FIRST WALL AND LIMITER LIFETIME IN PULSED TOKAMAK REACTORS

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December 1983

*Work supported by the U.S. Department of Energy.
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Introduction

Twenty per cent of the fusion power in a deuterium-tritium reactor is deposited on the surfaces of steady-state plasma and the front or divertor of the limiter during normal operation. Thus thermal fatigue is expected to play an important role in these structures for any burn cycle with a large number of pulses. In addition, surface erosion is anticipated due to both continuous sputtering and occasional large thermal dumps during plasma disruptions. Another life limit is imposed by neutron damage to these structures. The goal of this study is to identify the burn cycle conditions which maximize component lifetime, considering all these constraints simultaneously. The capital cost for the first wall/limiter system is not large compared to the overall power plant, however, the impact on reactor operations is tremendous if these structures require frequent replacement. Long periods for reactor maintenance appear uneconomical for an electric utility, and we thus feel there is a strong motivation for achieving lifetimes of many years for these components.

The damage to surfaces exposed to plasma disruptions is calculated in the first section. This data serves as input to the lifetime analysis which follows. In the next section the limiter is studied. The temperature profiles through the limiter are calculated for various conditions, and then a stress analysis is done to assess fatigue damage. The lifetime analysis of the limiter identifies the optimum thickness for surface coatings to maximize lifetime against disruptions, fatigue, radiation damage, etc. Finally, the fatigue life of bare first wall coolant tubes is studied. Again an analysis is done to find the optimum tube thickness for maximum first wall life. Our results are then related to the burn cycle parameters in order to indicate the length needed for a fusion burn in order to approach the benefits of purely steady-state operation. Full details of this study, including an extensive performance data base, are available as Ref. 1.

1. Disruptions

Disruptions can limit the lifetime of the limiter, divertor, and first wall. The surfaces of these components are subject to melting and vaporization resulting from the deposition of plasma energy in a relatively short time [2]. The primary disruption parameters are the energy deposition per unit area, the disruption time, and the frequency of disruptions. The reference disruption time is assumed to be 100 ms, and the range of energy densities vary as to whether first wall, leading edge, or the front face of the limiter is considered. Extrapolating to a full size reactor from INTOR [3], the maximum energy density deposited on the first wall is expected to be 800 J/cm², and for the limiter the maximum is 4500 J/cm². Two materials are investigated as potential first wall candidates, i.e. stainless steel and vanadium. For the limiter two coating materials are considered: beryllium and tungsten. The thermal response and the resulting vaporization losses and melt layer thickness are computed with the A*THERMAL computer code [4]. The code solves the heat conduction equation with temperature varying thermal properties and uses the surface temperature to compute the evaporation rate. No vapor shielding was accounted for in this analysis [5].

Figure 1 shows the total material erosion as a function of disruption energy density for 100 ms disruption time (reference case), for both first wall and limiter materials. Vanadium as a first wall material results in much less erosion than stainless steel. At these energies the main material erosion is from melting. For limiter materials, beryllium shows much higher erosion than tungsten. The threshold energy density to induce melting in beryllium is near 350 J/cm², while for tungsten it is about five times higher. This is mainly because of the very high melting point of tungsten.

![Figure 1. Disruption damage.](image-url)
magnetic field and is analyzed as a slab. Normal heating and disruptive loads are assumed to be twice as large on the front face as on the leading edge. However, the cylindrical geometry of the leading edge aggravates the heat removal problem as the surface coating becomes thicker. The constraints on the heat sink and surface coatings (tiles) also depend on these differences in geometry. Here we compute temperature profiles in the first subsection, and this is followed by a fatigue analysis.

2.1 Limiter Temperature Profiles

The objective of the thermal-hydraulics analysis is to provide temperature distribution in the coating and structural materials of the limiter. These temperature distributions will be used as input for stress analysis, and will also be used to determine if the temperatures are within the acceptance levels. One-dimensional steady-state analyses are carried out for both the front surface and the leading edge of the limiter.

