HEAT FLUX LIMITATIONS ON FIRST-WALL SHIELDS
FOR EARLY FUSION MACHINES

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HEAT FLUX LIMITATIONS ON FIRST-WALL SHIELDS
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Abstract

Methods for producing convective heat transfer systems having high thermal heat flux capability are discussed. It is shown that given sufficient flow velocity heat fluxes as high as \( \sim 6 \text{ kW/cm}^2 \) are possible. The limiting values are determined by thermal stress. Pressure drop and pumping power are significantly high in order to achieve the high flux values. Critical heat flux (burnout) is not limiting. The materials examined are Al, Nb, Mo, Stainless, V, T, and Ta. Water is the coolant. Application is for the first wall of a fusion reactor designed as a high neutron flux test facility.

Introduction

As studies on the technology of fusion reactors have progressed since about 1969, some technological problems have emerged, not seemingly as difficult as the sustaining of a D-T plasma satisfying the Lawson criterion, but nevertheless technologically difficult enough to rate primary attention next to creation of the plasma. Some of the key problems (not necessarily in order of difficulty) are:

1) The assessment of 14 Mev neutron damage to the total structure surrounding the plasma.
2) The effect of plasma components (e.g., D and T ions and neutrals, alphas, neutrons) on the "first wall" and vice versa.
3) Reactor startup.
4) Tritium breeding, inventory, processing, and recycling.
5) Access, repair, maintenance, and dependability.

The motivation for doing this particular study arose out of problems connected with FERF, but the results are of general applicability. The term "FERF" is an acronym for "Fusion Engineering Research Facility." The LLL interest in FERF grew out of a need for a facility operational around 1985 which would supply a very high flux (\( 10^{14} n/cm^2\text{sec} < 10^{15} \)) of fusion spectrum neutrons so that problem number (1) above might be studied. Fortunately, a device such as FERF acts not only as a neutron source but as a facility in which the entire spectrum of problems can be evaluated.

FERF is, in reality, a nonpower producing reactor subject to engineering constraints arising out of the particular set of physics conditions which allows production of neutron fluxes about an order of magnitude higher than one would expect in a conventional reactor. This factor of 10 is necessary for accelerated acquisition of data on neutron effects. To achieve this high neutron flux, the plasma physics parameters are such that a unique situation is created. The D and T neutral beam injection which effectively produces the required neutron flux by building up and sustaining the plasma volume also unfortunately
produces copious amounts of neutrals which hit the first wall. This is because
the charge exchange cross section at 60 KeV, the injection energy, is very
nearly the same value as the cross section for ionization as illustrated in
Figure 1. Because of the directionality of the injectors and because the re-
actor must pass through the startup and plasma buildup phase where the un-
attenuated neutrals hit the wall, the maximum thermal flux from these neutrals
range from values as high as ~3300 w/cm² for short times to values of ~1000
w/cm² for steady state (Ref. 1). Figure 2 shows the region within the reactor
where the flux is incident.

The subject of this paper is how this high heat flux may best be removed.
For FERF, two additional considerations arise in addition to the energy removal:
(a) The metallurgical effects of neutrals and neutrons should be separated to
make analysis less difficult. To do this, the short range neutrals (1-10 μ
burial depth in metals) are intercepted by a sacrificial first wall or first
wall shield (FWS). The effects of the neutrons can then be evaluated in a test
region immediately on the other side of this wall. (b) The cooling of the
first wall in FERF, compared to a commercial reactor, is not (economically)
limited in pressure drop or pumping power. The wall may also be changed several
times a year.

To remove the very large energy flux from the first wall, several methods
are possible and include the following:
1) High velocity, forced convective cooling with liquids in the nonboiling
and subcooled boiling regime.
2) Transpiration cooling.
3) Film cooling.
4) Film evaporation.
5) Ablation cooling.
6) Radiation cooling.

Methods 2-4 have in common the use of a liquid coolant film on the surface
of the wall facing the plasma. Plasma-wall interactions with this arrangement
would probably quench the plasma since liquids would have high sputtering coeffi-
cients. Ablative cooling involves the physical removal of wall material, which
probably would also quench the plasma. Radiation cooling in this geometry does
not solve the problem but merely transfers it to another surface. We have,
therefore, focussed our attention on method (1). It has the additional advan-
tage that it can be designated to produce low wall temperatures and, consequently,
higher allowable stress.

