials experiments can be found in our previous papers [12,14].

Typical deuterium plasma bombardment conditions were: ion bombarding energy of 300 eV; ion flux of 1.7×10^{18} ions s⁻¹ cm⁻²; plasma density of 1.4×10^{12} cm⁻³; electron temperature of 11 eV; and neutral pressure of 3×10^{-4} torr. These conditions were carefully repeated within 5-10 % for duplicated measurements. Here, the ion bombarding energy is controlled by applying a negative DC-bias to the target with respect to the plasma because the intrinsic energy of the ions in the PISCES plasma is around a few electron volts [15]. The typical thickness of the Debye sheath is about 10 μm and the ion gyro radius is about 2-3 mm. This means that the acceleration due to the negative bias significantly stretches the ion velocity component perpendicular to the surface within the sheath region. These accelerated ions are thus considered to impinge on the surface at approximately normal incidence, regardless of the gyro-direction.

Due to the heat flux of about 0.8 MW/m² under plasma bombardment, the target temperature rises naturally from ambient temperatures to 900 °C at an average rate about 5 degrees/s. Along with this temperature excursion, important experimental parameters: ion saturation current (i.e. ion flux to the target surface) from the Langmuir probe; CD-band radiation intensity from OMA; and target temperature were monitored at a rate of 0.5 Hz.

III. RESULTS AND DISCUSSION

A. TFTR-exposed graphite materials

The materials used here are: virgin POCO AFX-5Q graphite and the same material but pre-exposed to 7166 ohmically heated shots and 2756 neutral beam heated shots in TFTR as the bumper limiter in 1985-1987. In particular, TFTR-exposed graphite tile pieces are taken from the erosion-dominated area (position #N3-7) and the redeposition-dominated area (position #N3-15) of the bumper limiter. Details of the overall limiter configuration and plasma operation conditions during this period can be found elsewhere [16, 17].

It is important to note that the bumper limiter, consisting of two tons of graphite tiles, served as the key plasma interactive surface in attaining the S-mode plasma discharge (i.e. supershot) in TFTR [18]. Considerable effort has been made to understand the materials physics related to the interactions of S-mode plasmas with these graphite tiles [19]. Particularly, extensive analysis of deposited deuterium and impurities on these graphite tiles has been done [16]. From this analysis, the deuterium retention for the redeposited and eroded graphite tiles used in the present work is known to be 2×10^{18} D/cm² and 3×10^{17} D/cm², respectively. Such effort is to extrapolate the deuterium retention data to the on-site tritium inventory during the DT burning experiments planned in TFTR in 1990-1991[19].

In the present work, only basic surface analysis is done in order not to duplicate earlier efforts. Along with plasma erosion measurements in the PISCES-A facility, the graphite materials were analyzed with SEM (Scanning Electron Microscopy) and EMPA (Electron Micro Probe Analysis) respect to the surface morphology and surface composition, respectively. As will be described later, these surface characteristics are important in evaluating the data from chemical erosion yield measurements.

The surface morphologies of graphite materials before deuterium plasma bombardment are shown in Fig. 1. First, one finds a porous surface for virgin graphite (see Fig. 1-(a)). Here, "virgin" does not mean "as-machined" but means "pre-conditioned in PISCES-A" such that surface pores are fully opened. Generally, this pre-conditioned surface provides more reproducible erosion yield data. Notice that TFTR-eroded graphite (see Fig. 1-(b)) has a similar porous surface morphology with polishing scores. The pores appears to be somewhat plugged with polishing dust particles and some plasma deposits. In contrast, TFTR-redeposits (see Fig. 1-(d)) have characteristic features protruding at an

angle, indicative of the flow of redeposition. Detailed discussion of the impurity transport in TFTR can be found elsewhere [20]. From cross-sectional observations [4], TFTR-redeposits are known to have an archaeologically layered structure with a total thickness ranging from 30 to 60 μm . Obviously, the original graphite surface is completely coated with relatively thick tokamakium such that one sees no surface pore openings. The effects of plasma bombardment on the surface morphology will be discussed later.

