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Journal of Nuclear Materials 283–287 (2000) 1105–1110

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Effects of plasma disruption events on ITER first wall materials

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Abstract

In ITER, plasma disruption events may occur producing large fast thermal transients on plasma facing materials. Particularly important for the integrity of the first wall (FW) are relatively 'long' duration off-normal events such as plasma vertical displacement events (VDE) and runaway electrons (RE). An analytical methodology has been developed to specifically assess the effect of these events on FW plasma facing materials. For the typical energy densities and event duration expected for the primary and baffle FW, some melting and evaporation of the FW armor will occur without the beneficial effect of vapor shielding, and the metallic heat sink may also be damaged due to over-heating. The method is able to calculate the amount of melted and evaporated material, taking into account the evolution of the evaporated and melted layer and to evaluate possible effects of local temporary loss of cooling. The method has been used to analyze the effects of VDE and RE events for ITER, to study recent disruption simulation experiments and to benchmark experimental and analytical results.

1. Introduction

Several types of plasma disruption events (PDE) may occur in a Tokamak reactor. These events result in fast-transient high-thermal loads that can damage the armour and the heat sink materials of the plasma facing components. For the ITER project, studies [1] have been performed to define the possible PDE and the resulting thermal loads on the FW.

In studying the effects on FW, two main types of 'hard' off-normal events have been analyzed in detail

- Plasma Vertical Displacement Events (VDEs), due to a loss of plasma control, characterized by relatively slow (up to 0.3 s), high energy density thermal transients. Hard VDEs are always followed by a plasma disruption.
- Runaway Electron (RE) events generated by an avalanche mechanism that can occur during the current quench following a disruption. The high energy electrons (>10 MeV) can penetrate deep inside the materials resulting in a sudden (radially peaked) volumetric heating.

These 'hard' PDEs are specified in ITER as rare events (e.g., ~10 times total VDEs), which could occur when, at maximum reactor performance, there is a loss of plasma control together with failure of active protection systems. These events envelope all the other plasma disruption events on the FW from the thermal load and material damage point of view. The outcome of previous analyses and of specific ITER R&D activities on PDE experimental verification can be found in [2–5,9] and recently in [6].

Specific analytical methods have also been previously developed or improved by the ITER Joint Central Team to tackle these typical FW PDE problems. A new methodology has been recently developed to overcome some limitations of the previous methodologies. These were limited to mono-dimensional cases and were not able to consider volumetric heating distribution (RACLETTE [4]) or were not able to compute the evaporation layer [7]. The aim of this new methodology is to solve more precisely these transient thermal problems in complex two- and three-dimensional geometries, taking into account the moving boundary when vaporization

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0022-3115/00/$ - see front matter
PII: S0022-3115(00)00151-3

occurs, without dealing with complex plasma/vapor interactions but analyzing possible subsequent thermal–hydraulic effects. In fact, for the typical energy densities and event duration expected for the primary and baffle FW, vapor shielding is not expected to occur, and the metallic heat sink may be damaged due to over-heating, enhanced in severe cases by the occurrence of a local and temporary critical heat flux condition and its associated loss of heat transfer.

The method can also be useful for the simulation of plasma disruption experiments with focused beams and for the possibility of studying cases where evaporation occurs with a complex distribution (in two- or three-dimensions) of the heat load (as could occur for some RE).

The methodology has been presently used only in two-dimensional geometries to:

- re-evaluate the effects of VDE and RE on beryllium (Be), tungsten (W) and carbon (C), for the ITER typical primary and baffle FW loadings,
- analyze recent experiments on plasma facing materials, e.g., [6], and benchmark the experimental and analytical results.

2. Analytical methodology

The method consists of a computer routine that calculates the quantity of evaporated and melted material making use of a finite element (FE) code (ANSYS) to accurately compute the time and space evolution of the temperature, taking into account the moving evaporated and melted layer boundaries.

