ELSEVIER

Journal of Nuclear Materials 266–269 (1999) 660–665

journal of nuclear materials

Chemical sputtering from the pump limiter neutralizer in Tore Supra

R. Ruggiéri [a], E. Gauthier [a,*], J. Hogan [b], J.M. Layet [c], T. Loarer [a]

[a] *Association EURATOM-CEA sur la Fusion, CEA Cadarache, F-13108 Saint Paul lèz Durance, France*
[b] *Fusion Energy Division, ORNL, P.O. Box 2009, Oak Ridge, TN 37831-8072, USA*
[c] *Laboratoire de Physique des Interactions, Ioniques et Moléculaires (UMR CNRS 6633), Equipe Plasma-Surface, Faculté des Sciences de Saint Jérôme, F-13397 Marseille cedex 20, France*

Abstract

Carbon is widely used as plasma facing component in present fusion devices and is proposed for the divertor plates of ITER. The improvement in the control of the plasma edge parameters, limiting the power flux and the electron temperature in the divertor leads to an acceptable erosion rate of carbon due to physical sputtering and radiation enhanced sublimation. In these conditions, chemical sputtering will probably be the main mechanism of erosion for the carbon plate. In situ measurements of hydrocarbon production on the neutralizer plate of an outboard pump limiter have been obtained in Tore Supra. CD_4 has been monitored by means of optical spectroscopy and mass spectrometry for different electron temperatures and densities. Simulations performed with a Monte Carlo code (BBQ), show a good agreement with experimental data at high flux, low electron temperature. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Tore Supra; Chemical erosion; Carbon

1. Introduction

Carbon based material is used intensively as plasma facing components in present fusion devices due to its good thermal properties. Carbon fibre composite can sustain high heat load, in the range of 10 MW/m^2 during several thousand of cycles without any damage [1]. Nevertheless, carbon has a high erosion rate under bombardment and shows the particularity of having three different mechanisms of erosion: physical sputtering, chemical sputtering and Radiation Enhanced Sublimation (RES). In future machines such as ITER, the RES is expected to be avoided in normal operation by limiting the power flux to the divertor plate at 5 MW/m^2. Physical sputtering may be controlled or even suppressed by using a semi-detached regime, characterized by a very low electron temperature and high neutral pressure in the divertor [2]. In that case, the energy of ions and atoms impinging upon the surface would be lower than the threshold energy for physical sputtering by hydrogen. On the other hand, chemical erosion does not show any threshold value either in surface temperature or particle energy. Laboratory experiments have shown a decrease of the chemical sputtering yield with increasing flux, a flux dependence with $\phi^{-0.1}$ has been given in Ref. [3]. Extrapolation to the higher flux observed in the fusion devices leads to an uncertainty in the actual yield. Due to the large dispersion of the experimental data obtained on tokamaks, several models have been proposed and fit partially the measured values; flux dependence up to $\phi^{-0.6}$ can be found [4].

Under the conditions in ITER, the lifetime of the divertor tiles will be limited by chemical erosion of carbon [5]. It is very important to measure the chemical sputtering yield of carbon in order to predict with accuracy the erosion in ITER. We will present new experimental data obtained in Tore Supra and the interpretation of the results.

---

[*] Corresponding author.

PII: S0022-3115(98)00892-7

2. Experimental set-up

The outer pump limiter of Tore Supra is equipped with four turbomolecular pumps providing a pumping of 6 m^3 s^{-1} for deuterium gas. A schematic view of the limiter and main diagnostics used during the experiments described in this paper is shown in Fig. 1. The total pressure is measured on both parts of the limiter plenum (ion and electron side collection) and above the pumps by using three capacitor gauges. Partial pressure is obtained from a mass spectrometer differentially pumped and absolutely calibrated. The ion flux, density and electron temperature in the limiter mouth are measured by a set of Langmuir probes installed in both throats of the limiter. The surface temperature is monitored by an infrared detector, equipped with a filter peaked at 4 μm and with 0.1 μm bandwidth, looking at the neutralizer plate on the ion side. A visible spectrometer with a 1D optical multichannel analyser (OMA) connected with an optical fibre to an in situ telescope is looking at the neutraliser plate on the electron side. Two CCD cameras are installed with interference filters (431 nm, $\Delta\lambda = 1$ nm) on the electron side for the CD band emission and D_α (658 nm, $\Delta\lambda = 5$ nm) on the ion side. These cameras are equipped with a variable integration time card allowing to adjust the exposure time from 20 to 400 ms.