The results of surface elemental analysis (except for deuterium) are shown in Fig. 2 and summarized in Table 1. One finds small amount of impurities such as oxygen, iron, chromium and nickel for as-received TFTR-redeposits whereas there is no detectable surface impurity for the TFTR-eroded graphite. The composition ratio of these metallic impurities indicates the origin to be presumably Inconel in-vessel components. It should be noted that the EMPA technique characterizes the surface layer, by nature, only to a depth of about a few thousand angstroms. Yet these results are quantitatively consistent with earlier analysis done by the RBS (Rutherford Back Scattering) technique which probes to a depth of about 1 μm [16]. The effect of deuterium plasma bombardment on the surface chemistry will be described later.

B. Basic considerations of in-situ spectroscopic erosion yield measurements

In our previous work [21], an *in-situ* technique was developed to measure the material erosion yield quantitatively using plasma spectroscopy. This technique is capable of monitoring the time-dependent erosion behavior of materials along with changes in the surface structure under plasma bombardment. This capability is crucial, particularly when the surface has a structure of layered films like tokamakium. This *in-situ* spectroscopic technique has been applied to investigate the chemical erosion behavior of TFTR-exposed graphite under deuterium plasma bombardment.

Here, attention is paid to the radiation spectroscopy of excited CD-radicals. It is known that various hydrocarbon molecules are formed due to chemical sputtering of graphite [21]. One important aspect is that CD-radicals will be generated along with electron-impact molecular break-up processes, regardless of the initial molecular form. Details of the atomic physics of these molecular break-up processes are beyond the scope of the present paper and can be found elsewhere [23]. Yet one can consider that the intensity of the CD-band radiation qualitatively represents the total release rate of various hydrocarbon molecules from graphite. Typical spectra for the CD-band obtained from OMA are shown in Fig. 3-(a). The radiation intensity is integrated with respect to the wave

length from 4300 to 4312 Å for better accuracy of spectroscopic measurements. The validity of this concept was basically demonstrated by CH-band and CD-band intensity measurements in our previous work [24,25] although details of the experimental setup are different.

It is generally true that because the graphite surface acts as the source of hydrocarbons to be released, the CD-band radiation intensity attenuates as a function of penetration depth into the plasma. Shown in Fig. 3-(b) is the wave-length integrated CD-band intensity as a function of the distance from the virgin POCO AFX-5Q surface at temperatures around 600 °C where generally the chemical sputtering yield maximizes [26]. Notice that CD-radicals penetrate only about 7-8 cm into the plasma operated under typical conditions. The wave-length-integrated CD-band intensity is then integrated along with the distance from the surface. In the remainder of the paper, the resultant integrated value is referred to as the double-integrated CD-band intensity. This double integration enables us to treat semi-quantitatively the total amount of released hydrocarbon molecules.

Under these conditions, therefore, one can approximately use the relation [27]:

$$\Psi_{\text{tot}} = 4\pi (B_i / \Gamma) \langle \sigma v_e \rangle_{\text{tot}} / \langle \sigma_{\text{ex}} v_e \rangle \quad (1)$$

where Ψ_{tot} is the total hydrocarbon flux into the plasma, Γ is the branching ratio of the transition of interest to all other possible transitions from the excited levels, B_i is the double-integrated CD-band intensity, $\langle \sigma v_e \rangle_{\text{tot}}$ is the total reaction rate for electron-impact ionization and decomposition of CD-radicals and $\langle \sigma_{\text{ex}} v_e \rangle$ is the rate coefficient for electron-impact excitation of CD-radicals. Unfortunately, to the best of our knowledge, these rate coefficients have not been individually reported to date. However, the ratio of the rate coefficients in eq.(1) may be assumed to be independent of electron temperature if it is reproduced within an accuracy of 5-10%.

It is well known that atomic deuterium arriving at the graphite surface from the plasma can lead to a formation of hydrocarbons but that molecular deuterium is basically inert. The rates of arrival of atomic and ionic deuterium may not be significantly different in the high-recycling plasma-surface-interaction region. However, the chemical erosion yield due to deuterium atoms with thermal and epithermal energies is orders of magnitude below that of deuterium ions with an energy of 300 eV [26]. It is also true that the synergistic effect of having both atomic and ionic species on the erosion yield is not significant under these conditions [28]. Hence, the hydrocarbon formation may be treated approximately due to ion bombardment only. The chemical erosion yield as a function of temperature, $Y_c(T)$, can then be defined by the relation:

$$Y_c(T) \equiv k B_i/I_{sat} \quad (2)$$

where k is the calibration constant and I_{sat} is the ion flux. In eq. (2), the effect of fluctuation of the ion flux, if it exists, on the erosion yield measurement is cancelled by definition. The ion flux is equivalent to the ion saturation current measured with the Langmuir probe and is given by the relation [29]:

$$I_{sat} = 0.5 n_e (k_B T_e/m)^{0.5} \quad (3)$$

where n_e is the plasma density, k_B is Boltzman constant, T_e is the electron temperature and m is the atomic weight of plasma species. From our previous work [24], atomic deuterium ions (D^+) are known to be the major plasma species (80–85%) in the PISCES-A facility under operation conditions used here. As will be shown later, the semi-quantitative chemical erosion yield data from eq.(2) can be converted into absolute values by determining k through calibration by the weight loss method.

