Journal of Nuclear Materials 390–391 (2009) 53–56

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

From eroded material to dust: An experimental evaluation of the mobilised dust production in Tore Supra

C. Grisolia [a,*], S. Rosanvallon [a], A. Loarte [b], P. Sharpe [c], C. Arnas [d]

[a] Association Euratom/CEA, DRFC/SIPP, 13108 St Paul lez Durance, France
[b] ITER International Organization, 13108 St Paul lez Durance, France
[c] Fusion Safety Program, Idaho National Laboratory, Idaho Falls, ID 83415, USA
[d] Laboratoire PIIM, UMR 6633 CNRS-Université de Provence, 13397 Marseille, France

ABSTRACT

In a fusion reactor like ITER, in-vessel materials are subjected to interactions with the plasma. One of the main consequences of these plasma-material interactions is the creation of co-deposited layers especially with Beryllium and Carbon based materials. Due to internal stresses, part of these layers can crack leading to micro particle creation. The purpose of the following paper is to review the tokamak operation processes that lead to the erosion of the bulk material and then to layer creation. The proportion of these layers that are converted into micro particles will be evaluated in the case of Tore Supra experiments. For Tore Supra, this conversion factor (Cd) is close to 7–8% comparable to the current ITER retained value of 10%. In the second part of the papers, diagnostics which can be used to constraint the Cd value are proposed.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

During tokamak operation and due to high heat and particle fluxes, beryllium and carbon based Plasma Facing Components (PFCs) are eroded and material is re-deposited. Mainly due to internal stresses, these re-deposited layers are frequently fragile and breakable leading to micro particle creation. For ITER operation, it is of major interest to know the proportion of these deposited materials able to be converted into mobilisable dust. Indeed, for safety reasons (dust explosion, activated product dissemination), the total in vessel mobilisable dust quantity (Qd) must be limited to 1000 kg [1]. From the erosion sources, Qd could be predicted. In order to quantify this transfer process, a dust conversion factor (Cd) is used. Cd is the ratio between the total quantity of in-vessel mobilisable dust (Qd) over the total quantity of eroded material (Qe) produced during operation:

$$\mathrm{Cd} = \mathrm{Qd}/\mathrm{Qe}.$$

Qd can be experimentally obtained by vacuum cleaning for example. In the Cd evaluation, the only erosion processes to be taken into account are the ones acting on bulk material (since they are creating breakable material). Then the eroded materials are transported and deposited. Part of them turns to be converted into dust. An assessment of the upper in-vessel dust inventory could be obtained at any time knowing the eroded quantity and considering Cd = 1. However, this leads to an operational constraint (as micro particles removal) that could be released with a reduced Cd.

In this paper, a Tore Supra experimental estimation of Cd is presented with a special insight on the Qe evaluation for all the different erosion processes. The Qe accuracy as well as the needed improvements in order to constraint this evaluation is assessed.

The Tore Supra Cd value could be extrapolated to ITER operation in order to estimate the dust in situ inventory and compare this value to the safety limits. However, it appears clearly from this study that Cd assessment of the mobilisable particles must be available during the ITER life. In the second part of this paper, some of possible diagnostics will be presented in order to measure directly the ITER Cd value.

2. Tore Supra Cd evaluation

2.1. Dust in vessel quantity

The total in vessel quantity Qd has been evaluated for a 5 months (1999, 1438 shots) Tore Supra operation period. At the beginning of each major shutdown, the Tore Supra vacuum vessel is vacuumed and dust collected [2]. It was observed as in other devices that the dust collection was toroidally symmetric. Poloidally, the micro-particles distribution follows the gravity. From this careful observation, the total in-vessel dust collected during this campaign was estimated to be 31 g. It has to be pointed out that only the accessible zones are cleaned. This is not the case of the vertical

---

[*] Corresponding author.
E-mail address: Christian.Grisolia@cea.fr (C. Grisolia).

0022-3115/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2009.01.045

ports under the machine. However, the error induced is estimated to be less than 10%.

2.2. Eroded material quantity

In order to evaluate the global tokamak erosion, all the erosion processes have to be reviewed and eroded quantity assessed for each of them.

