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FIRST WALL AND LIMITER LIFETIME IN PULSED TOKAMAK REACTORS*

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FIRST WALL AND LIMITER LIFETIME IN PULSED TOKAMAK REACTORS[*]

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This study concentrates on the structural integrity of certain reactor subsystems under cyclic operation to answer the question: "How long a burn pulse is needed to achieve the benefits of steady-state operation?" Component lifetime in the steady-state is limited by three effects: radiation damage, disruptions, and sputtering erosion. Cyclic operation modifies one of these (the number of disruptions may increase with the number of burn cycles) and introduces a fourth life limit, thermal fatigue. Our design strategy is to determine the structure and coating thicknesses which maximize component lifetime against all life limitations. After calculating disruption damage (vaporization, melting) for candidate materials we present the lifetime analysis for different structures.

Introduction

Twenty per cent of the fusion power in a deuterium-tritium reactor is deposited on the surfaces of the first wall and the limiter or divertor neutralizer plates 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 to 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 thermal 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/cm^2, and for the limiter the maximum is ~2500 J/cm^2. 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 has been 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/cm^2 while for tungsten it is about five times higher. This is mainly because of the very high melting point of tungsten.

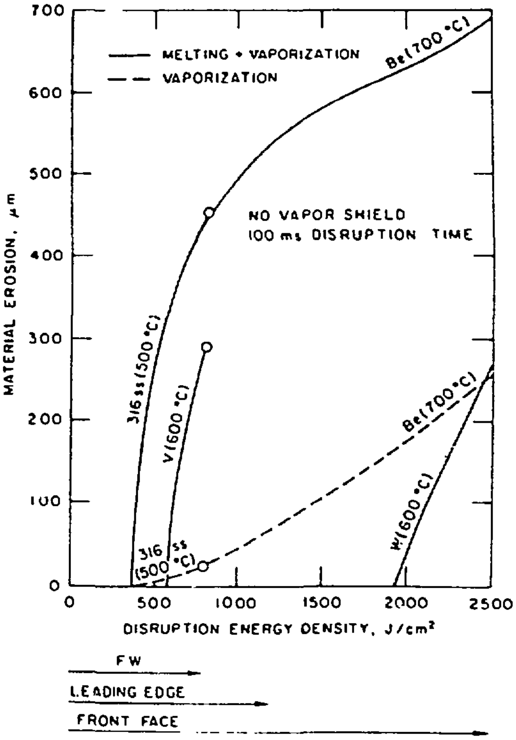

Fig. 1. Disruption damage.

2. Limiter Thermal Analysis

The belt limiter experiences qualitatively differing heat flow at the front face and at the leading edge. The front face is tangential to the poloidal 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.)

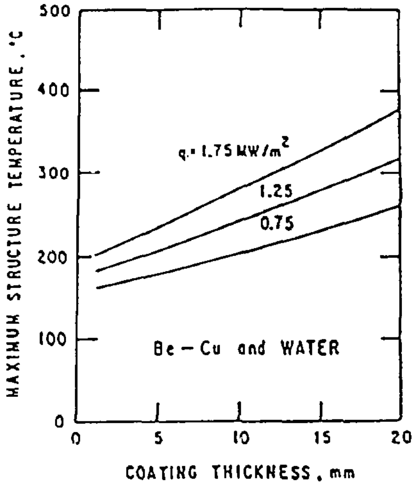

Fig. 2. Heat sink temperature in the limiter's leading edge.

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 ($\lesssim 1$ 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 ($\lesssim 2$ mm), beryllium-coated vanadium has longer fatigue life than tungsten-coated vanadium.

