DESIGN WINDOW FOR LIQUID METAL-COOLED LIMITERS

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ABSTRACT A design window for a liquid metal cooled limiter is being sought to establish the viability of the use of liquid metals as coolants for the limiter. The problem is approached by first establishing the constraints, then defining the geometrical configuration and design parameters, and finally, by analyzing a limiter without coating. The maximum allowable heat flux is found to be ~ 4 MW/m^2. It can be increased to 5 MW/m^2 if tapered or insulated feed pipes are used. The presence of coatings required to withstand particle erosion will further reduce the allowable heat flux.

INTRODUCTION

Liquid metals are strong candidates as breeders and coolants for fusion blankets.[1-2] A key feasibility condition defined recently for such blankets is identifying a viable non-water coolant for the in-vessel components such as limiters and divertor plates. The presence of water in close proximity to lithium or lithium-lead is considered an unacceptable safety risk.[1-3] The purpose of this work is to investigate the feasibility and attractiveness of liquid metals as coolants for the in-vessel components. In detailed calculations, a pumped limiter in a commercial tokamak reactor was used as an example. A technique used extensively in this work is that of defining the possibility of a design using a design window. A design window can be explained as a permissible region of operation defined by various limits.

A key problem with the design of the pumped limiter, or other in-vessel components, is the simultaneous presence of high particle and heat fluxes. High particle fluxes dictate thick walls in order to withstand erosion. High heat fluxes require thinner walls to minimize temperature and stresses. Present designs,[4] e.g., INTOR, use water coolant at low temperature (< 100 °C), and hence, low pressure. Low temperature operation permits the use of high conductivity materials such as copper and the low pressure reduces stresses.

Liquid metal cooling of the limiter introduces new and difficult problems. The combination of high melting point and considerable film temperature drop in laminarized fluid flow under the effect of magnetic field results in operating temperatures of the structural material much greater than those acceptable for copper alloys. The much higher thermal stress induced in other structural materials sharply reduces the maximum allowable heat flux. Another problem is the MHD pressure drop in the liquid metal coolant. The resulting pressure stresses further reduce the allowable heat flux.

DESIGN APPROACH

As the problem of cooling of a limiter with liquid metal was quite complicated, it was approached first by introducing various constraints which the design must observe; second, by choosing geometrical configuration and design parameters in accordance with the constraints; and last, by analyzing a limiter without coating. The introduction of coating on the limiter reduces the maximum allowable surface temperature if low z coatings are used. It also introduces a new constraint on the structure material, thus aggravating the thermal stress problem. As the possibility of a design window for a limiter without coating is better than that for a limiter with coating, it was decided to treat the simpler problem of a design window for a limiter without coating first. Future work will address the coating problem.

The constraints imposed on the limiter design were:

1) The limiter surface area should be large enough to provide lower particle and heat fluxes.
2) The space provided for particles to be pumped must be sufficient enough to provide efficient impurity removal.
3) The materials used for surface coating must not excessively contaminate the plasma.
4) The structural material must have good compatibility with the coolant.
5) As the corrosion due to liquid metals is temperature dependent, an upper limit on the interface temperature between the coolant and structure must be defined and observed.
6) The structural materials have a tendency to creep at higher temperatures. Thus, structural temperature during operation must

remain below a limiting value.
7) The inlet temperature of the coolant must be ~ 40 °C above the melting point.
8) The primary and secondary stresses arising in the material must remain below the 3 S_m value, as determined by the ASME code.
9) The primary stress in the material must remain below the S_m value, again as set by the ASME code.