Cool walls facing the plasma have the added attraction that aluminum alloys
such as SAP (sintered aluminum producing containing 5-10% Al₂O₃) or other more
common aluminum alloys may be considered. These materials produce relatively
short half-life species after neutron irradiation,² making the handling, dis-
posal, and replacement of first wall structures less of a problem.

In forced convective cooling, the maximum heat flux may be limited by any
one of several engineering constraints, including:
1) Allowable structural stresses.
2) Maximum allowable structural temperature.
3) Coolant pumping power requirements.
4) Coolant pressure drops.
5) Critical heat flux in boiling liquids.
6) Practical tube diameters, thicknesses, and lengths.

These constraints are examined in the following sections.

The concept selected for this study involves an array of closely packed
tubes or thin corrugated sheets joined to form a wall of flow channels. This
highly cooled wall can be used as the first wall shield (FWS) and designed to
be in front of the containment vessel to shield it from erosion. To be an attrac-
tive concept for FERF, the first wall shield should be substantially easier
and less costly to fabricate, install, maintain, and replace than the first wall
or front part of the containment vessel itself, particularly if frequent re-
placement proves to be necessary.
Thermal Stress Limitations

For the high heat fluxes of interest to this application, the design is strongly influenced by thermal stress. The thermal stress, \( \sigma_{\text{TH}} \), in a thin-walled tube is:

\[
\sigma_{\text{TH}} = \left[ \frac{aE}{2(1 - \nu)} \right] \Delta T_w
\]  

where \( \Delta T_w \) = temp across the tube wall, \( a = \) coefficient of thermal expansion, \( E = \) modulus of elasticity, and \( \nu = \) Poisson ratio. The surface energy deposition \( q \) and the conduction equation determined \( \Delta T_w \) so that

\[
\sigma_{\text{TH}} = \left[ \frac{aE}{2(1 - \nu)k} \right] q \delta
\]

where \( q = \) local heat flux, \( k = \) thermal conductivity, and \( \delta = \) tube wall thickness. The quantity in parenthesis is material and temperature dependent and is a useful guide for material selection.

Actually the total stress is complicated by the details of specific designs but is not less than the sum of the hoop stress and the thermal stress. So,

\[
\sigma_{\text{TOTAL}} \geq \frac{pD}{2\delta} + \left[ \frac{aE}{2(1 - \nu)k} \right] q \delta
\]

where \( p = \) pressure in the tube and \( D = \) tube diameter. However, we will assume as an aid for preliminary material selection that thermal stress dominates and plot two different criteria relative to thermal stress.

Using Equation (2) with property data taken at room temperature yields Figure 3 which is a plot of thermal stress vs thermal flux for representative materials. This serves to divide the materials into two categories — those that are clearly thermal stress limited at flux levels of interest and those materials that are acceptable.

We see that stainless steel, vanadium, and titanium have sharp sensitivity to thermal flux and are not likely first wall materials. The acceptable alloys are those of tantalum, molybdenum, niobium, aluminum, and the special material SAP. However, the use of aluminum alloys is uncertain, not because of high thermal stress, but simply due to low allowable working temperature. For niobium, molybdenum, and tantalum, the stresses are well below the yield point at 1000 w/cm².

An even more comprehensive material property parameter, \( M^* \), can be used to compare potential first wall materials

\[
M^* = \left[ \frac{2\nu k(1 - \nu)}{aE} \right] = \frac{\sigma_{\text{Y}}}{\sigma_{\text{TH}}} q \delta
\]

where \( \sigma_{\text{Y}} = \) short time tensile yield stress.

This parameter is most useful for the case of very high heat fluxes in thin-walled tubes where the thermal stresses dominate all other stresses including the hoop stresses. Under these conditions, the ratio \( \sigma_{\text{Y}}/\sigma_{\text{TH}} \) is essentially equal to the structural safety factor. If we use the same safety factor for all materials and the same tube-wall thickness, \( \delta \), then \( M^* \) is directly proportional to the maximum heat flux the material can safely handle.