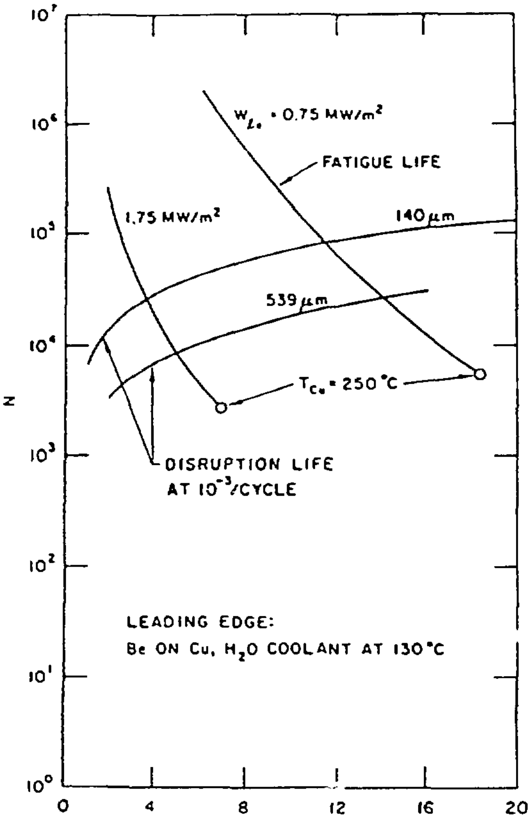

Fig. 3. Leading edge cycle life vs. fatigue and disruption erosion.

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% CW 316 stainless steel) and V-15Cr-5Ti 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 lifetime for various thermal wall loads on a tube of 316 stainless steel with an inner radius of 5 mm. Also shown in this figure (by open circles) are the maximum thicknesses corresponding to a maximum allowable metal temperature of 500°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, $P_m \leq S_{mt}$. The figure shows minimum thickness corresponding to a time-dependent stress limit S_{mt} 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.

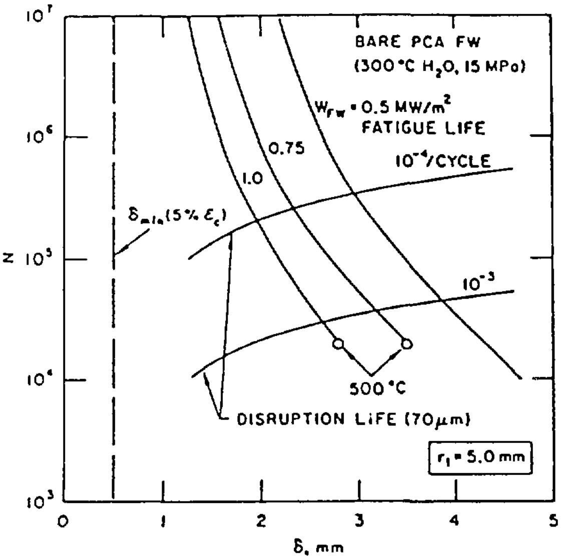

Fig. 4. First wall cyclic life vs. fatigue and disruption erosion.

Similar plots were made for the case of V-15Cr-5Ti 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 δ_{Be} if we restrict the substrate to 250°C (the onset for thermal creep, swelling): $\delta_{Be} \leq 18$ mm at a surface heat load $W_{\ell e} = 0.75$ MW/m^2 and $\delta_{Be} \leq 7$ mm at $W_{\ell e} = 1.75$ 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 μm of beryllium removal per disruption near the upper limits of leading edge thermal loads (~1200 J/cm^2). Hence the beryllium can be removed in the worst case after a number of cycles $N = \delta_{Be}[f \times 0.54 \text{ mm}]^{-1}$, where f is the average frequency (probability) of disruptions per burn cylce. Figure 3 displays N versus δ_{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/m^2, and mild disruption damage, 140 μm lost per disruption, the maximum lifetime is to be expected for $\delta_{Be} = 3.6$ mm, which results in a survival time of $N = 2.7 \times 10^4$ 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 $L_{rad} = 2$ yr. Then, at 80% availability, a fusion period $t_f = 1.8 \times 10^3$ 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 $t_f > 2$ h at $W_{\ell e} \approx 2.0$ MW/m^2. The motivation for long burns diminishes for more mild disruptions. In fact, according to Fig. 1, disruptions do no damage at thermal loads <300 J/cm^2, so very thin coatings with negligible fatigue could be selected in this limit. The first lesson we have learned is that $t_f = 1$ 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).