In light of the above constraints, the geometrical configuration of the limiter was chosen and is shown in Fig. 1. It is a curved double-edged limiter with one inlet and two outlet feed pipes which we shall call conduits, one inlet and two outlet horn-shaped pipes which are called manifolds, and minute cooling channels running on the face of the limiter. The cooling channels rise from the inlet manifold, each separating into two parts and then terminating at the outlet manifold. The coolant flows on the face of the limiter in cooling channels parallel to the toroidal magnetic field and flows perpendicular to the toroidal magnetic field in the conduits and in the manifolds. This flow pattern was primarily chosen because: 1) it provides shorter path lengths which are highly desirable to keep the rise in bulk temperature low because of the above mentioned limits, and 2) the flow is parallel to the toroidal magnetic field where the flow speed is highest in order to reduce the MHD pressure drop. However, large MHD pressure drops are still expected to occur in the conduits and manifolds if conducting wall pipes are used.

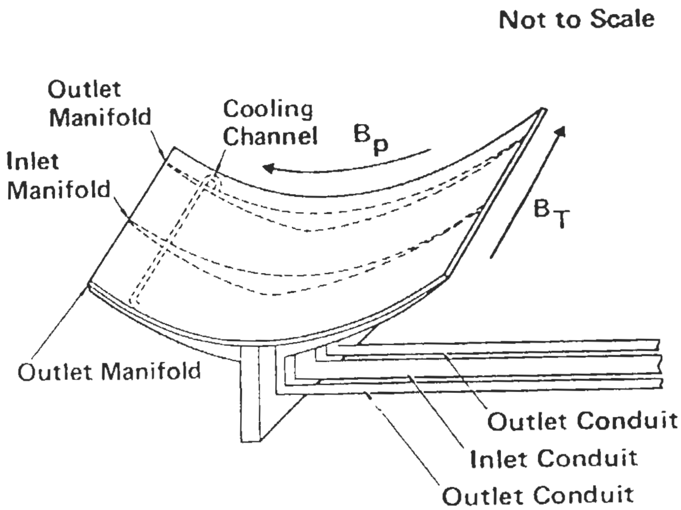


Fig. 1 Geometrical configuration of the limiter

For further analysis the structure material was chosen to be vanadium because of its high corrosion resistant properties and relatively acceptable characteristics as a heat sink material. Based upon previous studies,[1-2] a maximum value of 650 °C was selected for the interface temperature and a value of 670 °C for the structure temperature. The design was expected to endure up to 5 MW/m^2 heat flux. (The heat flux limits discussed in this paper refer to peak values). A Nusselt number of 8 was taken for heat transfer calculations accounting for the fact that flow in the coolant channels on the face of the limiter is not fully developed.[5] However, reliable data for the type of heat transfer problem encountered in the limiter was not found, and it is hoped that this issue will be investigated in detail later.

DESIGN CALCULATIONS AND RESULTS

The first step towards obtaining a design window was to determine the dimensions of the coolant channels. The dimensions of the coolant channels were chosen after a thermal and stress analysis. The channels picked for analysis were the one near the center of the "flat" face and the one at the leading edge. The coolant channel at the center is subjected to the maximum heat flux because it is nearest the plasma. The coolant channel at the leading edge has a different construction with particular constraints that require detailed stress analysis. Thus, these two channels were analyzed.

Figure 2 shows the construction and nomenclature of the two channels. For both thermal and stress analysis the finite element code,