C. Observations of erosion behavior of tokamakium

High-flux deuterium plasma bombardment was conducted for chemical erosion yield measurements. As described earlier, the target temperature rises due to the heat flux, as the plasma bombardment continues, from ambient temperatures to 900 °C at an average rate about 5 degrees/s. Shown in Fig. 4 are the data from simultaneous measurements of the target temperature and the double-integrated CD-band intensity for TFTR-redeposits as a function of plasma exposure time.

Notice the good reproducibility of data from duplicated runs. In order to make the spectroscopic measurements quantitative enough to compare for different materials, particular attention was paid to reproducing the plasma parameters. One should bear in mind that because TFTR-redeposits have layered structures, each having finite thickness, the total plasma fluence for an erosion yield measurement should be minimized. It follows that the ordinary weight loss method is not suitable for such a case. The plasma bombardment fluence for each run was about 2×10^{20} ions/cm², which is an order of

magnitude lower than the typical fluence used in our previous weigh loss measurements [25, 30].

The good reproducibility of spectroscopic data indicates that the nature of the plasma-facing surface is not significantly changed during erosion yield measurements. To ensure this point, TFTR-redeposits were analyzed again with SEM-EMPA after 7 duplicated erosion experiments. The plasma bombarded surface morphology is shown in Fig 1-(e). One finds that the original protruding structures still exist although the plasma erosion footprint can be recognized. Also, as shown in Table 1, there is no major change in the level of surface contamination due to impurities after repeated plasma bombardment. One finds that the oxygen level decreased by a factor of 3, indicative of the reducing effect of deuterium on metal oxides.

Similar erosion behavior measurements were performed for virgin POCO AFX-5Q and TFTR-eroded graphites. At least 5 measurements were duplicated for these materials and the CD-band spectroscopy data were well reproduced. The erosion yield data from these measurements will be described later in detail. After repeated deuterium plasma bombardment, TFTR-eroded graphite was analyzed with SEM and EMPA. One immediately finds increased pore openings (see Fig. 1-(c)), whereas no change is found in the surface composition (see Table 1).

D. Calibration of spectroscopic measurements

In order to obtain the chemical erosion yield, the CD-band spectroscopic data must be calibrated against absolute values such as those given by the weight loss method. It is important to mention here that the weight loss data correspond to the total erosion yield including both chemical and physical erosion effects. Obviously, one can only evaluate the chemical effect using CD-band spectroscopy. To the best of our knowledge, however, there have been virtually no data or theories separating these two effects.

For convenience of analysis, one may assume that the total erosion yield is given by the relation: $Y_{tot}(T) = Y_c(T) + Y_p$, where $Y_{tot}(T)$ is the total erosion yield from the weight loss method, $Y_c(T)$ is the yield component due to chemical erosion measured with CD-band spectroscopy and Y_p is the yield component due to physical erosion. Here, Y_{tot} is treated as temperature-dependent factors from observations. To evaluate the effect of physical erosion, one must compare $Y_{tot}(T)$ and $Y_c(T)$ at two different temperatures, i.e. $Y_{tot}(T_1)/Y_{tot}(T_2)$ vs. $Y_c(T_1)/Y_c(T_2)$.

For weight loss measurements, virgin POCO AFX-5Q was repeatedly subjected to deuterium plasma bombardment at around 500 and 800 °C at an ion bombarding energy of 300 eV. The resultant total erosion yields are estimated to be 0.068 and 0.044 C-atoms/ion at 500 and 800°C, respectively. The ratio (≈ 1.5) of these total erosion yields is found to be in excellent agreement with the ratio (≈ 1.6) of the CD-band intensities measured at these two temperatures. Immediately, one finds that the physical erosion effect is not significant, i.e. $Y_{\text{tot}}(T) \approx Y_c(T)$, under the conditions employed here. Therefore, the approximated chemical (i.e. total) erosion yield can be given by the CD-band spectroscopy calibrated against the weight loss method.