2.2.1. Erosion during normal operation

The eroded material quantity results from the sputtering of graphite PFCs by the plasma out-flux falling down onto eroded zones. In [2], basic estimation was obtained considering that the plasma outflux is equal to N_p/τ_p with N_p the mean value of the mean plasma density for all the campaign and τ_p the particle confinement time (200 ms). Considering a carbon sputtering yield equal to 0.02, and a plasma volume of 25 m^3, the total carbon eroded quantity was estimated to be 27 g.

However, more precise estimation has been done for other Tore Supra campaigns (2002–2003–2004) from Carbon2 (CII) brightness modelling [3]. It was shown that the carbon particle sources (Sc) is proportional to the conducted power (P_{cond}): Sc (particles/s) = 5×10^{20} P_{cond} (MW). The estimated value of the eroded carbon M_c during a complete campaign is thus proportional to the total injected energy (E_t): M_c (g) = $12.8 \times 10^{-3} E_t$ (MJ). The injected energy for the 1999 Tore Supra campaign studied here is close to 25GJ leading to an erosion of Carbon during normal operation of 360 g.

From this new evaluation, it appears that the value of eroded material during normal operation was underestimated in [2] by a factor 13.

The quantity of eroded material that must be considered in this work is the one coming only from the eroded zones which are well separated, in limiter machine, from the deposited one. The CII spectroscopic signals are well suited for this evaluation since they are directly related to carbon signal coming from erosion zones.

The above obtained M_c value is lower than the TEXTOR [4] ones where the carbon source is supposed to be 22 g/h leading to 88 g of eroded material thief applied to the 1999 Tore Supra campaign. The discrepancy observed (factor 4) is rather low and could be due to different operating plasma scenario. As an example, in Tore Supra, part of the plasma experiments is done using Lower Hybrid Current Drive system. In that case, the edge temperature is high and the erosion by sputtering more efficient.

In order to constraint as much as possible this erosion evaluation during normal operation, it is proposed to calibrate the erosion estimation by a known injected amount of carbon atoms or micro particles produced by laser ablation onto eroded zones.

2.2.2. Erosion during transient processes as disruption

The contribution of disruptions is much more difficult to assess since it does not rely on direct tokamak measurements but from extrapolation from laboratory studies.

The mean thermal content of a Tore Supra discharge is 500 kJ. The thermal quench time duration is estimated to be 250 μs. The surface of the interacting zone (S) is not known precisely. However, from previous results obtained in TEXTOR, it appears that in a limiter machine no broadening of thermal pattern is appearing during disruption [5]. S is comparable to the one observed during normal operation, S ~ 1 m^2. The fluence that it has to be taken into account is closed to 500 kJ/m^2.

Several experiments as plasma gun (QSPA, Troisk) [6] are dedicated to the estimation of erosion during transient events like ELMs or disruption. The QSPA experiment condition and a comparison with the ITER disruption and ELMs conditions are described in [6]. From QSPA, the erosion of the fibre that is parallel to the material surface presents a threshold energy of 400 kJ/m^2. At 500 kJ/m^2, the erosion is 0.1–0.2 μm/m^2 leading to a removal of 0.2–0.4 g of Carbon per square meter. The thermal properties of this fibres that is perpendicular to the high thermal conductivity direction is comparable to the one of the graphite used in Tore Supra during the studied experimental campaign. Therefore, with the Tore Supra disruption parameters, the eroded material per disruption M_c could be 0.2–0.4 g. With a disruption frequency of 10–15% during the considered period, this leads to 30–60 g of bulk PFCs erosion. The mean value of 45 g will be retained in the following.

