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Lifetime analysis of the ITER first wall under steady-state and off-normal loads

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Abstract
The lifetime of the beryllium armor of the ITER first wall is evaluated for normal and off-normal operation. For the individual events considered, the lifetime spans between 930 and $35 \times 10^6$ discharges. The discrepancy between low and high estimates is caused by uncertainties about the behavior of the melt layer during off-normal events, variable plasma operation parameters and variability of the sputtering yields. These large uncertainties in beryllium armor loss estimates are a good example of the experimental nature of the ITER project and will not be truly resolved until ITER begins burning plasma operation.

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1. Introduction

The ITER first wall (FW) has undergone in-depth conceptual evolution, after the recommendation of the 2007 ITER design review [1]. Requirements for the handling of parallel heat loads from the plasma and credible maintainability have been included as strong design drivers of the FW panel design. To facilitate FW panel replacement, a single independent panel covers each shield block.

The panel has its own supporting structure, a beam oriented in the poloidal direction. The beam is embedded in the shield block and held by a deep bolt. Toroidally oriented plasma-facing units are attached to the beam (figure 1). The design lifetime was reduced down to 15,000 plasma discharges, and the FW is now classified as a component for which in-vessel maintenance is explicitly planned. The FW panels are shaped to avoid heavy heat loads in the case of panel-to-panel misalignment: the panel edges (all toroidal and some poloidal) are recessed from the magnetic surfaces by setbacks of 10–70 mm [2]. The FW shaping design is an issue of compromise, since the requirements for tolerance against steady-state and transient loads are contradictory. A shaped surface increases the heat loads that are due to plasma particles following field lines compared with a perfectly toroidal surface. Limited damage is acceptable during rare events, while steady-state heat loads must be maintained for long periods within what is conventionally allowable for beryllium-clad components (1–5 MW m⁻²).

Detailed blanket design activities are ongoing in parallel with supporting analyses to consolidate the approach adopted. They address electromechanical, thermal, thermo-hydraulic and structural aspects. Allowances and criteria come from the general ITER requirements, the blanket system requirement documents or the ITER structural design criteria for in-vessel components. Design cases are categorized according to their probability of occurrence (categories I–IV), and stress or temperature allowables depend on the event category. This is a well-established procedure for engineering activities in which the scattering of numbers by unaccounted phenomena or approximations is moderate. The accuracy of the analysis allows the design to be based on ‘worst-case assumptions’. The capability of the design to withstand the specified number of cycles for each of the events must be demonstrated.

FW panel lifetime is also related to erosion of the beryllium armor, to avoid the direct exposure of heat sink material (copper alloy) on plasma wetted areas. While a large beryllium thickness would allow a longer lifetime, it is bounded by the maximum allowable surface temperature during operation (660–800 °C depending on the surface area of the hot region). The current design’s beryllium thickness is...
8–10 mm. Plasma-wall interaction (PWI) causes material loss during operation, namely ‘normal’ erosion during steady-state phases of plasma discharges (e.g. physical sputtering), but transient, ‘off-normal’ plasma events can also drive significant evaporation and melting, with consequences for the lifetime that can be equivalent to or greater than the effect of steady-state loading. In general, the lifetime is determined by material loss. Having precise estimates of the FW armor material loss is at the boundary of current understanding and modeling ability. Earlier publications have already shown a large scatter in beryllium lifetime estimates [3, 4].

While this is not a regulatory requirement, it is still important to have quantitative evaluations of the beryllium armor lifetime in light of currently available knowledge.

The first (and major) part of this paper concentrates on the assessment of the consequences of off-normal events. Acknowledging that sophisticated methods do exist for treating the case of melt layer motion [5–7], the focus here will be on reviewing all damage events. Wall lifetime is evaluated in section 2. Section 3 briefly addresses the current status of attempts to evaluate the expected steady-state erosion.

2. Armor loss due to off-normal events

In ITER, most off-normal PWI events can lead to armor material loss: uncontrolled edge-localized modes (ELMs), disruptions (mitigated and unmitigated) associated with possible runaway electrons, vertical displacement events (VDEs) and loss of plasma control associated with H–L-mode transitions. In all cases, the ITER heat and nuclear load specification (HNLS) [8] describes the heat load (magnitude, distribution and duration), with emphasis on the worst case loads to be expected in burning plasma phases. The sub-sections below describe the method used to obtain projected heat loads on FW panels. The beryllium loss is evaluated using a simple melt layer and evaporation analysis. Finally, a more advanced analysis is presented in which the case of a VDE is used to illustrate how the full-time-dependent heat load to the wall can be calculated and used to obtain a more precise accounting of the actual material loss.