E. Comparison of tokamakium and graphite materials

The calibrated chemical (i.e. total) erosion yields at an ion bombarding energy of 300 eV are plotted as a function of target temperature in Fig. 5. The data shown here represent the averaged erosion yield values from duplicated measurements for each material. One immediately finds for all graphite materials that the chemical erosion yield maximizes at temperatures around 550-600 °C. Notice that TFTR-redeposits exhibit a somewhat higher maximum erosion yield (about 15 %) and a significantly steeper temperature dependence than TFTR-eroded and virgin graphites. Unfortunately, there are virtually no data to be compared with those obtained here without confusing discussion of the flux dependence since the ion beam data were generally obtained at ion fluxes orders of magnitude below that used here. For the most reasonable comparison, the deuterium erosion yield data taken at ion bombarding energies of 100 and 200 eV in our previous work [25] are illustrated in Fig. 5. One finds that the maximum erosion yield obtained here for virgin POCO AFX-5Q graphite is well within an extrapolated region from these lower energy data.

Similar erosion yield measurements were once conducted, using ion beam (D^+) at 2 keV, for the graphite tiles pre-exposed in TFTR as the electron side of the movable limiter in 1984-1985 [32]. These graphite tiles were redeposited with metallic impurities such as nickel, iron and chromium to a total concentration as high as 2×10^{18} atoms/cm² [3], i.e. ≈ 20 at%, which is orders of magnitude above the level seen for the redeposits used in the present work (see Table 1). In contrast, a relatively low deuterium retention around 2×10^{17} D/cm² was found [5], presumably due to the high temperature operation of the movable limiter. At temperatures between 350 and 750 °C, significant reduction (as large

as a factor of 4) of the chemical erosion yield was observed for this tokamakium, relative to virgin POCO AXF-5Q. This suppression of chemical erosion was explained by the surface impurity effects that metallic deposits enhance recombination of hydrogen [26].

On the other hand, an increase in chemical erosion has been observed for amorphous carbon films, relative to graphite, exposed to hydrogen ions at energies of 900 eV [10] and 2 keV [11]. These amorphous carbon films were produced by plasma-assisted chemical vapor deposition processes (PACVD) in which the substrate temperature was controlled between 100 and 300 °C. The resultant carbon films were known to be incorporated with hydrogen to a relatively high concentration of 0.3-0.5 H/C [11], which is equivalent to the saturation concentration in bulk graphite materials [33]. Enhancement of chemical erosion may be pronounced particularly if comparison of amorphous carbon and bulk graphite is made at relatively low hydrogen ion fluences because the latter needs to be saturated to attain the steady state erosion condition [34,35]. In contrast, slightly suppressed chemical erosion has been also reported for diamond-like carbon produced by PACVD at temperatures between 850 and 900 °C [9]. The high temperature deposition process generally results in reduced hydrogen concentration in the resultant film. In this case, therefore, one might speculate the reduced erosion due to the sp³ carbon-carbon bonding in diamond. It is unfortunately true for these studies that observations are not well interpreted by any existing theories. Further experimental and theoretical effort is needed to reconcile the controversial data in this area.

From these observations, one might postulate that the chemical erosion is suppressed for metal-rich tokamakium whereas the opposite is true for hydrogen-rich tokamakium. As mentioned earlier, TFTR-redeposits used here are incorporated with a small amount of metallic impurities shown in Table 1 and with deuterium to a relatively high concentration of 2.1×10^{18} atoms/cm². Again, one sees increased chemical erosion yields for TFTR-redeposits at around the yield-maximizing temperature. Using the postulation described above, this increased erosion yield might be attributed to the high initial deuterium concentration. However, it is also true that because of the temperature dependence, the chemical erosion yield for TFTR-redeposits falls below those for TFTR-eroded and virgin graphites, particularly at temperatures above 650 °C. These temperature-dependent erosion characteristics are difficult to explain systematically. One possible interpretation is that protruding surface structures (see Fig. 1-(d)) might be locally heated to proceed the temperature excursion faster than the rest of the surface. Details are still unclear to date.