It is a problem collecting reliable and comparable values of the material properties (particularly the tensile yield stress) for the various materials as a function of temperature. We have tried to be as consistent as possible in the choice of these data used to calculate the \( M^* \) values plotted in Figure 4, but some uncertainties remain. Nonetheless, the qualitative trends shown in Figure 4 should be correct. In particular, the high yield stresses of Ta-16W and Mo-0.5Ti coupled with favorable property data (as measured by the low slopes on Figure 3) result in the highest heat flux capabilities. The niobium and aluminum alloys form an intermediate group of materials which are still possible.
choices, particularly if the wall temperatures can be kept low. The alloys of titanium and stainless steel and commercially pure vanadium are the least attractive of the materials investigated for these high heat flux applications.

Transient Behavior

In addition to problems of thermal stress, the choice of wall materials is influenced by the transient (startup) behavior of the reactor. Thermal fluxes on the wall during this time interval or during a time interval when the plasma is lost but fuel injection continues are as high as 3300 w/cm². It will be assumed that with this high flux the critical heat flux for convective heat transfer may be exceeded (although, as will be shown subsequently, this does not appear to be the case if the Rosas correlation is correct). The critical heat flux is the point at which there is a sharp reduction of the local heat transfer coefficient caused by replacement of the liquid by vapor at the heated surface. Critical heat flux sets the upper limit for convective heat transfer, and burnout (tube melting) can occur.

We are concerned with the time-temperature history of the tube wall but particularly the outer surface of the tube facing the plasma. There are two parameters that may be used to gage the temperature of the tube wall. The first parameter is:

$$\Delta T_\infty = \frac{q\theta}{\rho C_p \delta}$$

where $\theta$ is time, $\rho$ is density, and $C_p$ is the specific heat. This is the exact solution of the time history of the temperature of a thin plate of infinite thermal conductivity without heat removal. The second parameter, the Fourier number, is useful for the cases where the thermal conductivity is finite:

$$F = \alpha' \frac{\theta}{\delta^2} = \frac{k}{\rho C_p \delta^2}$$

which includes $\alpha'$, the thermal diffusivity. It can be shown that for finite thermal conductivity at the point x into the tube wall:

$$T(x) - T(0) = f(F, \Delta T_\infty, x/\delta)$$

This is plotted in Figure 5.

The following table sums up the $\Delta T_\infty$ values and the Fourier numbers for a representative tube wall thickness, $\delta$, of .001 meter and a heat flux of $q = 3300$ w/cm². The time $\theta$ is in seconds.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta T_\infty$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>44000</td>
<td>112000</td>
</tr>
<tr>
<td>Nb</td>
<td>41500</td>
<td>109000</td>
</tr>
<tr>
<td>Mo</td>
<td>129000</td>
<td>135000</td>
</tr>
<tr>
<td>Al</td>
<td>142000</td>
<td>138500</td>
</tr>
<tr>
<td>Ti</td>
<td>142000</td>
<td>138500</td>
</tr>
<tr>
<td>Ta</td>
<td>142000</td>
<td>138500</td>
</tr>
<tr>
<td>V</td>
<td>142000</td>
<td>138500</td>
</tr>
</tbody>
</table>

Using these values of $F$ and $\Delta T_\infty$ for different times $\theta$, the temperatures of the front face $T_{FP}$ can be determined from Figure 5 by noting that the $x/\delta = 0$ line refers to the front face, that the dashed line is for $\Delta T_\infty$ and that the ratio of their two intercepts on the ordinate is the factor by which $\Delta T_\infty$ is to be multiplied to obtain the temperature of the front face.

The front face temperature rise as a function of time is plotted in Figure 6. We see that the aluminum alloys have only about 40 milliseconds before the front face starts to melt while the tantalum alloys have over 170 milliseconds. The principal point to be made from these results is that it is more reasonable to choose high melting point materials such as tantalum in preference to aluminum to provide as much time for transient plasma buildup or loss as possible.
This is particularly true for very high heat flux cases, since there is considerable uncertainty about the critical heat flux under these conditions.