3. Results

To investigate the chemical sputtering, a series of discharges in reproducible conditions of plasma wall interaction have been performed. The discharges were fuelled by deuterium gas and to avoid helium contamination of the plasma, a helium conditioning discharge prior to the experimental day was cancelled. It has been shown previously [6] that helium could modify the chemical erosion of carbon. The plasma current was set at 1.4 MA, the toroidal field at 3.3 T, the plasma was leaning on the pump limiter located at 3.12 m. The steady state line average density (ohmic plasmas) was varied on a shot-by-shot basis in order to construct a density scan. A few shots have also been performed with 1 and 2 MW of Lower Hybrid additional power, allowing to extend the electron temperature range. The ion flux in the throat increased by more than one order of magnitude from 10^{22} to 1.2×10^{23} m^{-2} s^{-1}. Since at low density and high temperature, the carbon concentration is quite large in the scrape off layer, a correction of the ion flux in the throat has been done as function of the Z_{eff} as described in Ref. [7]. As the deuterium flux increases, the electron density increases from 10^{18} to 8×10^{18} m^{-3} while the electron temperature decreases from 50 to 10 eV. Fig. 2 shows the temperature and density measurements deduced from Langmuir probes as function of the flux, for several shots. Chemical erosion during these discharges has been monitored by the partial pressure evolution of the deuterated methane (CD_4, mass 20 on the mass spectrum) and by emission of the CD band around 430 nm. While the mass spectrometry measurements are integrated over the all surface of the limiter, the second method provides a 2D distribution of CD emission with a space resolution of the interaction between the plasma flow and the neutralizer plates. The CCD camera with the CD band filter is not absolutely calibrated, consequently, quantitative measurement of the chemical erosion can only be deduced from mass spectrometry. The mass spectrum from mass 2 to 50, is acquired in 150 ms. Although the C_2 hydrocarbon contribution is not negligible, especially at

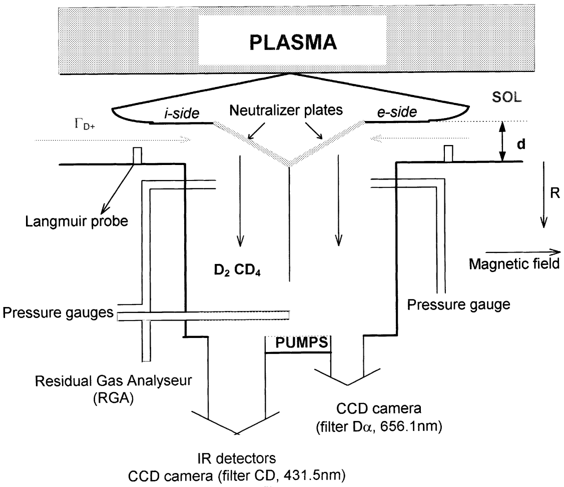

Fig. 1. Experimental set-up.

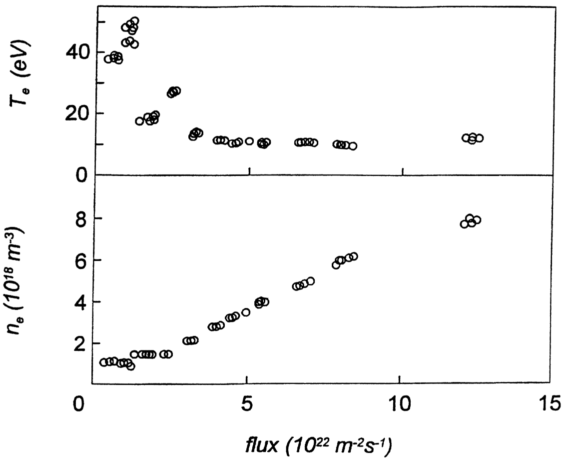

Fig. 2. Electron density and electron temperature as a function of deuterium ions flux in the throat of the outer pump limiter.