The incoming heat flux, the volumetric heating distribution, the re-irradiation to an external environment, and the convection to the cooling means are directly applied to the FEM model. For each time-step the temperature distribution is obtained by the FE code. For each finite element of the exposed surface, the erosion rate [4,7] is calculated from a gas kinetic relation in function of the actual surface temperature, and the outgoing heat flux due to the evaporation is calculated multiplying the erosion rate by the latent heat of vaporization and the material density.

The erosion rate for each element is integrated in time to obtain the total evaporated thickness and its effect on the energy balance in each time step. When an entire element is vaporized, it is eliminated from the model and the boundaries and the applied loading conditions are moved to the element below. The method is then able to evaluate the predicted shape of the eroded surface. The melting layer is directly computed by the ANSYS code on the base of the material enthalpy. As in other models [4,5] the heat transfer to the coolant can be applied as a function of the wetted wall temperature to take into account subcooled boiling and the eventual occurrence of local critical heat flux.

3. VDE and runaway electron analysis

3.1. Schematization and assumptions

A two-dimensional analysis has been performed for the FW. The typical FW geometry has been schematized as shown in Fig. 1. Exploiting symmetry only half a tube has been modeled. Selected FW relevant cases have been analyzed, varying for each material the armour thickness and the event duration. Materials used were:

- Beryllium grade S65C, Tungsten and carbon fibre composite SEP CARB N31B for the armour.
- DS-Copper alloy for the heat sink with 316 LN stainless steel cooling liner tube.

Material properties have been taken from [8]. The emissivity was chosen as 0.4 for Be and W and 0.9 for C.

3.2. Thermal loads

The input thermal loads have mainly been taken from previous studies for the 1998 ITER design [1]. Maximum energy densities of 60 and 50 MJ/m^2 on the FW are considered for the VDE and RE analyses, respectively. Typical durations of 0.1 and 0.3 s have been considered for the VDE; only 0.3 s has been analyzed for the RE event.

During the VDE all the energy is deposited on the FW as surface heating. Therefore, heat fluxes of 200 and

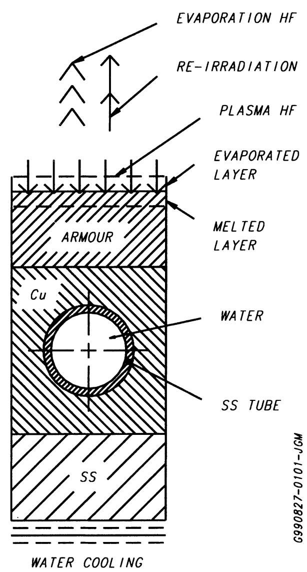

Fig. 1. Analysis model.

600 MW/m^2, constant in time, have been applied when the durations are 0.3 and 0.1 s, respectively.

During the RE event the energy is instead deposited as peaked volumetric heating, due to the deep penetration of the high energetic electrons. Carbon has not been included in the RE analyses. The following volumetric heating distribution through the armour thickness [1,9] has been applied for RE:

FW with Be armour

$$q''(\mathrm{Be}) = 7.05 \times 10^{10} \exp(-x_{\mathrm{Be}}/0.00217). \quad (1)$$

$$q''(\mathrm{Cu}) = 9.6 \times 10^{9} \exp(-x_{\mathrm{Cu}}/0.00137). \quad (2)$$

FW with W armour

$$q'''(\mathrm{W}) = 3.63 \times 10^{11} \exp(-x_{\mathrm{W}}/0.00046), \quad (3)$$

$$q'''(\mathrm{Cu}) = 0, \quad (4)$$

where q''' is the volumetric heating in W/m^3 and x is the current depth of each layer in [m].