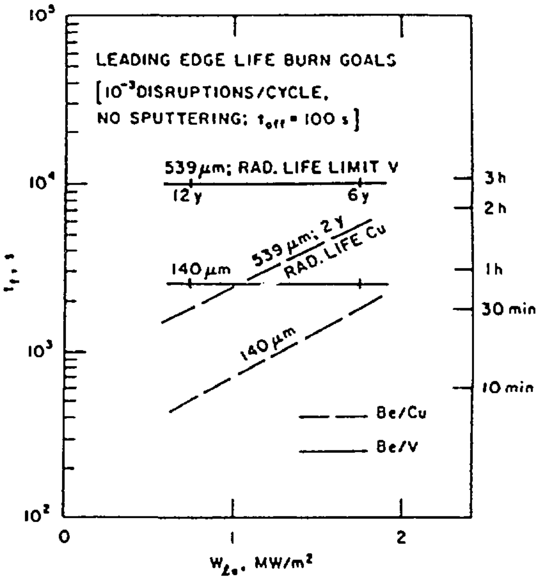

Fig. 5. Fusion burn length goals to equate fatigue, disruption, and radiation life of limiter's leading edge.

It may well be that a commercial reactor would be designed with more radiation resistant materials in order to extend the period between limiter repairs. As an example we consider a vanadium heat sink at the leading edge, clad with beryllium. The 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 δ_{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 $L_{rad} = (24\ MW\text{-}y/m^2)/W_n$, and, for the sake of illustration, we assume a neutron wall load $W_n = (8/3)\ W_{\ell e}$. 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 $\dot{\delta}_{Be} = 1$ 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 number of acceptable fatigue cycles is found. For the copper heat sink N is now smaller than for the cases dominated by disruptions so a longer t_f ($\gtrsim 2$ h) is needed to obtain a 1-2 yr lifetime of the leading edge; for the vanadium substrate N is now larger, so a shorter t_f ($\lesssim 100$ s) is permissible.

Tungsten has also been proposed as a limiter coating at the leading edge. If the plasma temperature exceeds ~50 eV at the leading edge the high net sputtering of tungsten will preclude its use. However, at lower 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, δ_W, would be specified. Since our fatigue calculations showed very large cycle lifetimes for either copper or vanadium substrates with $\delta_W \lesssim 1$ mm we find that fatigue may not be an issue for the leading edge whenever a tungsten cladding can be used.

An identical lifetime analysis was done for the front face of the limiter. The beryllium coating was assumed to be removed at 690 µm and 170 µm per disruption, representing the worst case and more typical disruption damage (2500 J/cm^2 and 500 J/cm^2, respectively). The optimum δ_{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 life of the heat sink (24 MW-yr/m^2 for vanadium and 4 MW-yr/m^2 for copper). The results are displayed in Fig. 6. Our first observation is that $t_f \gtrsim 45$ 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 $t_f \sim 1\text{-}1.5$ h. Of course, if the frequency of disruptions were $f \ll 10^{-3}$ then thinner beryllium 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.