low energy [8], only the CD_n hydrocarbon behaviour has been analysed in this paper. The mass 4 signal (deuterium) being saturated, deuterium partial pressure has been deduced from the capacitance gauge measurements; the relative error on the deuterium pressure is less than 10%. Measurements have been taken during the plateau of the discharges which last about 10 seconds in the ohmic cases and between 20 and 30 s in LH heated discharges. All the parameters are stationary except the surface temperature which follows a law at $Pt^{1/2}$, where P is the power flux to the neutralizer and t the duration of the discharge. A strong effect on the CD_4 formation has been observed when the surface temperature rises above 700 K, unfortunately due to the transient effect, it is not possible to exclude a thermal desorption contribution in the CD_4 production. Therefore, chemical sputtering yield dependence with surface temperature has not been investigated; all the data have been taken at the same temperature of 500 K. CD_4 production as function of ion flux is plotted on Fig. 3, showing a monotonic increase of chemical impurity production with the flux. Best fit of the experimental data gives a relation as

$$P_{CD_4} \propto P_{D_2}^{0.7},$$

where P_{CD_4} is the partial pressure of CD_4 and P_{D_2} is the partial pressure of deuterium.

This dependence is comparable with those obtained in a divertor configuration on JT-60U [9]. However, from our analysis, this result does not allow to conclude, as found elsewhere [10] that the chemical sputtering yield decreases with flux as $\phi^{-0.3}$. This would mean that CD_4 flux measured at the pump is equal to the flux leaving the carbon wall or in other term, that the mean free path of CD_4 is larger than the limiter dimensions, which is not the case. That the reasons why the dissociation process of CD_4 must be carefully taken into account in the simulations, in order to provide the CD_4 production at the surface and therefore the chemical sputtering yield. Fig. 4 shows a profile on the toroidal direction of CD band emission in the limiter, integrated along the line of sight. The maximum emission is localized at the edge of the neutralizer, close to the throat. The CD band signal integrated over the interference filter could be polluted by line emission or Bremsstrahlung emission. The time evolution of one point of the neutralizer viewed by the CCD camera and peak value of CD band on the OMA spectrum are plotted on Fig. 5. Although they are not taken at the same time location, high correlation between both measurements gives good confidence in the CD band profile obtained with the camera and the CD filter.

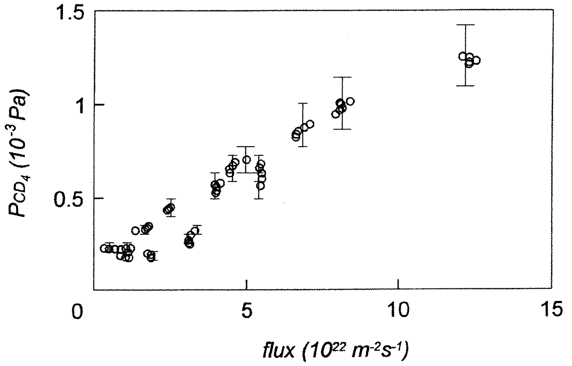

Fig. 3. CD_4 partial pressure measured at the pump as a function of the flux to the limiter.

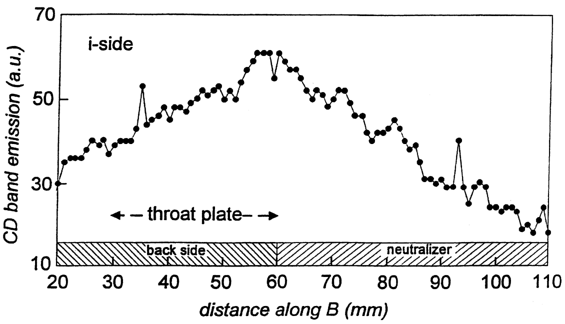

Fig. 4. CD band emission profile on toroidal direction measured with the CCD camera with CD band filter at 430 nm.