2.1. Surface energy density during off-normal events

The surface energy density on the panel is calculated using the technique adopted in [2] for the steady-state heat flux. It is briefly summarized here, illustrated for the case of a VDE thermal quench (TQ).

1. The radial profile of the energy density parallel to the total magnetic field, $q_\parallel$, is defined on the outboard midplane, as prescribed in the HNLS. For the unmitigated TQ illustrated here, $q_1 = 250 \text{ MJ m}^{-2}$, with an energy decay length of $\lambda_{q1} = 30 \text{ mm}$.

2. This parallel heat load profile is projected onto the real FW panel surface (in three-dimensional space), by following equilibrium magnetic flux surfaces. The projection accounts for the local incidence angle of the field lines to the FW panel surface and provides the real heat load that enters the surface. In what follows, this quantity will be referred to as the incident heat load.

3. Short-distance shadowing by immediate neighboring panels is calculated by magnetic field line tracing. The very short heat flux decay length between neighboring panels is neglected, so that no parallel heat load is applied in the shadowed area.

Figure 2 illustrates the computed energy density distribution on FW panel 17 (the lower outer wall) during a downward VDE. The wetted area takes the form of two large triangular-shaped regions with the panel edges mostly shadowed, except the upper edge. In this case, the peak surface energy density is $\sim 22 \text{ MJ m}^{-2}$, whereas most of the surface energy is in the range $10–20 \text{ MJ m}^{-2}$. For some events, large energy densities ($>30 \text{ MJ m}^{-2}$) can impinge on edges and sides faces (top and bottom, left- and right-facing faces). These regions receive a small heat flux by normal (steady-state) plasma operation and as such some damage can
be accepted provided there is no threat to panel integrity (no water leak).

The peak surface energy density on the ITER FW during the TQ of VDE is found to be between 14 and 30 MJ m\(^{-2}\). For subsequent VDE analyses, a mean VDE energy density of 22 MJ m\(^{-2}\) is retained. The maximum surface energy density corresponding to other events is given in the first column of table 1. It ranges from 1 to 120 MJ m\(^{-2}\). Runaway electrons disperse their energy in volume, so the above method for evaluating damage is not appropriate and is not investigated further here.

2.2. Off-normal events and associated lifetime

In the following section, material loss is evaluated for panels equipped with beryllium plasma-facing components (PFCs) capable of steady-state power handling up to 5 MW m\(^{-2}\). These panels have the highest ‘in-service’ surface temperature, which can be close to the maximum permitted value of 660 °C for the design heat flux of 5 MW m\(^{-2}\).

Beryllium material loss is found by calculating the evaporated and melt layer thicknesses, using moving boundary codes. Two such codes have been used, namely Raclette [4, 9] and a dataset making use of the free finite-element analysis code CAST3M (www.cast3m.cea.fr/cast3m/index.jsp). In the latter, evaporation is calculated using the beryllium flux expression defined in the Raclette publication. Both melt layer calculation schemes have been benchmarked against each other and good agreement has been found.

The calculation scheme assumes a layered system with 8 mm of beryllium bonded onto a 5 mm thick copper chromium zirconium heat sink. Cooling conditions are a water temperature of 140 °C, a velocity of 5 m s\(^{-1}\) and a pressure of 3 MPa. These thermo-hydraulic parameters give a heat transfer coefficient of 40 000 W m\(^{-2}\) K\(^{-1}\) between the heat sink and the cooling channel. However, they have a very small influence on the melt layer and evaporated thickness, since a few milliseconds events mainly affect the surface.

Unlike the case of major disruptions, when the off-normal loads are present for only a few ms at the TQ, VDEs show a longer time history and the heat loading calculations must account for the time interval before the TQ, during which hot plasma is in contact with the FW. Beginning with a steady-state power load density of 5 MW m\(^{-2}\) (applied from \(t = 0\) to 15 s in the simulation; figure 3), the full power plasma contact duration on the wall is typically 300 ms (from 15 to 15.3 s) with a power flux density equal to 40 MW m\(^{-2}\). At the TQ (occurring at 15.3 s), a surface energy density of 22 MJ m\(^{-2}\) is assumed, deposited over 1.5 ms. Assuming a square power profile, the heat flux density is 14 700 MW m\(^{-2}\) during the TQ.

The melt layer and evaporated thickness are represented by the ‘initial’ curves in figure 4. Surface melting begins at \(t = 15.1\) s, and the melt layer increases steadily until \(t = 15.3\) s (time of the TQ), where it reaches a thickness equal to 0.75 mm. The TQ itself adds a further 0.09 mm of melted layer. The unmitigated VDE results in a total melted layer of 0.86 mm thickness.