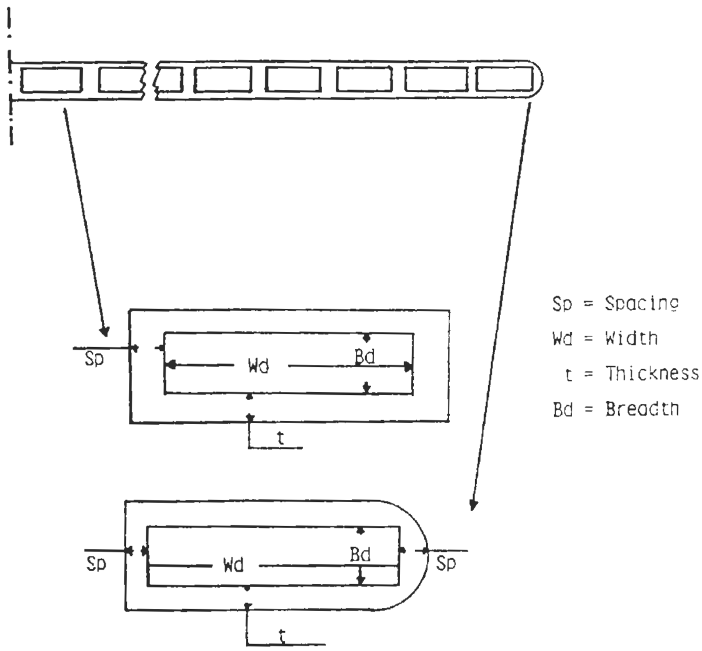


Fig. 2 Details of the leading and center channel

ANSYS,[6] was used. To study the effect of changing wall heat flux, inside pressure, wall thickness, width and breadth of channel, and spacing between channels a sensitivity study was performed. The results of the sensitivity study are presented in Table 1. It was observed that, for both cases, total stress is highly sensitive to wall heat flux, wall thickness and spacing between channels. It was noted that total stress in the most critical element increases with an increase of any of the above variables. Another important observation was that total stress is least sensitive to variations in inside pressure for that below 30 MPa, however, rises sharply at pressure above 60 MPa.

Table 1. Results of the Sensitivity Study

Center Channel

PARAMETER	SENSITIVITY	REMARKS
Heat Flux	High	Stress increases with increasing heat flux
Inside Pressure	Medium	Stress increases; increase rapid at high pressures
Channel Width	Low	Stress increases with increasing width
Channel Breadth	Low	Stress rises and falls --peaks at 5 mm
Wall Thickness	High	Stress increases as wall thickness grows
Channel Spacing	High	Stress increases as channel spacing grows

Leading Channel

PARAMETER	SENSITIVITY	REMARKS
Heat Flux	High	Stress increases with increasing heat flux
Inside Pressure	Medium	Stress increases rapidly at high pressures
Channel Width	Low	Stress increases with increasing width
Channel Breadth	Low	Stress is almost independent of breadth
Wall Thickness	High	Stress increases as wall thickness grows
Channel Spacing	High	Stress increases as channel spacing grows

The results of the sensitivity study were used to choose cooling channel dimensions, shown in Table 2. Notice that the wall thickness of 1.2 mm assumes that there is no erosion, e.g., very low plasma edge temperature, or that a coating will be used. With these dimensions the center channel can withstand heat flux of 5 MW/m^2 and the leading channel a heat flux of 3 MW/m^2, and both can operate safely at an inside pressure of up to 40 MPa without violating the 3 S_m limit.

Table 2. Dimensions of the Channels

Center Channel

PARAMETER	VALUE
Channel Width	12 mm
Channel Breadth	3 mm
Wall Thickness	1.2 mm
Channel Spacing	1.7 mm

Leading Channel

PARAMETER	VALUE
Channel Width	12 mm
Channel Breadth	3 mm
Wall Thickness	1.2 mm
Channel Spacing	1 mm

Choice of dimensions of the cooling channels essentially meant that once coolant velocity is chosen in the cooling channels, the total mass flow rate to the limiter can be determined. The determination of the mass flow rate would lead to a decision about wall thickness, cross section area, and coolant velocity in the manifolds and conduits once the hoop stress limit is applied. Here, because of the constraint of not excessively blocking the limiter slot (the space behind the limiter for pumping), an additional criterion was introduced to establish the viability of a particular design. This criterion is stated as:

The total length blocked by the feed pipes in the toroidal direction must be less than half the total toroidal length of the limiter.

With this additional criterion in place there were three possibilities for the overall design, namely:

1) liquid metal cooled limiter using untapered, uninsulated conduits;
2) liquid metal cooled limiter using tapered conduits;
3) liquid metal cooled limiter using insulated conduits.