E. Removability of tokamakium by He-discharge conditioning

It was pointed in our previous work [35,36] that surface pore openings of isotropic graphite materials significantly affects hydrogen plasma recycling behavior. Hydrogen, particularly in the form of epithermal neutral, arriving from the edge plasma can penetrate into these pores and reside there during plasma discharge. This in-pore storage leads to a reproducible transient pumping. Therefore, redeposition of thick tokamakium that plugs surface pores will hinder the hydrogen pumping effect of this kind.

In major tokamaks such as TEXTOR [37] and DIII-D [38], DC helium glow plasma discharges have been recently used for conditioning graphite in-vessel components. Upon changes of discharge scenario, the surface once redeposited with tokamakium might then have to serve as a crucial component to provide the pumping effect. In such a case, tokamakium should be removed, ideally *in-situ* during wall conditioning, to obtain the porosity-induced hydrogen pumping effect. To date, however, there have been no data on the removal of tokamakium by helium plasma discharges.

In order to provide preliminary information in this regard, TFTR-redeposits were exposed to a continuous helium plasma in the PISCES-A facility immediately after repeated chemical erosion measurements. Helium plasma bombardment was done at an energy of 150 eV, at a flux about 2.5×10^{18} ions $s^{-1} cm^{-2}$ and to a fluence of 9×10^{21} ions/cm². Significant arcing was observed for the first 5-10 minutes of helium plasma bombardment. Usually one sees no arching effects after long exposure to a deuterium plasma. This noticeable arcing may be a part of tokamakium characteristics although details are still unknown.

Shown in Fig. 1-(f) is the surface morphology of the TFTR-redeposited graphite tile after helium bombardment. One finds a porous surface, typical of POCO AFX-5Q graphite, for the majority of the area while islands of tokamakium still remain on the surface. One can easily expect the porosity-induced pumping effect from this surface morphology. Assuming that TFTR-redeposits have a uniform thickness of 50 μm [4] and an areal atomic density of 2×10^{15} C-atoms/cm², one estimates the removal rate to be about 0.055 C-atoms/He-ion. This crude estimate is not similar to the physical sputtering yield of 0.049 C-atoms/He-ion [13]. Also, this helium plasma bombarded surface was analyzed with EMPA and the result is shown in Table 1. Notice that helium conditioning has provided the same degree of cleanliness as virgin graphite.

IV. SUMMARY

Re-sputtering of tokamak-redeposited materials has long been a crucial question in the fusion community. The present work provides data on this question. The chemical and physical sputtering behavior of graphite materials pre-exposed in TFTR as the bumper limiter were investigated. Clearly, the nature of tokamak-redeposits depends on the machine design and discharge scenario. Here, the redeposited material in TFTR is used as an example of tokamakium.

The chemical sputtering yield for TFTR-redeposits has been found to be somewhat higher at the maximizing temperatures around 550-600 °C than that for virgin graphite. This increased maximum erosion yield is attributed to the incorporated deuterium in the redeposited material. Also, a significantly steeper temperature dependence was observed, which has not been explainable to date. On the other hand, the chemical erosion yield of TFTR-eroded graphite is essentially the same as that of virgin graphite.

In addition, the removability of tokamakium has been examined using Helium plasma bombardment, which is used for wall conditioning in major tokamaks. The removal process is found to proceed at a rate similar to the classical physical sputtering yield and lead to a surface that has the same degree of cleanliness and porosity as a well conditioned graphite surface.

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Table 1 Summary of EMPA surface analysis data.

Surface element	<u>TFTR-redeposited</u>			<u>TFTR-eroded, Virgin</u>
	As-received (at%)	After D-bomb. (at%)	After He-bomb. (at%)	As-received/after D-bomb. (at%)
C	98.75	99.62	99.93 - 99.95	99.93 - 99.95
O	1.1	0.29	0.05 - 0.07	0.05 - 0.07
Cr	0.03	0.01	Not detected	Not detected
Fe	0.04	0.03	Not detected	Not detected
Ni	0.06	0.02	Not detected	Not detected
Si,S,Cl etc.	0.03	0.03	Not detected	Not detected

FIGURE CAPTIONS

Fig.1: Scanning electron micrographs of:

- (a) Virgin POCO AFX-5Q (after pre-conditioning in PISCES-A);
- (b) As-received TFTR-eroded surface;
- (c) TFTR-eroded surface after D-plasma bombardment in PISCES-A;
- (d) As-received TFTR-redeposited surface;
- (e) TFTR-redeposited surface after D-plasma bombardment in PISCES-A; and
- (f) TFTR-redeposited surface after D and He-plasma bombardment in PISCES-A.