A comparable value of carbon erosion during disruption has been already published [7]. However, this estimation is strongly questionable. Firstly, the value retained for the deposited energy per square meter during Tore Supra disruption is based on a crude estimation of the interacting surface and of the time duration of the thermal quench which can be easily underestimated. Then, the threshold energy of graphite erosion could be also underestimated. Laser ablation experiments are also facing the same problem of the evaluation of the material threshold energy (E_{th}) for graphite erosion. In the laser experiment, ablation depends strongly on the competition, during the laser pulse, between energy deposition that occur at the material surface for IR laser light and thermal energy diffusion which is proportional to the square root of the laser pulse duration [8]. As a consequence, the ablation threshold energies for 1 μs laser pulse is 3 times higher than for 100 ns. An extrapolation from the known ablation graphite energy threshold gives a value of $E_{th} \sim 700$ kJ/m^2 for a 500 μs pulse, slightly higher value than the one proposed from plasma gun experiments. It sounds reasonable since plasma energy in QSPA is deposited in the material surface vicinity with a low ion sputtering (due to low ion energy). With the accuracy of the measurements listed above especially on the disruption thermal deposited pattern and on the uncertainties on E_{th}, the carbon eroded quantity estimated to be 45 g appears strongly overestimated and could be equal to zero.

From recorded fast CCD or IR camera data during tokamak disruptions, a high quantity of micro-particles is regardless observed. This production could be attributed to deposited layers flaking. Indeed, as for laser ablation experiments, E_{th} for deposited layer could be reduced from bulk threshold energy by a factor of 5 leading to a E_{th} smaller than 100 kJ/m^2. Moreover, deposited layers could be fragile due to the thermal stresses which can be released during thermal shock induced by the disruption thermal quench or even during normal operation as seen during the DITS campaign [10].

2.2.3. Erosion during maintenance activities like conditioning

The main conditioning procedure of Tore Supra is helium Glow Discharges (He-GD) done with 3 A/300 V of Glow Current/Voltage. With a total of 100 m^2 of wall facing the low temperature glow plasma, the current density is 3 μA/cm^2 and the ions flux onto the inner wall is equal to 1.9×10^{17} m^{-2} s^{-1}. Considering a carbon sputtering yield of 9×10^{-2} for 300 eV impinging helium ions, the net eroded carbon from the Tore Supra limiters ($S \sim 20$ m^2) is 3.4×10^{17} s^{-1}. For 1 day of He-GD, 0.6 g of C are sputtered. During the 5 months of Tore Supra operation and with regular He-GD cleaning sequence, at least 10 g of C could have been eroded.

It can be shown that the Tore Supra glow parameters are producing micro particles and the eroded carbon is transported and deposited onto the vessel walls. As a confirmation, during the entire life of the machine, the stainless steel vessel walls are covered by carbon layers and appear completely brown. From this observation, a rough estimation of carbon quantity on the walls could be as high as 100 g. The stability of this layers are crucial to control the in vessel dust inventory. Shutdown conditions are essential to preserve all the layers integrity. Several observations [9] have shown the influence of moisture on the evolution of carbon deposited layers as a function of time. Cracks appear leading to embrittlement of the deposited layers, flaking and thus to dust creation. However, from Tore Supra observations, it seems that it takes days to observe, at room temperature, layer destruction by steam oxidation.

In contrary to the campaign studied above, Tore Supra is now an all actively cooled machine. During current operation campaign, He-GDs are not used at a so high frequency. As an example, during the last 2007 campaign for several tens of plasma pulses, no He-GDs were undertaken and no operation constraints were observed [10]. It will be the case in the ITER machine and as a consequence the material erosion during conditioning will be reduced.

2.3. Total quantity eroded and Cd evaluation

The quantity of Carbon eroded in Tore Supra during this 5 months of operation is therefore composed of:

- 360 g eroded during normal operation.
- 45 g eroded during disruptions. This is a very pessimistic value. In reality, it seems that no erosion occurs during disruption at this level of sprayed thermal energy.
- 10 g eroded during He-GD.

Total eroded quantity is then comprised between 415 g and 370 g if no erosion is considered during thermal quench. The late value appears to be the most probable one. For this Tore Supra campaign, Cd is between 7% and 8%.

This estimation is in agreement with the value recently published by JT60U [11] (7%) and with the ITER retained value (10%).

As in the current axis-symmetric divertor machine, the most important erosion process in ITER will be the erosion during normal operation if the ELMs and disruption energies are kept at a value less than 500–1000 kJ/m^2.