**Pressure Drop and Pumping Power Constraints**

For the steady state flux, it is desirable to keep the FWS (first wall shield) temperature low to maximize allowable stress and thus maximize heat flux capability. The decrease in the allowable stress with temperature is illustrated in Figure 4 since it is the dominant effect causing the decrease of \( M^* \). The maximum temperature of the outer surface of the tube at the exit, is given by:

\[
T_{w(\text{MAX})} = T_{w(\text{EX})} = T_{B(\text{IN})} + \Delta T_B + \Delta T_{\text{FILM}} + \Delta T_w
\]

where

\[
\Delta T_B = T_{B(\text{EX})} - T_{B(\text{IN})} = \text{fluid bulk temperature rise, inlet to exit}
\]

and

\[
\Delta T_{\text{FILM}} = (T_B - T_{w1})_{\text{EX}} = \text{temperature rise from the bulk fluid to inner tube wall}
\]

and

\[
\Delta T_w = (T_{w0} - T_{w1})_{\text{EX}} = \text{temperature rise across the wall.}
\]

These temperature variations are shown in Figure 7. We have no control over the \( \Delta T_w \) for a given material and wall thickness since it is proportional to the heat flux. Consequently, to minimize \( T_{w(\text{MAX})} \), we must minimize \( T_{B(\text{IN})} \), \( \Delta T_B \) and/or \( \Delta T_{\text{FILM}} \).

For this design, liquid water has been selected as the coolant, and the lowest possible value of \( T_{B(\text{IN})} \) of about 0°C has been used. To keep the \( \Delta T_B \) and \( \Delta T_{\text{FILM}} \) low, high flow velocities are required as illustrated in Figure 8. This leads to high pressure drops, \( \Delta p \), and high pumping power. The pressure drop, \( \Delta p = \frac{fL}{D^4} \frac{G^2}{2} \) is plotted versus the flow rate parameter, \( G = \rho u \), in Figure 9.

Converting these pressure drops to pumping power required per square meter of FWS surface area facing the plasma:

\[
\frac{P_{\text{PUMP}}}{A_{\text{FW}}} = \frac{\pi D_1 \Delta p}{4L} = \frac{\pi f G^3}{B \rho^2}
\]

**Typical Results for the Reference Design**

For the reference design calculations, we have chosen \( D = 10 \text{ mm}, \sigma = 0.5 \text{ mm}, \) and \( L = 1 \text{ mm} \) for a representative coolant tube. An inlet water pressure of 280 psi was chosen because it is an even multiple of one of the pressures used in critical heat flux correlations which will be discussed subsequently. To illustrate the calculational procedure in arriving at the maximum allowable heat flux, data for Nb-1Zr have been used in the following figures.

Figure 10 shows how the total stress; thermal plus hoop stress, varies with heat flux for three different tube wall thicknesses. The hoop stress which is the intercept at \( q = 0 \), increases as the tube wall thickness decreases. However, the total stress is lowest for the 0.25 mm tube wall for heat fluxes above \( \sim 600 \text{ w/cm}^2 \). We chose a \( \delta = 0.5 \text{ mm} \) based on ease of fabricability for tubes of this diameter and because of consideration of erosion caused by sputtering.

In Figure 11, we have replotted these data for \( \delta = 0.5 \text{ mm} \) as a function of the maximum wall temperature at the tube exit for three typical values of the bulk temperature rise. If we superimpose the allowable stress \( (2/3 \sigma_y) \) vs temperature curve on this plot, we obtain the locus of possible maximum operating points.
For each bulk temperature rise, there is a particular value of the mass flow parameter, $G$, and the allowable heat flux, $q$, at each intersection point. These values are replotted in Figure 12. This stress-limit curve forms the upper boundary for the maximum allowable heat flux for the material under investigation.

Several other constraints can be shown on this type of "performance map." A second constraint is that on the fractional pressure drop. The upper limit on the fractional pressure drop is for $\Delta p/\rho u = 1.0$ which occurs at $G = 64,000$ kg/m$^2$-s for the conditions of Figure 12. This is shown along with a limit boundary for $\Delta p/\rho u = 0.5$ (at $G = 43,500$ kg/m$^2$-s). This latter value is a more practical engineering upper limit since it allows for additional pressure drops in the bends, headers, and other piping necessary to connect the FWS tubes to the water pump. The $\Delta p$ constraint forms the right-hand boundary of the permissible operating regime of Figure 12.