Fig.2: EMPA data for:

- (a) As-received TFTR-redeposited surface;
 - (b) TFTR-redeposited surface after D-plasma bombardment in PISCES-A; and
 - (c) TFTR-redeposited surface after D and He-plasma bombardment in PISCES-A.
- Virgin POCO AFX-5Q and TFTR-eroded surfaces exhibit essentially the same spectra as those in (c), before and after the erosion measurements in PISCES-A.

Fig.3: Typical CD band spectroscopy data taken during deuterium plasma bombardment:

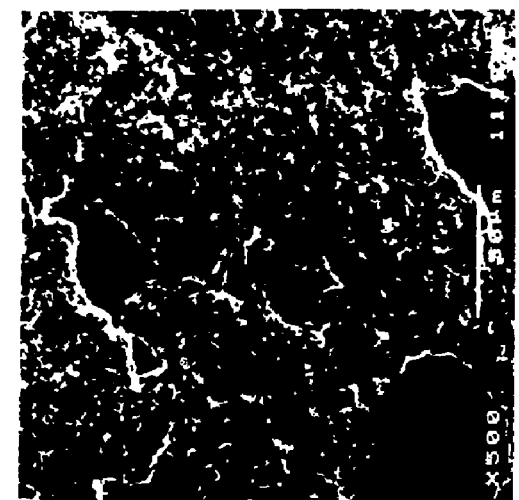
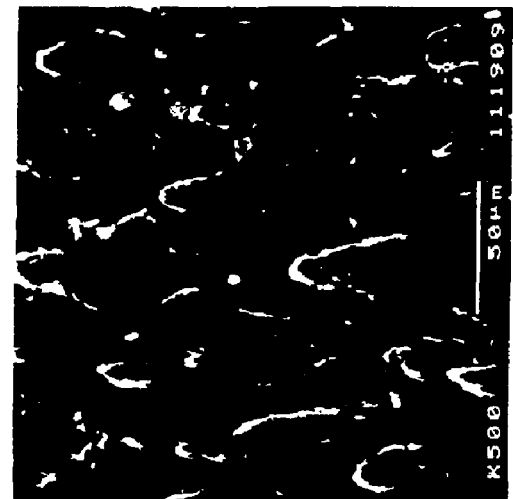
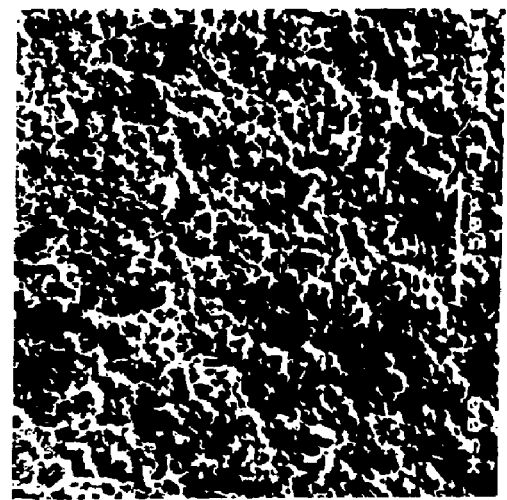
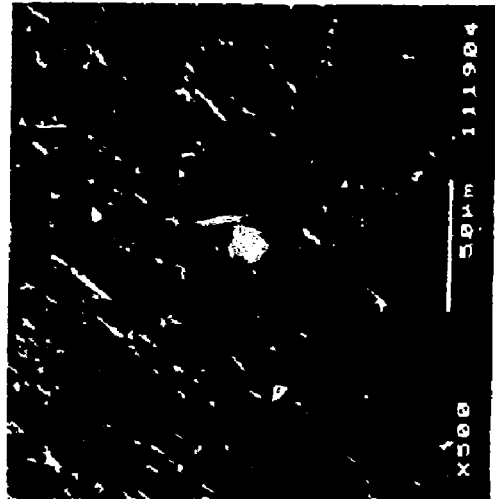
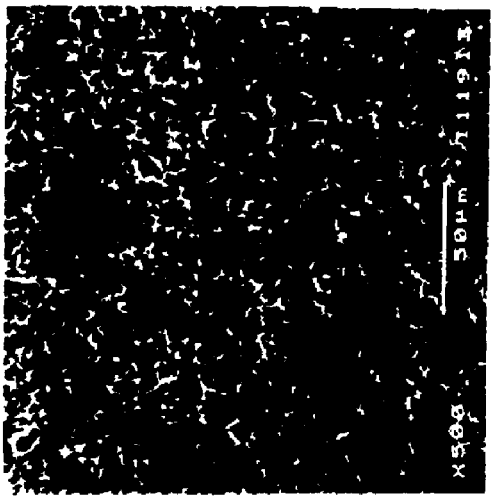
- (a) CD-band spectra in the wave length range from 4230 to 4370 Å; and
- (b) Integrated CD band intensity as a function of distance from the surface. The (0,0) band head is at 4312 Å and the band degrades to the blue. For spectroscopic measurements, a wave length band of 12 Å centered at 4306 Å is cut out (see text).