Figure 2 shows the results at the leading edge with water as coolant and beryllium/copper as coating/structure materials. It was observed that both maximum coating and structural temperatures increase with coating thickness. The increase in structural temperature with coating thickness at the leading edge is the result of reduction in heat transfer area radially towards the coolant channel. Additional results were obtained with tungsten coating on a water-cooled copper leading edge; and both beryllium and tungsten coating on a vanadium heat sink cooled with liquid lithium. Likewise, temperature profiles were computed for the front face with beryllium coating on either water-cooled copper or lithium-cooled vanadium. (High sputtering rates may prevent the use of tungsten coating on the front face.)

![Fig. 2. Heat sink temperature in the limiter's leading edge.](image)

2.2 Thermal Fatigue of the Limiter

A possible life limiting mode for the limiter is fatigue crack initiation. This section will consider the cyclic design life based on fatigue of the limiter for the two structural materials (copper and vanadium alloys) and two coating materials (beryllium and tungsten). Typical fatigue properties of the various structural alloys are given in Ref. 1. For the purposes of design, a safety factor of two on strain range or 20 on life (whichever gives smaller life) is applied on the fatigue curves.

The idealized cylindrical leading edge geometry is used for stress analysis. Figure 3 shows the fatigue life of copper as a function of the coating thickness and surface heat flux. In general, the fatigue life decreases with increasing coating thickness and increasing surface heat flux. Beryllium-coated copper has longer life than tungsten-coated copper. For small coating thicknesses (<1 cm), the use of a stronger copper alloy (e.g., AMAX-MZC) instead of pure annealed copper can increase the design fatigue life significantly. For the alternative heat sink alloy (V-15Cr-5Ti), we find, in general, the fatigue life of vanadium is much greater than for copper. However, in the case of vanadium the fatigue life decreases more rapidly with increasing thickness than in the case of copper. Except for small coating thicknesses (<2 mm), beryllium-coated vanadium has longer fatigue life than tungsten-coated vanadium.

![Fig. 3. Leading edge cycle life vs. fatigue and disruption erosion.](image)

The top surface of the limiter is analyzed as a flat plate constrained to deform with the cooler back part of the limiter. The fatigue life of both copper and vanadium heat sinks, as functions of the coating thickness and surface heat flux was calculated. Despite higher surface heating loading, the design life of the top surface is comparable to that of the leading edge. See Ref. 1 for additional data curves.

3. Thermal Fatigue of First Wall

For the purpose of this study, the first wall has been modeled as infinitely long annular cylinders (tubes, ducts) of circular cross section [6]. Since the provision of margin against erosion will require a wall thickness which is greater than the needed minimum to contain the internal pressure, significant thermal stresses due to thermal gradient through the wall will
be generated during steady-state operation. The cyclic nature of these thermal stresses in a pulsed reactor can potentially limit the useful design life of the first wall because of fatigue. Both PCA (25% Cr 316 stainless steel) and V-15Cr-5T1 have been considered in this study as potential structural materials for the case of water-cooled and lithium-cooled reactors, respectively. The design fatigue curves for 316 stainless steel and the vanadium alloy are given in Ref. 1.

Figure 4 shows the plot of wall thickness versus cyclic life-time for various thermal wall loads on a tube of 316 stainless steel with an inner radius of 3 mm. Also shown in this figure (by open circles) are the maximum thicknesses corresponding to a maximum allowable metal temperature of 600°C. The fatigue curves and the maximum temperature limit give upper bounds to the wall thickness for a given surface heat flux. A lower bound for the wall thickness is set by the primary stress criterion, \( P_{cr} \leq S_{cr} \). The figure shows minimum thickness corresponding to a time-dependent stress limit \( S_{cr} \) corresponding to a maximum radiation-induced creep strain of 5%. Since radiation-induced creep is considered nondamaging, a 5% creep strain limit may be reasonable. The difference between the lower bound and the upper bound for thickness may be considered as the margin against erosion.