4. Discussion

Chemical sputtering has been extensively studied both in the laboratory and in fusion devices [3,11]. In the

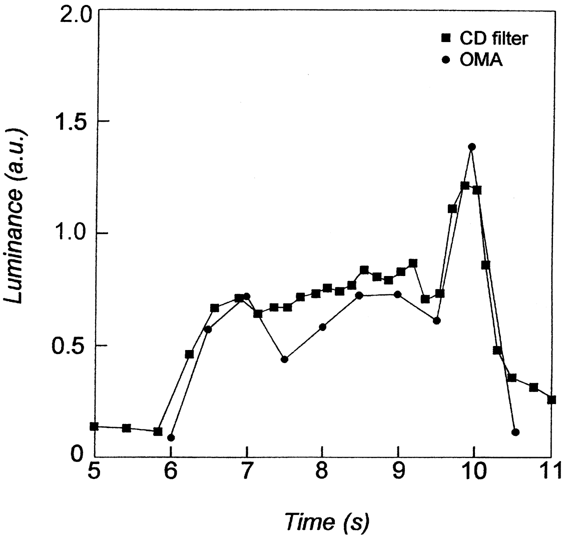

Fig. 5. Time evolution of CD band emission measured with the OMA and the CCD camera with CD band filter at 430 nm.

former case, chemical sputtering yield is directly measured, usually from weight loss or mass spectrometry measurements. This provides a better understanding of the process and allows the development of models which satisfactorily describe the chemical sputtering yield dependence with surface temperature, ions energy and flux [12]. In fusion devices, the chemical sputtering yield is deduced from the interaction of the molecules leaving the surface and the impinging plasma; this may explain the larger discrepancy observed on different tokamaks [10,12]. Moreover, depending on the method (mass spectrometry versus visible spectroscopy for instance) results can vary significantly even on a single machine [13].

Analysis of the experimental results has been performed by using Monte Carlo code with actual geometry of the outer pump limiter of Tore Supra. The BBQ scrape-off layer impurity transport code [14] incorporates a particle transport model patterned after that of the LIM code [15], including parallel streaming along field lines, anomalous perpendicular diffusion, parallel friction and electrostatic drifts. In addition, for chemically sputtered impurities, the Langer–Erhardt database [16] for CD_4 break-up reactions is incorporated, as described in Ref. [17]. The models for impurity generation by sputtering are taken from analytic fits to laboratory data of Ref. [8] and from experimental measurements presented and compared with the Roth formulae in Ref.