**Critical Heat Flux**

A third engineering constraint for liquid coolants is that of the critical heat flux for dryout or burnout. Data are limited for critical heat flux at the very high values of mass flow rate ($G > 10,000$ kg/m$^2$-s) in which we are interested. However, there are some Aerojet data on critical flux using water as a coolant in this high mass flow regime for which Rousar developed some correlations (Ref. 3). The best fit to these data is shown in Figure 13. The dramatic difference of Rousar from other correlations such as MacBeth's is quite evident. However, the data on which the MacBeth and other similar correlations are based seem to be for values of $G \leq 7000$-8000 kg/m$^2$-s while the Aerojet data is at the higher mass flows.

On that basis we have tentatively accepted the higher $q_{\text{crit}}$ values based on the Aerojet data as valid for our application. These $q_{\text{crit}}$ values are plotted on the performance map of Figure 12 and form the minimum mass flow boundary of the permissible operating regime for the reference design.

It can be seen that the maximum allowable heat flux for Nb-Zr is at the intersection of the stress constraint curve and the pressure drop curve. The water is in the nonboiling regime at this point far below the critical heat flux curve. The maximum heat flux is $\sim 2$ kW/cm$^2$ with Nb-Zr tubes. At this condition, the pumping power is $\sim 380$ kW per square meter of first wall surface area.

It should be noted in Figure 12 that the stress-limit curve is quite flat for Nb-Zr because the allowable stress is a weak function of temperature in this temperature region. As a result, it is possible to back off slightly on the heat flux and save a substantial amount on the pumping power. For example, at $G = 29,000$ kg/m$^2$-s, the maximum allowable $q$ is still about 1.9 kW/cm$^2$, while $\Delta p/\rho$ is reduced to 0.25; this cuts the pumping power required to 120 kW/m$^2$, about one-third of the previous value.

It should be noted that as we reduce the mass flow the subcooled boiling regime is reached. This regime is where most industrial applications operate to obtain the low fractional pressure drops and pumping powers required for good plant efficiency. However, for an experimental fusion facility, we are not strongly constrained in pumping power, and consequently we can operate at the higher values of $G$ in the nonboiling regime up to some economic limit on pumping system costs and/or electric power available to run the pumps.

**Comparison of Materials for the Reference Design**

The maximum allowable heat flux capabilities for all the materials investigated are shown in the bar chart of Figure 14. Clearly Ta-10W and Mo-STi are superior.
The upper limit for heat flux for each material is based on short time
tensile property data where we use two thirds of the yield stress. For long-
time operation, we have insufficient data on neutron damage and other factors
affecting the allowable working stresses to choose a design safety factor. As
a rough guess, we suggest that one third the allowable yield stress be used.

All these maximum heat flux values are well below the critical heat flux
curve except for Ta-10W. Hence, all materials except Ta-10W are operating in
the nonboiling regime at this maximum heat flux condition, provided that the
Rousar correlation is valid.

It should be noted that the maximum tube-wall temperatures for all the
materials were below the values where creep effects become dominant. For ex-
ample, the highest temperature for the Ta-10W was ~1000°C and for the niobium
alloys, the maximum temperatures were < 400°C. For the aluminum materials, the
maximum exit temperature was constrained to be about 120°C.

The aluminum materials were originally included in this study specifically
because of their low induced activity. However, it appears that the rate of
diffusion of the neutron-produced vacancies to the grain boundaries with subse-
quent void formation is in inverse proportion to the melting point of the
material. Consequently, the useful lifetime of structures made of the lower
melting point materials may be shorter than for high melting point materials.

Effect of Parameter Variations

The parameters chosen for the reference design (L = 1 m, D = 10 mm,
δ = 0.5 mm, P_in = 280 psi) are not optimized; they were simply chosen as reason-
able first guesses for first-wall panel dimensions in the highest heat flux
areas.