As it appears above, the Cd evaluation is not an easy task. All the erosion processes must be considered and the eroded material evaluated. Even if it is clear that for direct comparison with the safety limits, the ITER in-vessel erosion must be measured on line, it is difficult to believe that erosion assessment will rely only on 'on line' spectroscopic measurements even if calibrated by laser ablation material injection. PFC erosion measurements during shutdown must also be foreseen. Mobilisable particles have then to be carefully collected.

However, in order to allow efficient ITER operation without regular dust collection always linked with shutdown, a measurement of the total quantity of mobilisable in vessel dust must be also available. In the following chapter, a list of diagnostics which can be used is presented.

3. In situ tokamak dust measurements

In order to assess the Cd conversion factor, PFC erosion diagnostics are needed. As we have discussed, Qe is assessed via code evaluation of the erosion using the plasma edge impurity diagnostics. This technique is well suited for in-vessel wall erosion assessment or for limiter erosion surfaces. However, it is much more difficult for divertor area due to the difficulty to diagnose the impurity in the divertor region (line of sight and spectroscopic signals interpretation). It seems that the link between impurities signal and erosion is almost impossible in the outer divertor region of an axi-symmetric machine.

For a more reliable measurement, net erosion techniques able to measure the PFCs depth evolution as laser metrology such as speckle interferometry [12] must be used. Confocal spectroscopy [10] that is under development at Tore Supra for tokamak applications seems valuable to assess the PFCs erosion. These techniques have been already tested at a laboratory scale and need to be integrated in the complex tokamak environment. It has to be stressed that erosion diagnostics [12] are the only one that could estimate the in-vessel dust quantity considering Cd = 1 and thus enable direct comparison with the safety limits.

For in vessel dust measurements, several diagnostics operating on a shot to shot basis are also under development. Electrostatic grids [13] could be installed in places where dust is accumulating as under the divertor or under the ITER dome. This system relies on homogeneity assessment and the link with local measurements and Qd is not obvious. Optical techniques could be also used. Laser extinction [14] is the simplest one since it is measuring the attenuation of the laser light intensity along its propagation in the dust cloud. However, the interpretation of the measured signal turns to be very challenging because of the heterogeneity (in size, composition, shape,...) of the micro particles supposed to be produced during tokamak operation. Furthermore, this airborne dust measurement relies on the use of gas puffing to put the micro particles in suspension. The link between the airborne dust measured and the mobilised dust relies on complex fluid codes that do not exist yet. However, optical system as laser extinction could be inserted on in-vessel inspection robot and thus available for global assessment independently of in-vessel in-homogeneity. Finally, mobilisable dust can also be measured via vacuum cleaner recovery that can be introduced remotely and used during shutdown. This diagnostic system that could be also used for dust removal has already proven its efficiency [15]. It seems nevertheless that accessibility will be an issue as well as the link between dust recovered and the real quantity of dust that could be mobilised. As for erosion the need of tokamak (or relevant scale mock-up) integration and test is mandatory in order to assess these diagnostics capabilities and accuracy in realistic conditions. As a conclusion, a set of complementary systems seems to be available to measure the in-vessel mobilisable dust. This value could be then compared with ITER safety limits.

4. Conclusions

In this paper, the dust conversion factor has been estimated in a current operating tokamak. It is between 7% and 8%. This Cd value is closed to the ITER prediction (10%). The most important process leading to material erosion is normal plasma operation. Tore Supra disruption is not though as inducing a large erosion quantity even if this study cannot be conclusive since direct measurement are not existing and since the thermal discharge energy content is closed to the threshold energy for graphite erosion.

Using the procedure presented here, Cd must be evaluated among several operating worldwide tokamaks in order to address the consequences of different operating mode (influence of ELMs for example) and material configurations (metal and non metal) on the dust in-vessel quantity. In particular, special care must be put on the in vessel quantity collection.

Several diagnostics have also been reviewed. It appears clearly that a set of techniques are available to assess the dust in-vessel inventory. However, there is an urgent need of an integrated demonstration that has to be planned in a tokamak environment or in a relevant scale mock up.

References

[1] S. Rosanvallon, C. Grisolia, P. Andrew, S. Ciattaglia, P. Delaporte, D. Douai, D. Garnier, E. Gauthier, W. Gulden, S.H. Hong, S. Pitcher, L. Rodriguez, N. Taylor, A. Tesini, S. Vartanian, A. Vatry, M. Wykes, in: Presented at the 18th Plasma Surface Interaction Conference, Toledo, J. Nucl. Mater., 390–391 (2009) 57.