In order to compare the PDE effects on the different materials, common steady state conditions have been imposed before the onset of the event. Most of the analyses have been performed considering the steady state conditions of the primary FW with 0.5 MW/m^2 heat flux and the following volumetric heating (function of the FW thickness):

FW with Be armour

$$q'''(\mathrm{Be}) = 5.26 \times 10^{6}, \quad (5)$$

$$q'''(\mathrm{Cu/SS}) = 8.1 \times 10^{6} \exp(-x/0.19). \quad (6)$$

FW with W armour

$$q'''(\mathrm{W}) = 17.76 \times 10^{6}, \quad (7)$$

$$q'''(\mathrm{Cu/SS}) = 6.13 \times 10^{6} \exp(-x/0.17). \quad (8)$$

FW with C armour

$$q'''(\mathrm{C}) = 3.71 \times 10^{6}, \quad (9)$$

$$q'''(\mathrm{Cu/SS}) = 7.97 \times 10^{6} \exp(-x/0.08). \quad (10)$$

One additional analysis for each material has been made (reference armour thickness 10 mm), considering a typical baffle FW geometry with a reduced SS tube thickness (0.5 mm) and a steady state heat flux of 2 MW/m^2, keeping the same volumetric heating.

3.3. Heat transfer to the coolant

For all the analysis the heat transfer to the coolant inside the tube has been taken as a function of the wetted wall temperature. As in [4], the model takes into account the effect of subcooled boiling and the occurrence of local critical heat flux (by zeroing the heat transfer at the corresponding wall temperature, ~284°C). The correlations used can be found in [4]. The heat transfer at the back of the shield SS plate has been considered 1.6 kW/m^2/K and the bulk water temperature 150°C.

3.4. Analytical results

All the analyzed cases and the main results are summarized in Tables 1–3. In the analyzed parameter range and consistent with the findings from [4] and [5], the results show that

- For all the materials the melted and evaporated thicknesses do not increase much with the armour thickness. The Cu and SS temperature, and the heat flux to the coolant instead increase considerably when the armour is thinner.

Table 1
Results of the VDE analysis-primary FW conditions[a]

Run#	Armor Mat.	Armor thick (mm)	Event time (s)	Melted thick (μm)	Evapor thick (μm)	T_{max} Cu°C at time (s)	T_{max}SS°C at time (s)	HF_{max} to coolant (MW/m^2)
1	Be	5	0.3	700	535	519/0.85	434/1.25	3.47
2	Be	10	0.3	700	538	366/2.14	325/2.35	2.03
3	Be	30	0.3	760	555	245/8.60	229/9.05	0.89
4	Be	10	0.1	380	632	299/1.74	221/2.86	1.37
5	W	5	0.3	1150	099	1212/0.74	1026/1.25	6.90
6	W	10	0.3	1220	102	745/1.75	610/1.94	6.98
7	W	30	0.3	1220	104	364/7.33	327/7.75	2.05
8	W	10	0.1	763	277	569/1.55	479/1.74	4.28
9	C	5	0.3	–	380	1068/0.49	877/0.97	7.75
10	C	10	0.3	–	386	670/1.75/	609/2.14	8.14
11	C	30	0.3	–	393	364/5.12	326/5.46	2.04
12	C	10	0.1	–	709	506/1.05	428/1.37	3.37

[a] Steady State Heat Flux 0.5 MW/m^2, SS liner 1 mm Ø (Energy Density 60 MJ/m^2).

Table 2
Results of the VDE analysis–baffle conditions[a]

Run#	Armor Mat.	Armor thick (mm)	Event time (s)	Melted thick (μm)	Evapor thick (μm)	T_{max} Cu°C at time (s)	T_{max} SS°C at time (s)	HF_{max} to coolant (MW/m^2)
13	Be	10	0.3	810	576	407/1.94	345/2.14	3.38
14	W	10	0.3	1250	114	838/2.14	769/2.58	8.50
15	C	10	0.3	–	413	738/1.57	673/1.94	8.07

[a] Steady State Heat Flux 2.0 MW/m^2, SS liner 0.5 mm Ø, (Energy Density 60 MJ/m^2).