![Fig. 4. First wall cyclic life vs. fatigue and disruption erosion.](image)

Similar plots were made for the case of V-15Cr-5T1 with a tube of radius 25 cm. In contrast to the case of 316 stainless steel, the maximum metal temperature limit of 600°C sets an upper bound for the wall thickness for fatigue life of up to 10^6 cycles. We also note that because of the superior thermal properties vanadium tubes can have significantly larger wall thickness than 316 stainless steel tubes.

4. Lifetime Analysis and Burn Goals

We begin by considering the limiter’s leading edge, and we first consider the copper heat sink with water coolant and a beryllium coating. Reference to Fig. 3 shows an upper limit to the coating thickness \( \delta_{Be} \) if we restrict the substrate to 250°C (the onset for thermal creep, swelling): \( \delta_{Be} \leq 18 \text{ mm at a surface heat load } W_{Be} = 0.75 \text{ MW/m}^2 \text{ and } \delta_{Be} \leq 7 \text{ mm at } W_{Be} = 1.75 \text{ MW/m}^2 \). As the figure shows, fatigue life increases with thinner coatings. However, thinner coatings are more easily eroded by repeated disruptions. From Fig. 1 we might expect up to 539 \text{ mm of beryllium removal per disruption} near the upper limits of leading edge thermal loads (-1200 J/cm²). Hence the beryllium can be removed in the worst case after a number of cycles \( N = 6_{Be}[f \times 0.54 \text{ mm}]^{-1} \), where \( f \) is the average frequency (probability) of disruptions per burn cycle. Figure 3 displays \( N \) versus \( \delta_{Be} \) for \( f = 10^{-3} \) (one disruption per thousand burn cycles) and two different coating removal rates. The optimum coating thickness is the intersection of fatigue and disruption curves. For example, for high leading edge heating, 1.75 MW/m², and mild disruption damage, 140 \text{ mm lost per disruption, the maximum lifetime is to be expected for } \delta_{Be} = 3.6 \text{ mm, which results in a survival time of } N = 2.7 \times 10^4 \text{ burn cycles.}

Finally we fold into our analysis the radiation life limit for the heat sink. Our philosophy will be that the fusion burn length, \( t_f \), should be long enough that the cycle life, \( N \), is at least as long as the radiation life, \( L_{rad} \). Thus, we compute the minimum, \( t_f = \left( 0.8 \times L_{rad} \times N^{-1} \right) - t_{off} \). As an illustration, the copper heat sink is believed to have poor radiation resistance, and one might expect to require its replacement every \( L_{rad} = 2 \text{ yr} \). Then, at 80% availability, a fusion period \( t_f = 1.8 \times 10^{-3} \text{ s} \) would be needed in order for a cyclic lifetime \( N = 2.7 \times 10^4 \) to equal the radiation lifetime. Figure 5 shows these burn goals for the beryllium/copper leading edge under different conditions. In the case of severe disruption damage there is a strong motivation to achieve \( t_f \geq 2 \text{ h at } W_{Be} = 2.0 \text{ MW/m}^2 \). The motivation for long burns diminishes for more mild disruptions. In fact, according to Fig. 1, disruptions do not damage at thermal loads <300 J/cm², so very thin coatings with negligible fatigue could be selected in this limit. The first lesson we have learned is that \( t_f = 1 \text{ h} \) may be adequately long to eliminate fatigue as a life-limiting consideration if the limiter leading edge has a heat sink with poor radiation resistance. This set of circumstances might typify a near-term tokamak constructed with conventional technology (water-cooled copper heat sink).