[2] Ph. Chappuis, E. Tsitrone, M. Mayne, X. Armand, H. Linke, H. Bolt, D. Petti, J.P. Sharpe, J. Nucl. Mater. 290–293 (2001) 245.

[3] J.T. Hogan, E. Dufour, P. Monier-Garbet, C. Lowry, Y. Corre, J. Gunn, R. Mitteau, E. Tsitrone, C. Brosset, J. Bucalossi, T. Loarer, I. Nanobashvili, B. Pegourie, P. Thomas, in: Proceedings of the 21st IAEA Fusion Energy Conference, 2006.

[4] M. Majer, V. Rohde, T. Pütterich, P. Coad, P. Whienhold, Phys. Scripta T111 (55–61) (2004).

[5] M. Ciotti, T. Denner, G. Maruccia, K.H. Finken, J. Hobirk, A. Kremer-Flecken, G. Maddaluno, R. Mank, P. Pasqua, F.C. Schuller, R. Zanino, J. Nucl. Mater. 266–269 (1999) 1023.

[6] (a) A. Zhiltlukhin, N. Klimov, I. Landman, J. Linke, A. Loarte, M. Merola, V. Podkovyrov, G. Federici, B. Bazylev, S. Pestchanyi, V. Safronov, T. Hirai, V. Maynashev, V. Levashov, A. Muzichenko, J. Nucl. Mater. 363–365 (2007) 301; (b) G. Federici, A. Zhitlukhin, N. Arkhipov, R. Giniyatulin, N. Klimov, I. Landman, V. Podkovyrov, V. Safronov, A. Loarte, M. Merola, J. Nucl. Mater. 337–339 (2005) 684.

[7] C. Grisolia, Ph. Sharpe, J. Winter, C. Arnas, S. Rosanvallon, A. Vatry, Ph. Delaporte, in: Proceeding of the ICRFM Conference, Nice (2007), under publication in J. Nucl. Mater. (2008).

[8] A. Semerok, S.V. Fomichev, J.-M. Weulersse, F. Brygo, P.-Y. Thro, C. Grisolia, J. Appl. Phys. 101 (2007) 084916.

[9] E. Salançon, T. Dürbeck, T. Schwarz-Selinger, W. Jacob, J. Nucl. Mater. 363–365 (2007) 944.

[10] B. Pegourié, C. Brosset, E. Tsitrone, A. Beaute, S. Bremond, J. Bucalossi, Y. Corre, E. Delchambre, C. Desgranges, P. Devynck, D. Douai, A. Ekedahl, A. Escarguel, C. Fenzi, C. Gil, J. Gunn, P. Hertout, S. Hong, F. Kazarian, M. Kocan, L. Manenc, Y. Marandet, O. Meyer, P. Monier-Garbet, P. Moreau, P. Oddon, F. Rimini, P. Roubin, F. Saint-Laurent, F. Samaille, S. Vartanian, C. Arnas, C. Dominique, P. Martin, M. Richou, in: Presented at the 18th Plasma Surface Interaction Conference, Toledo, J. Nucl. Mater., 390–391 (2009) 550.

[11] Asakura et al., Private Communication, in: First Workshop on the "Dust in Fusion Plasmas" (DFP/EPS 2007) Satellite Meeting of the 34th EPS Conference on Plasma Physics Warsaw, Poland, 2007.

[12] P. Dore, E. Gauthier, J. Nucl. Mater. 363–365 (2007) 1414.

[13] C. Voinier, C.H. Skinner, A.L. Roquemore, J. Nucl. Mater. 346 (2005) 266.

[14] F. Onofri, K.F. Ren, C. Grisolia, Presented at the 18th Plasma Surface Interaction Conference, Toledo, J. Nucl. Mater., 390–391 (2009) 1093..

[15] N. Bekris, J.P. Coad, R.-D. Penzhorn, S. Knipe, L. Doerr, R. Rolli, W. Nägele, J. Nucl. Mater. 337–339 (2005) 659.