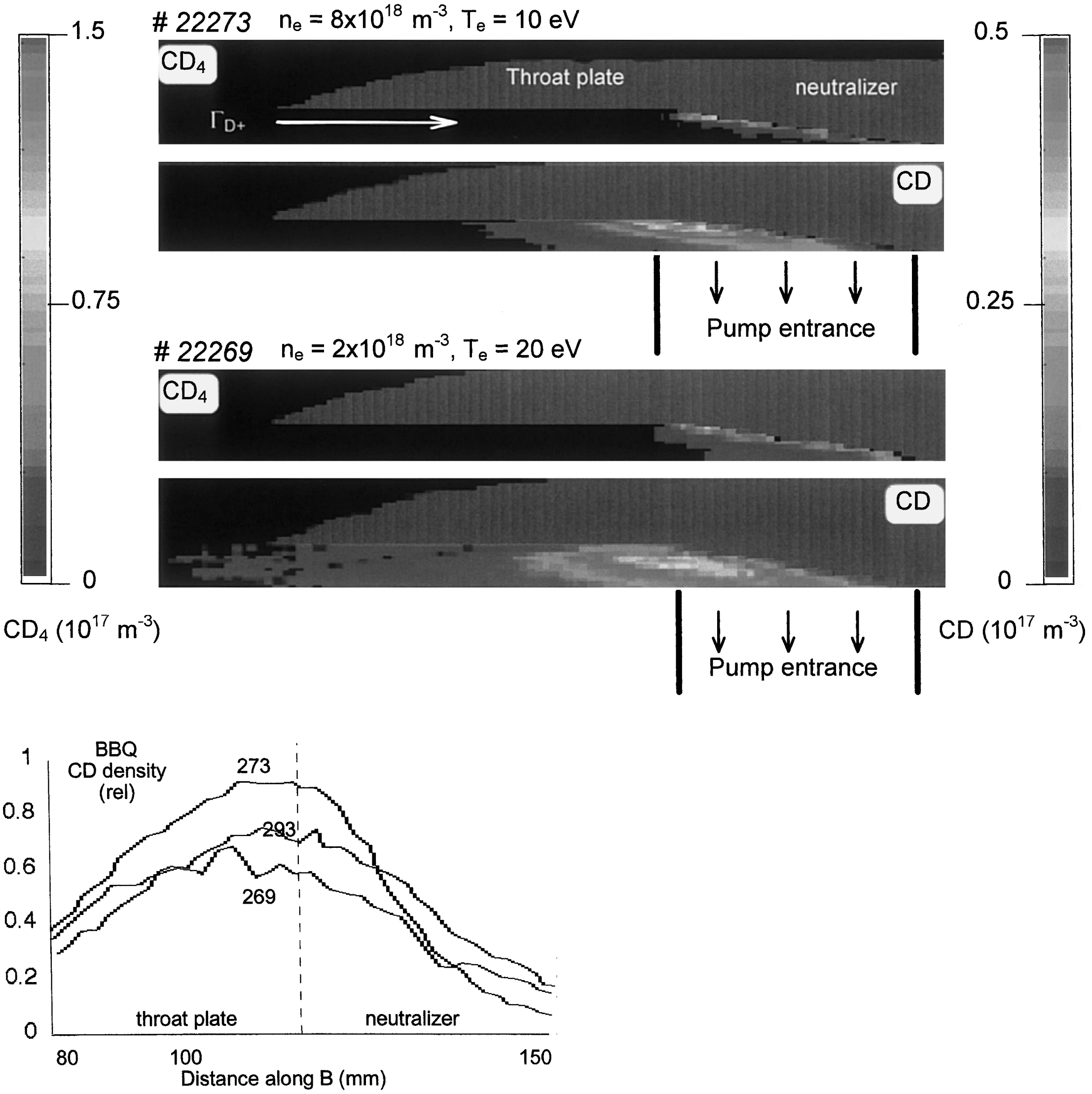

Fig. 6. 2D distribution of CD_4 molecules and CD radicals in the throat of the OPL, calculated by BBQ code (a), simulated CD density integrated over the CCD camera line of sight (b).

[12]. The particle flux dependence for the sputtering coefficient is assumed the same (that of Ref. [12]) in both. The detailed 3-D plasma-facing geometry of the pumped limiter throat region is treated, with an assumed wall temperature distribution taken from detailed finite-element thermal calculations of Koski et al. [18]. The pumping efficiency for the cases in question has been extrapolated from previous detailed DEGAS studies of pumping efficiency for this limiter geometry [19]. Langmuir probe measurements of electron density and temperature close to the neutraliser plate are used to determine the background plasma (electrons and deuterium ions) in the simulation.

Calculated spatial distributions in the neutralizer region are shown in Fig. 6(a,b). Fig. 6(a) compares the spatial variation of CD_4 and CD density for discharges 22269 and 22273. The different behavior in the intensity patterns reflect the higher mean free path for both CD_4 and CD radicals, for the lower density case. Fig. 6(b) show the CD density distribution along the field over the same field of view as presented in Fig. 4. The CD profiles are also relatively flat in the simulation. These cases are calculated using sputtering values from Ref. [8]. Since the comparison of candidate sputtering yield models with the experiment depends, in part, on measurements in the pumping plenum, Fig. 7 shows the calculated disposition fractions of the CD_4 flux produced at the neutralizer plate as a function of incident D+ flux for nine discharges with similar neutralizer surface temperatures, whose parameters are described in Fig. 2. Most of the CD_4 generated by chemical sputtering is either redeposited (on the side wall, top or bottom surfaces of the neutralizer region) or can eventually escape into the main plasma. Only the pumped fraction (4–10%) contributes to the measured CD_4 partial pressure in the plenum. Fig. 8 compares the expected values calculated from the simulation using both Refs. [8,12] values with the measured partial pressures in the plenum. For these discharges the neutralizer surface temperature ($\sim$500 K) was in a region where the results from Ref. [8] are $\sim$10 × higher than the values in Ref. [12]. The Ref. [8] levels are closer to the experimental data for the outboard pump limiter.