The effect of the above criterion on an uninsulated, untapered walled conduit design can be observed in Fig. 3. It is a plot of path length versus coolant velocity in the cooling channels. As is obvious for a wall heat flux of 4 MW/m^2, it will be possible to satisfy the above criterion, although not for a wall heat flux of 5 MW/m^2. This can be seen from the plot, since for coolant velocities up to 7-8 m/s the maximum permissible path length does not exceed the minimum required path length. Above 7-8 m/s coolant velocity the pipes get so thick that a design can be practically ruled out. This, however, does not occur for a design employing tapered conduits. For a coolant velocity between 5 to 6 m/s the above mentioned criterion can be met for a wall heat flux of 5 MW/m^2. This can be observed in Fig. 4.

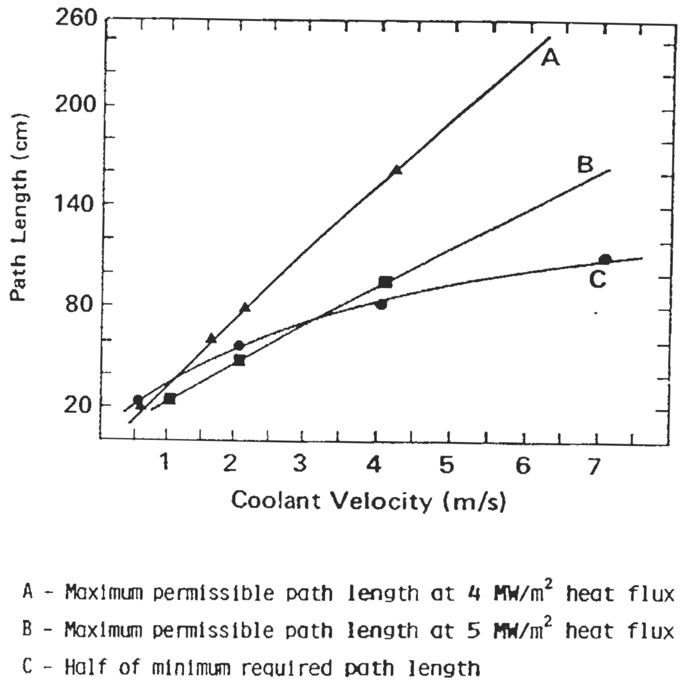


Fig. 3 Design margin with untapered conduits at 4 and 5 MW/m^2 heat flux

The overall design with all limits in place was considered for the cases with tapered and insulated conduits. The design window obtained for these cases is shown in Figs. 5-8. It exists for both the cases, however, decreases considerably for an increase in wall heat flux from 4 to 5 MW/m^2. It is also observed that the design window, for a design employing tapered conduits, at 5 MW/m^2 is very narrow, which essentially means that it will be possible to have a design, but without much flexibility in operation. Also noted is that a design employing insulated conduits appears to be the most attractive if insulators can be developed for the harsh radiation and corrosive environment.