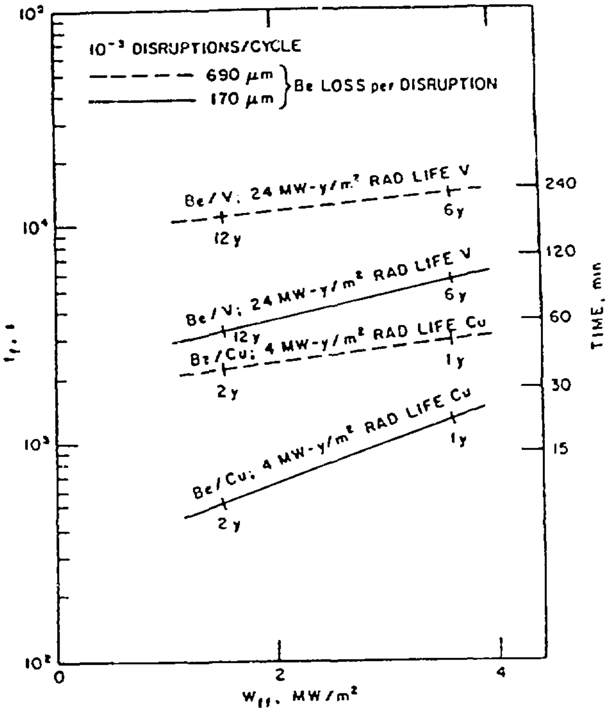

Fig. 6. Fusion burn goals to equate cyclic and radiation life of limiter's front face.

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^{-4}, assuming modest thermal energies in the disruption (380 J/cm^2 removing 70 µm of PCA). The tubing is assumed to fail once disruptions thin the wall to $\delta_{PCA} = \delta_{min}$. For neutron-induced damage we might permit 5% creep. Thus, for 70 µm loss per disruption we find a disruption controlled cycle lifetime of $N = (\delta_{PCA} - \delta_{min})(f \times 0.07\ mm)^{-1}$. As with the limiter we select the intersection of the fatigue and disruption curves to find the δ_{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 $L_{rad} = (12\ MW\text{-}yr/m^2)/W_n$, with $W_n \simeq 4 \times W_{FW}$. The results, shown in Fig. 7, indicate that relatively short burns, $t_f \gtrsim 40$ 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, $t_f \sim 4$ 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 MW-yr/m^2. The 600°C creep limit on vanadium constrains δ_V to $\lesssim 10$ mm, 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

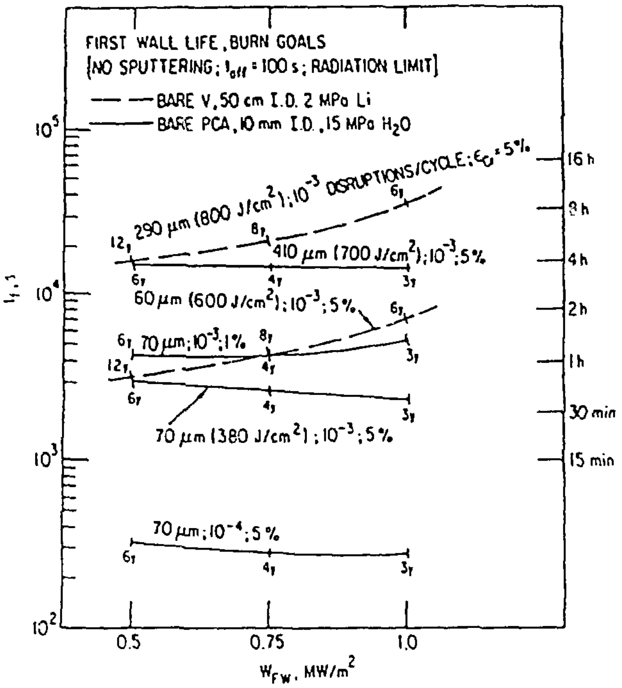

Fig. 7. Fusion burn goals to equate cyclic and radiation life of first wall.

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 $t_f \sim 8$ 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 necessary to arrange for longer burns. This will be possible, 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 ($t_f \sim 100$ s), operating in the internal transformer mode [1], will not be attractive unless disruption frequency is $f \lesssim 10^{-5}$ and sputtering erosion is $\delta \lesssim 1$ cm/yr.

Generally speaking the higher wall and limiter 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 display general trends. Reactor availability should improve with several factors: use of more radiation and fatigue resistant materials; reduction in the frequency 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 characteristics, as we have shown.

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