Many uncertainties remain, of course. In the earlier detailed comparison of the break-up components of CD_4 (through CD_4+, $CD_n + \ldots$) with spectroscopic measurements of these species in the PISCES device [17] only a factor-of-two correspondence was seen, although the trends were well reproduced. The pumping efficiency, while expected to be similar to that of D_2 from basic considerations, has not been directly determined. Nevertheless, good agreement can be observed, especially in the high flux – low temperature cases, between experimental and simulated values, by using the Mechs et al. [8] chemical sputtering yield formulation. The relative discrepancy observed at lower flux corresponds to higher electron temperature discharges, heated by Lower Hybrid. In these cases, the partial pressure ratio calculated by the code are well below the experimental values. This is likely due to the error bars on the electron temperature measurements (which could be due to a non-maxwellian distribution) and uncertainties in the atomic physics process (CH_4 ionisation cross section varies by two order of magnitude between 10 and 50 eV [20]) rather than a sudden variation of the chemical sputtering yield.

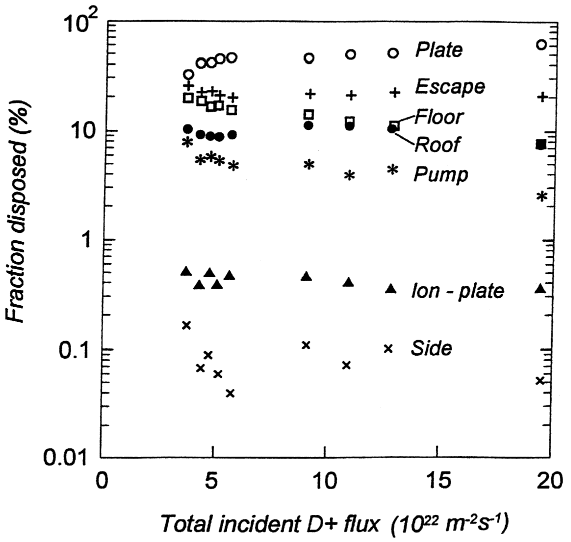

Fig. 7. Chemical impurity generation at OPM neutralizer and fraction disposed.

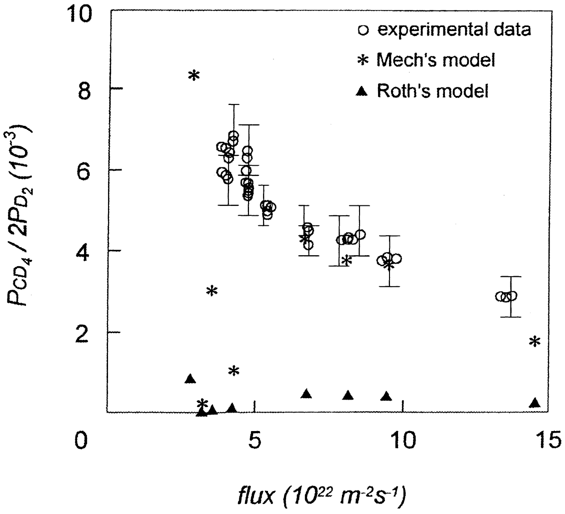

Fig. 8. Equivalent effective erosion yields, experimental values compared BBQ simulations using chemical sputtering models from Mech et al. [12] and Roth and Garcia-Rosales [8].