Evaporation is insignificant before the TQ. During the TQ, the total cumulated evaporated thickness is 0.42 mm. The allowable number of events to end of life for an 8 mm Be thickness ranges from 19 (only evaporated beryllium and none of the melt layer is lost) to 6 events (both the melt layer and evaporated material are lost). These two limiting cases (zero or complete melt layer loss) represent the upper and lower estimates (columns 11 and 12 in table 1) for the evaluation of beryllium lifetime.
Table 1. Heat load parameters of off-normal events and the associated material loss and lifetime. (The results obtained with Raclette and those obtained with CAST3M are indicated by a ‘#’ sign.)

<table>
<thead>
<tr>
<th>Event</th>
<th>Energy density (incident on PFC) (MJ m(^{-2}))</th>
<th>Duration (ms)</th>
<th>Heat flux density (incident on PFC) (MW m(^{-2}))</th>
<th>No. of events</th>
<th>Max. Be temp. ((^\circ)C)</th>
<th>Max. Be/Cu temp. ((^\circ)C)</th>
<th>Max. Be melt layer thickness (mm)</th>
<th>Max. Be evap. thickness (mm)</th>
<th>Allowed no. of events at a given loc. based on melt + evap.</th>
<th>Allowed no. of events at a given loc. based on evap. only</th>
<th>Lifetime (lower estimate)</th>
<th>Lifetime (higher estimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled ELMs</td>
<td>2</td>
<td>0.375</td>
<td>10000</td>
<td>0</td>
<td>2724(^*)</td>
<td>317(^*)</td>
<td>0.22(^*)</td>
<td>0.25(^*)</td>
<td>17(^*)</td>
<td>32(^*)</td>
<td>Beyond the design basis</td>
<td></td>
</tr>
<tr>
<td>Disruptions (DMS success)</td>
<td>1</td>
<td>3.</td>
<td>333</td>
<td>1350</td>
<td>1559</td>
<td>363</td>
<td>0.01</td>
<td>4.5 \times 10(^{-5})</td>
<td>796</td>
<td>1.77 \times 10(^6)</td>
<td>8849</td>
<td>1.9 \times 10(^6)</td>
</tr>
<tr>
<td>Disruptions (DMS success)</td>
<td>1</td>
<td>9.</td>
<td>111</td>
<td>1350</td>
<td>1276</td>
<td>363</td>
<td>0</td>
<td>2.5 \times 10(^{-6})</td>
<td>3.2 \times 10(^6)</td>
<td>3.2 \times 10(^6)</td>
<td>35 \times 10(^6)</td>
<td>35 \times 10(^6)</td>
</tr>
<tr>
<td>Disruptions (DMS failure)</td>
<td>10</td>
<td>3.</td>
<td>3333</td>
<td>150</td>
<td>3000</td>
<td>374</td>
<td>0.8</td>
<td>0.06</td>
<td>9</td>
<td>133</td>
<td>930</td>
<td>13333</td>
</tr>
<tr>
<td>Disruptions (DMS failure)</td>
<td>10</td>
<td>9.</td>
<td>1111</td>
<td>150</td>
<td>2398</td>
<td>370</td>
<td>0.7</td>
<td>0.07</td>
<td>10</td>
<td>114</td>
<td>1039</td>
<td>11429</td>
</tr>
<tr>
<td>VDE (DMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Loss of control</td>
<td>2.2</td>
<td>0.5</td>
<td>300</td>
<td>40</td>
<td>135</td>
<td>2300(^*)</td>
<td>379(^*)</td>
<td>0.81(^*)</td>
<td>0.038</td>
<td>9(^*)</td>
<td>210(^*)</td>
<td>1048(^*)</td>
</tr>
<tr>
<td>2. Quench</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>VDE (no DMS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Loss of control</td>
<td>22</td>
<td>1.5</td>
<td>300</td>
<td>40</td>
<td>15</td>
<td>2832(^*)</td>
<td>381(^*)</td>
<td>0.86(^*)</td>
<td>0.42(^*)</td>
<td>6(^*)</td>
<td>19(^*)</td>
<td>6250(^*)</td>
</tr>
<tr>
<td>2. Loss of control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(H–L-mode transition)</td>
<td>120</td>
<td>3000</td>
<td>40</td>
<td>0</td>
<td>1746</td>
<td>519</td>
<td>0.4</td>
<td>0.8</td>
<td>7</td>
<td>11</td>
<td>Beyond the design basis</td>
<td></td>
</tr>
</tbody>
</table>
The design number of unmitigated VDEs is 15, originating from an expected number of 150 full-power VDE events (HNLS) assumed to occur in the first-half of ITER operation and adopting a 90% success rate of the ITER disruption mitigation system (DMS), currently undergoing conceptual design. Assuming a constant occurrence probability of unmitigated VDEs, this lifetime translates to between 6250 and 19 048 full power discharges.