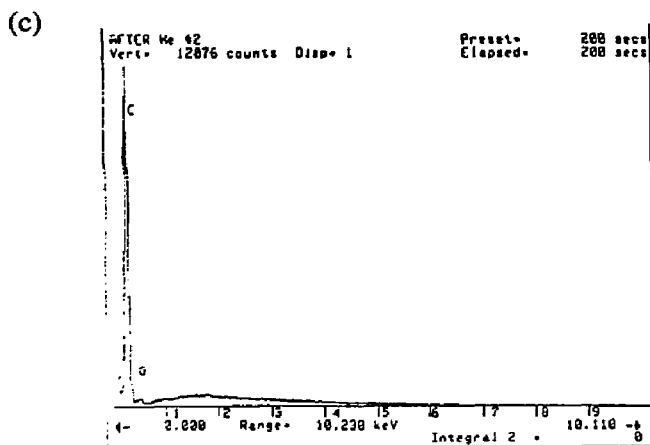
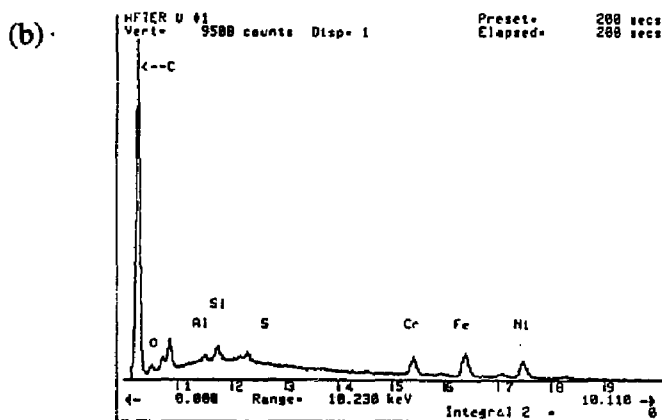
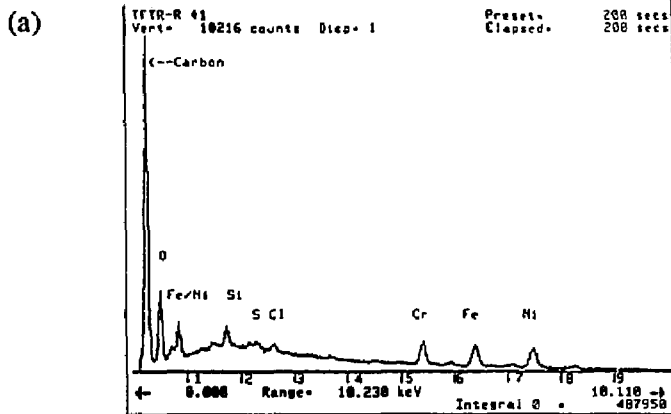
Fig.4: Data from erosion yield measurements done for TFTR-redeposited surface:

- (a) the temperature; and (b) double-integrated CD band intensity as a function of plasma exposure time. Deuterium plasma bombardment was done at 300 eV (see text for detail).

Fig.5: Calibrated total (chemical) erosion yields under deuterium plasma bombardment for virgin, TFTR-eroded and TFTR-redeposited graphite surfaces as a function of temperature. Deuterium plasma bombardment was done at 300 eV (see text for detail). *The maximum total erosion yield data for POCO HPD-1 graphite at around 570 °C under deuterium plasma bombardment at 100 and 200 eV from our previous work [24] are also illustrated for comparison.

Fig. 1





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Fig. 3