![Fig. 5. Fusion burn length goals to equate fatigue, disruption, and radiation life of limiter's leading edge.](image)
superior fatigue resistance of vanadium results in a much longer cyclic life than the copper heat sink. For moderate damage rates, disruptions are the life-limiting concern, so $\delta_{\text{Be}}$ should be maximized to the temperature limit. The corresponding number of burn cycles can again be converted to a burn length such that the cycle lifetime at least equals the radiation lifetime. For vanadium, however, radiation resistance is believed to be much better than for copper -- we take $L_{\text{rad}} = (24 \text{ MW-yr/m}^2)/W_n$, and, for the sake of illustration, we assume a neutron wall load $W_n = (8/3) W_{\text{Be}}$. The results are shown in Fig. 5. Compared to a copper heat sink there is strong motivation to achieve longer burns for severe disruptions burn times approaching 3 h are desired. These slightly longer burns are needed in order to achieve the full potential radiation life of the limiter, in the six- to twelve-year range.

In the desirable situation where disruptions can be completely eliminated from tokamak reactors we must consider sputtering as an erosion mechanism. We assume that net erosion can be controlled, and for the sake of illustration, we examine burn cycle implications for $\delta_{\text{Be}} = 1 \text{ cm/yr}$. Since sputtering life is so short, radiation damage does not concern us in this limit. The beryllium coating is increased to the temperature limit to maximize life against erosion, and the minimum acceptable burn length is calculated such that the cyclic lifetime was equal to the radiation lifetime. However, the one- to two-year burn cycles is found. For the copper heat sink $N$ is now larger, so a shorter $t_f$ ($\approx 100 \text{ s}$) is permissible.

Tungsten has also been proposed as a limiter coating at the leading edge. If the plasma temperature exceeds $500 \text{ eV}$ at the leading edge the high net sputtering of tungsten will preclude its use. However, at low temperatures this appears to be an ideal coating. Sputtering is then low and redeposition is very effective due to the short mean free path of tungsten ions. In addition, disruptions do little damage to a tungsten coating since, at the leading edge, the thermal load is likely to be less than the threshold for melting and vaporization; see Fig. 1. Hence, at such low temperatures erosion may not be significant for tungsten coatings. A thin tungsten cladding, $\delta_{\text{W}}$, shows very large cycle lifetimes for either copper or internal radius. For the vanadium substrate $N$ is now larger, so a shorter $t_f$ ($\approx 10 \text{ s}$) is permissible.

An identical lifetime analysis was done for the front face of the limiter. The beryllium coating was assumed to be removed at 600 $\mu\text{m}$ and 170 $\mu\text{m}$ per disruption, representing the worst case and more typical disruption damage ($2500 \text{ J/cm}^2$ and $500 \text{ J/cm}^2$, respectively). The optimum $\delta_{\text{Be}}$ was inferred for a disruption probability $f = 10^{-3}$ to obtain the maximum cycle lifetime, and the minimum fusion burn, $t_f$, was calculated such that the cyclic lifetime was equal to the radiation lifetime of the heat sink (24 $\text{ MW-yr/m}^2$ for vanadium and 4 $\text{ MW-yr/m}^2$ for copper). The results are displayed in Fig. 6. Our first observation is that $t_f > 45 \text{ min}$ is adequate for the front face with a copper heat sink, even with the worst disruption damage. However, the one- to two-year radiation life of copper is so short that there will be great incentive to consider materials such as vanadium. Then we find, in order to achieve the six-fold increase in limiter life, the burn length must be extended, so as not to aggravate the fatigue problem. For moderate disruptions we need $t_f \approx 1\text{-}1.5 \text{ h}$. Of course, if the frequency of disruptions were $f < 10^{-3}$ then thinner beryllia coatings, with resulting longer fatigue life for the substrate, would be appropriate. In the extreme where sputtering erosion limits the lifetime to 1 to 2 yr the burn length would need to be only 15–30 min in order to eliminate thermal fatigue as a concern with a vanadium substrate.