Good agreement at high flux between simulations and experimental data are obtained by using Mech et al. [8], From this curve and the yields introduced in the simulation, we can deduce a chemical sputtering yield of 3×10^{-2} at temperature of 500 K and flux of 10^{23} m^{-2} s^{-1}.

5. Conclusion

Chemical sputtering has been investigated on a pump limiter neutralizer in Tore Supra. CD_4 formation has been monitored by optical spectroscopy and mass spectrometry, surface temperature has been controlled by infrared detectors. During a shot by shot density scan, ion flux in the throats of the limiter has increased from 10^{22} to 1.2×10^{23} m^{-2} s^{-1}. CD_4 partial pressure measured at the pumps shows a monotonic increase with the flux; experimental data have been fitted with a $\phi^{0.7}$ law. Numerically simulations with BBQ code using two different chemical sputtering yield formulae have been performed. Results show that Mech's model reproduces CD_4 production at high flux. Chemical sputtering yield of 3×10^{-2} is obtained with an ion flux of 10^{23} m^2 s^{-1} and a surface temperature of 500 K.

Acknowledgements

The authors acknowledge M.H. Mathieu and S. Vartanian for their technical support during the experiments.

References

[1] P. Chappuis, J. Nucl. Mater. 241–243 (1997) 27.
[2] G. Janeschitz, K. Borass, G.J. Federici et al., Nucl. Mater. 220–221 (1995) 733.
[3] J. Roth, E. Vietzke, A.A. Haasz, Suppl. Nucl. Fusion 1 (1991) 63.
[4] A. Pospieszczyk, V. Philipps, E. Casaratto et al., Proceedings of the 22 EPS Conference on Contr. Fusion and Plasma Phys., Bournemouth, 1995, pp. II–313.
[5] R. Parker, G. Janeschitz, H.D.J. Pacher et al., Nucl. Mater. 241–243 (1997) 1.
[6] E. de la Cal, E. Gauthier, J. Vac. Sci. Technol. A 15 (5) (1997) 2597.
[7] T. Loarer, T. Uchan, M. Chatelier, J. Nucl. Mater. 196–198 (1992) 1078.
[8] B.V. Mech, A.A. Haasz, J.W. Davis, J. Nucl. Mater. 241–243 (1997) 1147.
[9] N. Hosogane, M. Shimada, K.J. Shimizu et al., J. Nucl. Mater. 220–221 (1995) 415.
[10] J.W. Davies, A.A. Haasz, J. Nucl. Mater. 241 (1997) 37.
[11] E. Vietzke, A.A. Haasz, in: W.O. Hofer, J. Roth (Ed.), Physical Processes of the Interaction of Fusion Plasmas With Solids, 1996, Academic Press, New York.
[12] J. Roth, C. Garcia-Rosales, Nucl. Fusion 36 (1996) 1657.
[13] A. Pospieszczyk, V. Philipps, E. Casaretto, J. Nucl. Mater. 241–243 (1997) 833.
[14] J. Hogan et al., Integrated impurity model for actively cooled plasma-facing components, Proceedings of the 16th International Conference on Plasma Physics and Controlled Fusion Research, Montreal, 1996, IAEA Vienna, 1997, to be published.
[15] P. Stangeby, C. Farrell, S. Hoskins et al., Nucl. Fusion 28 (1988) 1945.
[16] A.B. Ehrhardt, W.D. Langer, Collisional processes of hydrocarbons in hydrogen plasmas, Princeton Plasma Physics Laboratory report, PPPL-2477, 1987.
[17] J. Hogan, A. Pospieszczyk, Modeling of hydrocarbon fuelling, ORNL Report ORNL/TM-11542, 1990.
[18] J. Koski, F.M. Hosking, R.D. Watson et al., Fusion Technol. (1988) 802.
[19] L. Owen, M. Chatelier, J.J. Hogan et al., Nucl. Mater. 196 (1992) 1125.
[20] H. Tawara, Y. Itikawa, H. Nishimura et al., Suppl. Nucl. Fusion 2 (1992) 41.