Table 3
Results of the RE analysis-Primary FW conditions[a]

Run#	Armor Mat.	Armor thick (mm)	Event time (s)	Melted thick (μm)	Evapor thick (μm)	T_{max} Cu°C at time (s)	T_{max}SS°C at time (s)	HF_{max} to coolant (MW/m^2)
16	B	10	0.3	2230	160	526/2.57	453/3.06	3.80
17	W	10	0.3	127	10	739/1.75	604/1.94	6.85

[a] Steady State Heat Flux 0.5 MW/m^2, SS liner 1 mm Ø (Energy Density 50 MJ/m^2).

- In VDEs, evaporation is more severe for Be (~0.5 mm) than W, but W has a larger melting thickness (~1.2 mm W/0.5 mm Be).
- The PDE erosion is less severe for C which is therefore able to resist >2 times number of events (in terms of evaporation erosion).
- The PDE effects on the wall structure are severe for W and C due to the high W and C temperature and stored energy. The Cu temperature is expected to be critical from the structural point of view for the 10 mm thick W and C armours and reaches melting for 5 mm. Thicker armours are therefore mandatory for these materials. In all analyzed cases with Be, the cooling structures and the armour/heat sink joint do not reach temperatures which threaten the structural integrity.
- Depending on the stability of the melted layer (i.e., if it is partially removed from the exposed surface by gas pressure and gravity) and on its original thickness, Be armour can withstand a few VDE or RE (5–10) at the same location but protects the heat sink structure from serious damage.
- For all materials when the event duration is decreased (0.1 s) the effects on the structural materials is less severe. More evaporation and less melting occurs and the total damage is lower. The effect on C is just an increase of the evaporated layer (cases 4, 8, 12).
- The higher thermal loads of the baffle (case with 2 MW/m^2) result in a slight increase of the damage. (cases 13–15).
- The RE effect on W melting is not much different from that of the VDE (slight increase of melted layer and Cu temperature) due to the shallow electron penetration. For Be instead the amount of melting and the maximum Cu temperature are considerably increased due to the deeper penetration. However the maximum Cu temperature can still be considered acceptable.

4. Evaluation of the experimental results

Two PDE experiments performed using the Judith electron beam in Jülich, have been analyzed. A small (12 l × 12 w × 5 t mm) sample plate in Be has been exposed to five heat shocks of 2250 MW/m^2, ~5.5 ms each, distributed in a surface of 16 mm^2 (total energy ~62 MJ/m^2). A similar plate in W has been exposed recently, respectively to 377 MW/m^2, in 51 mm^2, for 100 ms (total energy ~37.7 MJ/m^2). For W this value is the maximum incoming heat flux presently achievable in Judith and it is lower than that of Be due to higher electron reflection. An indirect measure of the incoming heat flux is made in Judith [6] by collecting the electrons entering the specimen and measuring the resulting electrical current.

Two-dimensional analyses have been carried out. The heat flux was distributed over an equivalent circular surface and an axi-symmetric model was used; this modelization gave the best results in two-dimensional simulations. A heat convection ($h = 500$ $W/m^2/K$, $T_{bulk} = 20°C$) has been applied at the bottom of the samples to simulate the heat transfer to its copper sample holder.

In Table 4 the experimental results are compared with those analytical. An excellent agreement is found for the W sample. For Be a good agreement is found in the evaporated layer thickness, a higher difference is instead found in the melted layer thickness. This can be explained by the fact that, due to facility requirements, the Be ex-

Table 4
Experimental and analytical results

Case	Melting layer (μm)	Crater depth (μm)
Be-Experim.	350–400	450–560
Be-Analytic.	155	550
W-Experim.	750	50
W-Analytic.	720	~50

perimental simulation was made performing short multi-shots at high power densities which caused multiple melting and re-solidifications. The re-solidified material had somewhat different properties (e.g., due to higher porosity), which influence the calculation results. Also higher melting is expected because of the larger movements of the melted pool (e.g., with respect to W) due to Marangoni flows [10]. The central profiles of the real and calculated (half) craters are shown in Figs. 2 and 3.