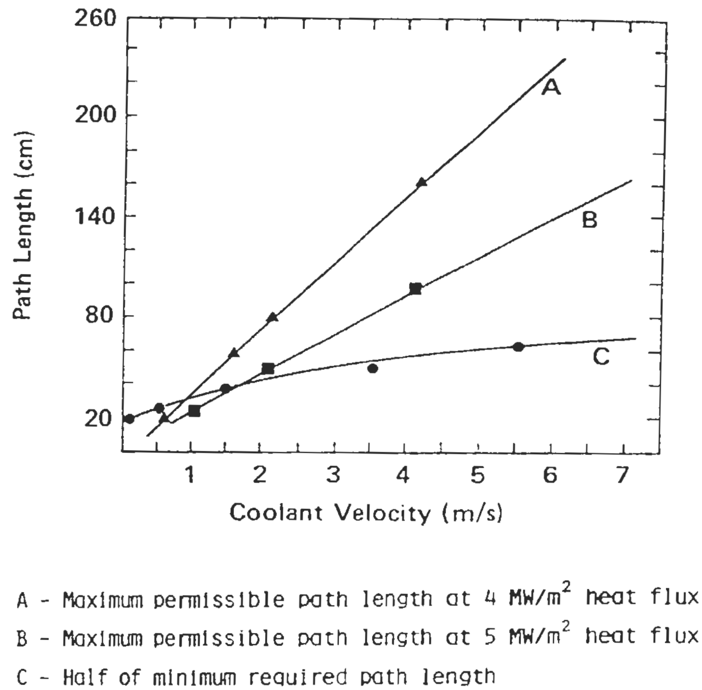


Fig. 4 Design margin with tapered conduit at 4 and 5 MW/m^2 heat flux

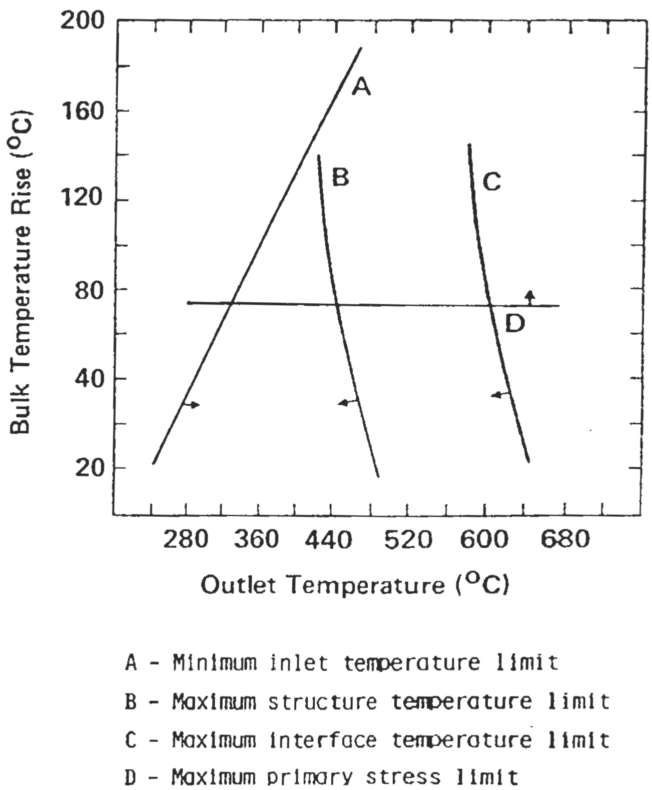
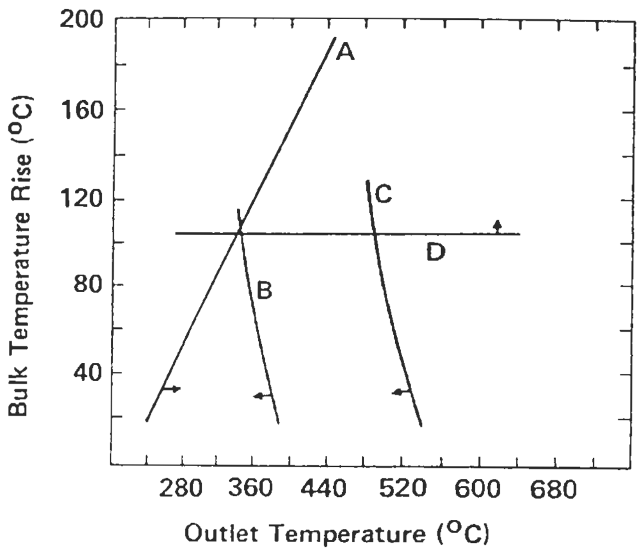