For the 135 mitigated VDEs (90% of 150), the TQ heat load is assumed to be reduced by a factor of 10. The allowed number of events in this case spans from 9 to 210. The lifetime varies from 1048 to 23 392 full power plasma discharges.

A similar analysis has been performed for all the main off-normal events (table 1). For example, uncontrolled type-I ELMs in the reference main off-normal events (table 2) varies from 1048 to 23 392 full power plasma discharges. The number of events in this case spans from 9 to 210. The lifetime varies from 1048 to 23 392 full power plasma discharges.

Major disruptions are associated with incident energy densities at the TQ of 10 MJ m$^{-2}$, deposited over a time interval of 3–9 ms. Just as in the VDE case, the initial incident power flux density is assumed to be 5 MW m$^{-2}$. A TQ of 3 ms duration corresponds to an incident power load of 3333 MW m$^{-2}$ assuming a constant power flux. A thickness of beryllium of 0.06 mm is evaporated and the melt layer depth is 0.8 mm, equivalent to a lifetime between 9 and 133 events applying the same limiting cases as above. For the 9 ms disruption, similar results are obtained, with the number of allowable events ranging from 10 to 114. Again, however, it is important to note that although the ITER FW is to be designed for 1500 major disruptions at full power, the DMS must achieve 90% success rate, so that the number of unmitigated disruptions is 150. The calculated lifetime ranges from 930 to 13 333 discharges.

Similarly to the VDE case, the DMS must ensure that TQ energy loads of major disruptions are reduced by an order of magnitude. It is in fact the FW lifetime (together with that of the divertor targets and the electromagnetic forces on the vacuum vessel) that set the criteria that must be achieved by the ITER DMS.

The number of possible mitigated disruptions varies from 796 to $3.2 \times 10^9$ (corresponding to a lifetime range of 8849 discharges to 35 $\times 10^9$ discharges) according to the limiting criteria based on material loss. The evaluated lifetime spans five orders of magnitude, demonstrating the current lack of ability of modeling to achieve more concrete predictions.

Uncontrolled transitions from H-mode to L-mode confinement on ITER represent a serious threat to the FW integrity. During such an event, the full-energy plasma makes a large excursion toward the inner wall and may remain in contact for several seconds (consideration of poloidal field coil capability indicates 3 s). The incident heat load is 40 MW m$^{-2}$. In this case, modeling indicates melt and evaporated layer thicknesses of 0.8 and 0.4 mm, respectively. In fact, these numbers are relatively meaningless in the sense that critical heat flux is attained under these energy loads at $t \sim 1$ s in the cooling channels of the beryllium tiles affected, implying a high probability of loss of water containment and mandatory replacement of the affected panel(s). Such events must be avoided by the plasma control system, possibly by triggering DMS before the panel is damaged. The FW lifetime will depend on the performance of the DMS system.

2.3. Refined analysis based on the true time profile of the heat load

For the unmitigated VDE described above, the surface energy density during the phase of the VDE where the plasma separatrix contacts the wall is 12 MJ m$^{-2}$. At the TQ, it is 22 MJ m$^{-2}$ (see figure 2). The total is then 34 MJ m$^{-2}$, and the full energy is assumed to be deposited in the same location, in an area previously loaded to the full power flux density design level of 5 MW m$^{-2}$. This assumption is conservative because the plasma moves along the wall during the instability. The peak heat load also moves, so that the surface energy density at the TQ does not occur at the same location as that at which the plasma first contacts the wall in limiter configuration (figure 5).

A dynamic analysis has been performed using a series of 34 equilibria from a simulation of a full-power VDE event in ITER covering a time interval of 831.1 ms. The time steps vary over the modeling interval 0.5–50 ms. Three snapshots are given in figure 6, showing how the peak heated area moves from FW panels on blanket module 11 to those on module 10, its poloidal neighbor. The TQ itself occurs at $t = 831.1$ s when the last closed flux surface is in contact with module 10.