While no full optimization study has been performed, several calculations
were made varying the tube dimensions and the inlet water pressure. For example,
thinner tube walls increase the heat flux capability as shown in Figure 10,
since the thermal stresses always dominate at the high heat fluxes. Longer tube
lengths, larger tube diameters, and higher water pressures were found to de-
crease the maximum heat flux capability somewhat for a fixed fractional pres-
sure drop of 0.5. Further studies to find optimized designs for specific ap-
lications are certainly warranted.

Conclusions

The results of our study indicate that a tubular wall of refractory metal
alloys such as Ta-10W can probably handle energy fluxes from the plasma as high
as 6.4 kW/cm² using high velocity water coolant. This value is for a specific
geometry (L = 1 m, D = 10 mm, δ = 0.5 mm) and inlet water pressure (280 psi).
For Mo-0.5Ti under the same conditions, the maximum value is about 5.6 kW/cm².
The niobium alloys and aluminum materials have maximum values of about 2 kW/cm².
Other materials, vanadium, the titanium alloys, and the stainless steels had
heat flux capabilities below 1 kW/cm² for this application and geometry.

When the fractional pressure drop in the tubes is held at 0.50, the pump-
ing power is about 380 kW per square meter of first wall area subjected to the
high heat fluxes. Substantially lower values of pumping power can be obtained
by a relatively small reduction in the maximum allowable heat flux. For ex-
ample, the pumping power can be reduced by a factor of three with only a 5-10%
reduction in the allowable heat flux.

I should be noted that there exist some important uncertainties in the
analysis such as the critical heat flux under these conditions and the neutron
damage effects which require experimental studies. In the meantime, it is
recommended that about one-half the maximum heat flux capability of the various
materials be used for design purposes.

Even though these maximum heat flux results are not optimized values, they
are sufficiently high to indicate that water cooled first walls for early experi-
mental fusion machines can probably be designed with some margin of safety for the unexpected.

References

1. FERF Report in Preparation, LLL.

2. FERF Report in Preparation, LLL.


5. Personal Communication, Prof. A. Mukherjee, Dept. of Mechanical Engineering Univ. of California, Davis.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
Figure 1. Ionization and charge exchange cross section vs energy.
Figure 2. Cross section of the plasma region of FERF.
Figure 3. Thermal stress vs thermal flux for some materials of interest in a FERF first-wall application.
Figure 4. Comparison of various promising first-wall shield materials in terms of a material property parameter related to thermal stresses in thin-walled tubes.
Figure 5. Temperature response of thickness plate (0 \leq x < \delta) with insulated rear trace x = 0 after sudden exposure to constant heat input q at x = 0.
Figure 6. Surface temperature of the tube wall vs time for constant flux input of 3300 w/cm² w/o heat removal.
Figure 7. Variation of the key fluid and wall temperature along a tube with uniform axial heat input.
Figure 8. Reduction of bulk and film temperature drops with increasing coolant mass flow rate.
Figure 9. Pressure drop in round tubes using water coolant in the non-boiling flow regime.
Figure 10. Total stress as a function of thermal flux for three different tube thicknesses.
Figure 11. Actual total stress and allowable stress variations with Nb-12 tube wall temperature. The intersection point define the maximum operating conditions for each case.
Water coolant: \( \text{pin} = 280 \text{ psi} = 19.3 \text{ bars}, T_{B_{\text{IN}}} \approx 0^\circ \text{C} \)

Nb-1 Zr tubes: \( D_i = 10 \text{ mm}, \delta = 0.5 \text{ mm}, l/D_i = 100 \)

Approx \( q_{\text{car}} \)

Maximum allowable heat flux, \( q_{\text{MAX}} \)

Stress limit: \( \sigma_{\text{TOT}} = \sigma_{\text{ALLOW}} \)

Permissible operating regime

\[ \frac{\Delta p}{\text{pin}} = 0.5 \]

\[ \frac{\Delta p}{\text{pin}} = 1.0 \]

Figure 12. Typical performance map showing the permissible operating regime for the reference first-wall design using Nb-1Zr tubes.
Figure 13. Critical heat flux correlations for uniform heat fluxes on round tubes with water coolant flows.
Figure 14. Estimates of the short-time and long-time heat flux capability of various tube-wall materials for the reference case with water coolant ($\Delta p/p$ constrained to be 0.5 for all cases).