We next analyze the first wall lifetime, starting with the bare PCA water-cooled tubes. In Fig. 4 we display the cycle lifetime against disruptions for $f = 10^{-3}$ and $10^{-5}$, assuming modest thermal energies in the disruption (380 J/cm$^2$ removing 70 $\mu\text{m}$ of PCA). The tubing is assumed to fail once disruptions thin the wall to $\delta_{\text{PCA}} = 6 \mu\text{m}$. For neutron-induced damage we might permit 5% creep. Thus, for 70 $\mu\text{m}$ loss per disruption we find a disruption-controlled cycle lifetime of $N = (\delta_{\text{PCA}} - \delta_{\text{min}})/(f \cdot 0.07 \text{ mm})^{-1}$. As with the limiter we select the intersection of the fatigue and disruption curves to find the $\delta_{\text{PCA}}$ which yields the maximum cycle life, $N$. Next we compute the fusion burn period needed for the cycle lifetime to equal the radiation life, which we take to be $L_{\text{rad}} = (12 \text{ MW-yr/m}^2)/W_n$ with $W_n = 4 \times W_{\text{Be}}$. The results, shown in Fig. 7, indicate that relatively short burns, $t_f \geq 40 \text{ min}$, suffice to eliminate the cycling factor from concern when there are infrequent or mild disruptions.

It is conceivable that the disruption damage could be more troublesome, however. Merely increasing the energy deposition from 380 J/cm$^2$ to 700 J/cm$^2$ multiplies the melting and vaporization loss by a factor of six for PCA (see Fig. 1). This motivates a design goal for much longer fusion burns; as shown in Fig. 7, $t_f \geq 4 \text{ h}$ is needed to realize the full radiation life potential in this case.

Finally, we consider the burn goals needed to achieve the full benefits of radiation resistant structure such as vanadium. In this exercise we calculate burn lengths needed for an assumed lifetime of 24 $\text{ MW-yr/m}^2$. The 600°C creep limit on vanadium constrains $\delta_{\text{v}}$ to $\leq 10 \mu\text{m}$, and we find disruption erosion dominates fatigue as a consideration. Our results, displayed in Fig. 7, show that $t_f$ will be at least as
Fig. 7. Fusion burn goals to equate cyclic 
and radiation life of first wall.

long as required for the PCA first wall in order to 
achieve twice the in-reactor lifetime (6-12 yr versus 
3-6 yr). In the pessimistic disruption scenario 
depicted we find $t_f \approx 8$ h is desirable at high wall 
loads.

We conclude with some general observations. 
Our results typically show that "near-term" structures 
such as copper limiters and a steel first wall can 
tolerate relatively short fusion burns because their 
radiation life is thought to be short. In order to 
take full advantage of advanced materials, such as 
vanadium, with longer radiation life it will be neces-
sary to arrange for longer burns. This will be possi-
ble, for example, with noninductive current drive or 
with very large major radius reactors with high volt-
second ohmic transformers. On the other hand, reactors 
with short burns ($t_f \approx 100$ s), operating in the internal 
transformer mode [1], will not be attractive unless 
disruption frequency is $f \leq 10^{-5}$ and sputtering erosion 
is $\epsilon \leq 1$ cm/yr.

Generally speaking the higher wall and limi-
ter thermal loads are more demanding on our designs. 
In the first place this is because we have assumed 
the higher thermal loads are associated with higher neutron 
damage and therefore shorter in-reactor life. In the 
second place these higher thermal loads exacerbate the 
fatigue problem and generally require longer burns in 
order to not surpass the limit on cycle lifetime.

Finally, we repeat that our results only dis-
play general trends. Reactor availability should 
improve with several factors: use of more radiation 
and fatigue resistant materials; reduction in the fre-
quency and severity of disruptions; reduction in net 
sputtering erosion; selection of disruption resistant 
materials (e.g. tungsten, if low plasma temperatures 
can be obtained); operation at lower wall loads; and 
operation with longer fusion burns. At this point it 
is not possible to specify a unique goal for the burn 
length since it depends on a variety of operating char-
acteristics, as we have shown.

*Work supported by U.S. Department of Energy.
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