The real heat flux distribution as a function of time is shown in figure 7 for the two most loaded points (P10, P11) on the panels of modules 10 and 11. The square symbol gives the surface energy density at the TQ. By integration of the power flux over the duration of the plasma contact, it is calculated that P11 receives 11.7 MJ m$^{-2}$ before the TQ and 14.4 MJ m$^{-2}$ at the TQ. Point P10 is loaded by 5.2 MJ m$^{-2}$
before the TQ and 20.8 MJ m$^{-2}$ at the TQ. The curves in figure 7 demonstrate that the point receiving the highest heat load before the TQ (point 11) is only moderately loaded at the TQ itself, while the situation is reversed for point 10.

As in the previous section, melt layer and evaporated thicknesses are calculated using the real, time-dependent heat load. The time traces are given in figure 4 (traces with P10 and P11 labels). For the two points identified in figure 7, the melt and evaporated thicknesses are, respectively, 0.716 and 0.264 mm (point 11) and 0.424 and 0.374 mm (point 10). The lifetime is now 8163–30 303 discharges, meaning an improvement of 30–60% of the lifetime compared to the initial assumption of section 2.2. Although this is an improvement compared with the simple superposition of VDE + TQ heat loads, it does not fundamentally change the wall lifetime.

Such detailed analyses are severely time-intensive (50 h computer time). It is not planned to pursue a systematic investigation of this topic, in view of the small improvement achieved.

3. Armor loss during normal operation

Beryllium armor loss during normal operation is associated with net erosion of beryllium surfaces by plasma particles during steady-state phases. To estimate the erosion, a local ‘limiter-like’ situation on shaped outer wall blanket modules was first simulated using appropriate mirrors and absorbers in the simulation domain to approximate particle losses toward the upper or lower divertors and to remote main chamber locations. A full account of this work can be found in [10, 11]. The net peak erosion expected during the $Q_{DT} = 10$ reference plasma scenario ranges from $2.5 \times 10^{-3}$ to 0.06 mm h$^{-1}$ Be (accounting for uncertainties in the ITER plasma loads—the highest and the lowest density conditions—and Be sputtering yields). The corresponding beryllium lifetime is evaluated to be between 1500 and 36 000 full performance discharges. This analysis has been performed for the baseline H-mode plasma magnetic equilibrium, for which the separation between the first and the second separatrices is $\Delta R_{sep} \sim 10$ cm at the outboard midplane. For configurations with lower $\Delta R_{sep}$, the erosion rate can be even higher. In addition, because the interactions will be more intense near the second X-point region, the results mentioned in this study are expected to represent a lower limit to the erosion prediction that will result from the more complex divertor-like situation at the top of the machine (a more accurate assessment of the PWIs occurring in the secondary divertor region is currently in progress). What is of interest is that in a very approximate sense, both the steady-state and transient erosion analyses yield similar ranges of discharges before the end of life is reached on some FW panels.

4. Discussion and conclusion

The ITER FW design must be such that an adequate lifetime is ensured in the face of both steady-state and transient heat loadings throughout the expected experimental program life of the FW panels. For a lifetime of about 10 years, corresponding to half of the currently planned ITER burning plasma operation lifetime, the FW design is such that the panel lifetime is roughly consistent with the range of erosion/damage due to the expected thermal loading (both transient and steady state).

The upper ends of the estimated ranges provide some margin, while for the worst-case assumptions, the design falls short of the requirements. The picture given here is incomplete, because possible superposition of events has not yet been considered. For example, it is likely that some superposition of damage caused by VDE and normal operation will occur on the outboard blanket rows 10–11 and 17–18, possibly further reducing the lifetime. On the other hand, other assumptions are quite conservative. For example, assuming the peak design steady power loading of 5 MW m$^{-2}$ in combination with transient loads is a severe ‘worst-case assumption’. In general, the actual steady-state operation heat load will be some fraction of the peak. Off-normal heat pulses incident on cooler surfaces will yield thinner melt layers and hence a longer lifetime. Moreover, the analysis presented here assumes full power discharges from day one, while in reality, many plasma discharges will be performed at a lower plasma energy. In addition, it has been assumed that all off-normal events of a given type occur at the same location, while in reality, events will to some extent be scattered over the wall.
surface, thus avoiding full superposition. In view of these strong pessimistic assumptions, actual plasma operation is going to bring some relief. The reality of plasma operations, when they begin, is that the real loading distribution, in terms of the numbers of events, severity and distribution on the FW, is likely to be somewhat less pessimistic than assumed here from the pure point of view of the engineering design specification. The large uncertainties that currently characterize the ITER beryllium FW armor loss estimates are a good example of the experimental nature of the ITER project and will not be fully resolved until ITER begins burning plasma operation.

References