5. Conclusions

The effects of VDE and RE events on FW armour materials have been analyzed using a new analytical methodology, which is able to take into account the time evolution of the evaporation and melting layers in two-dimension and three-dimension as well as the subcooled boiling heat transfer to the coolant and the occurrence of local critical heat fluxes.

Given the parameters of the 1998 ITER design the method shows that beryllium can withstand the specified low number of hard PDEs (~10), taking into account:

- the statistical distribution of the event location on the plasma chamber surface,
- the additional mitigation effect derived by the erosion of protruding parts which could result in a larger surface sharing of the thermal load.

Worse damage may occur for Be as a consequence of an RE event (>2 mm melted layer). The RE load values may be conservatively high for Be since in JET no hard RE event occurred when Be was used. However in ITER the dominant RE process may be the result of an avalanche effect which is not important in present tokamaks. Therefore a definitive assessment is possible only with more precise data on the RE events (number and peak loads).

Carbon (in the form of CFC) is the most robust armour, being able to withstand twice the number of events of any other armour. However, due to its high evaporation rate, Be offers a better protection for the cooling structures than W and C, whose armour should be at least 10 mm to avoid serious damage to the metallic heat sink and the joint.

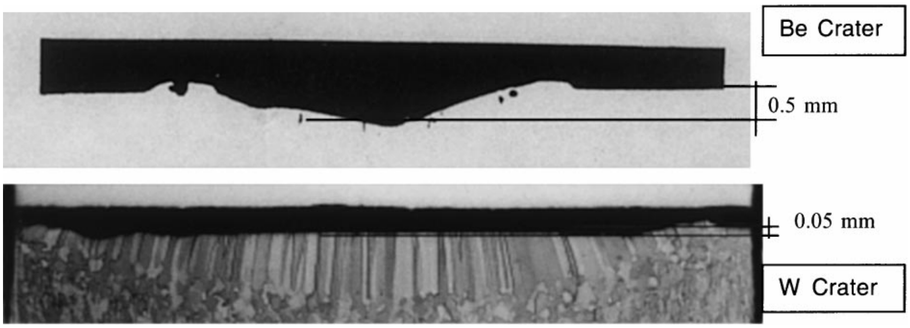

Fig. 2. Central profile of the craters obtained in the experiments.

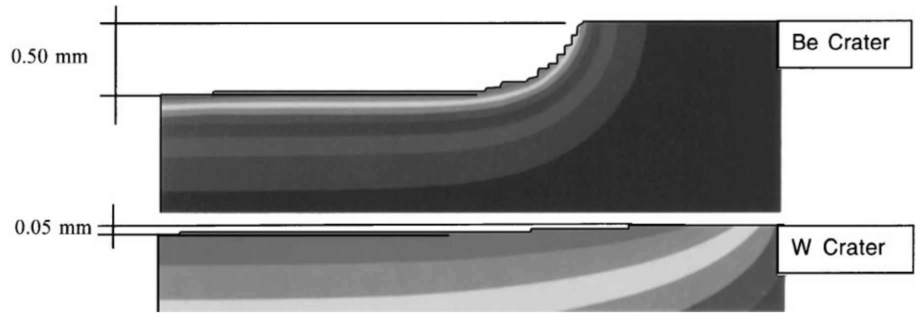

Fig. 3. Half profile of the crater obtained by analysis.

In analyzing PDE simulation experiments using an electron beam facility an excellent agreement has been obtained between the experimental and the analytical results for W samples. A good agreement has also been obtained in predicting the erosion layer thickness for Be, but higher differences were instead found for the melted layer, mainly due to the difficulties in modelling the more complex Be experiment.

Acknowledgements

We would like to acknowledge the precious support of Dr.s M. Rödig (FZ Jülich, G. Janeschitz (ITER) and H. Pacher (EFDA). This report was prepared as an account of work undertaken within the framework of the ITER EDA Agreement. The views and opinions expressed herein do not necessarily reflect those of the parties to the ITER Agreement, the IAEA or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER EDA Agreement.

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