Fig. 5 Design window with tapered conduit at 4 MW/m^2 heat flux



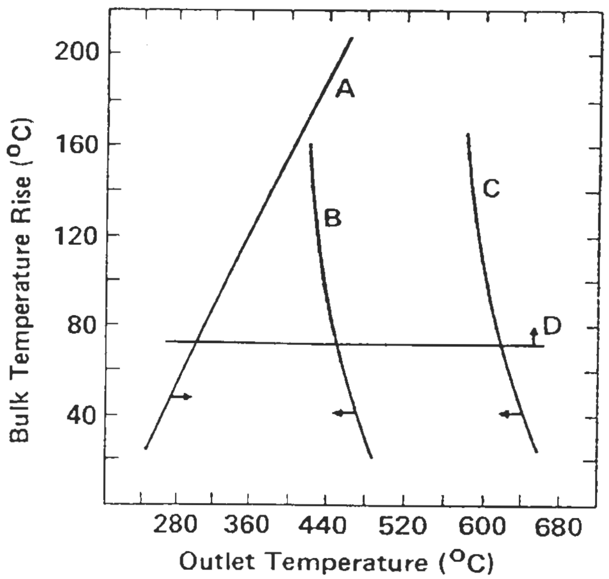
A - Minimum inlet temperature limit

B - Maximum structure temperature limit

C - Maximum interface temperature limit

D - Maximum primary stress limit

Fig. 6 Design window with tapered conduit at 5 MW/m^2 heat flux



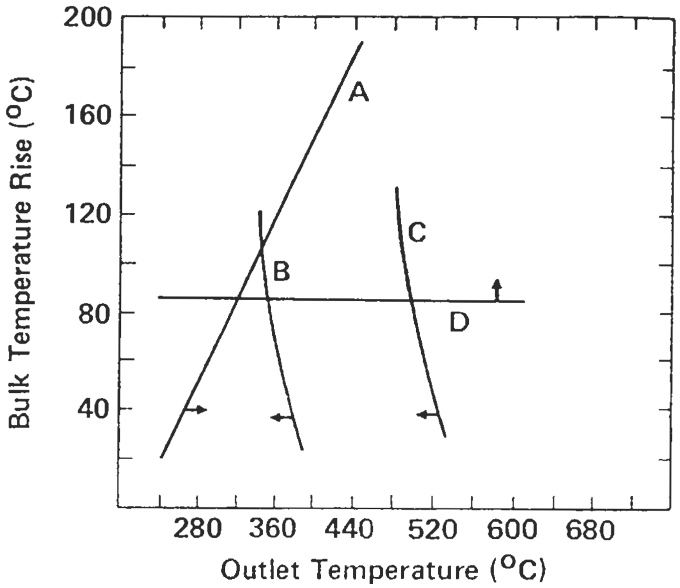
A - Minimum inlet temperature limit

B - Maximum structure temperature limit

C - Maximum interface temperature limit

D - Maximum primary stress limit

Fig. 7 Design window with insulated conduit at 4 MW/m^2 heat flux



A - Minimum inlet temperature limit

B - Maximum structure temperature limit

C - Maximum interface temperature limit

D - Maximum primary stress limit

Fig. 8 Design window with insulated conduit at 5 MW/m^2 heat flux

CONCLUSIONS

Design of limiters with liquid metal cooling appears very difficult but feasible under certain conditions. In light of the above analysis it can be concluded that (for an uncoated limiter):

1) Coolant should be constrained to flow parallel to toroidal magnetic field in the coolant channels.
2) Design of limiter coolant channels appears difficult at 5 MW/m^2 peak heat flux due to large thermal stresses arising in the structure.
3) For conducting walls with no tapering in the feed pipes the maximum permissible peak heat flux is 4 MW/m^2.
4) Insulating or tapering the thickness of the feed pipes increases the allowable peak heat flux to 5 MW/m^2.
5) A limiter design employing insulated feed pipes appears to be the most promising, if suitable insulators can successfully be developed. All the results are based on thin structural material facing the plasma with no coating. This is valid only if no surface erosion occurs. Coating will further reduce the allowable heat flux.

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