University of California, San Diego

UCSD-ENG-107

Advanced Heat Sink Material for Fusion Energy Devices

A. R. Raffray, J. E. Pulsifer and M. S. Tillack

August 31, 2002

Fusion Division
Center for Energy Research

University of California, San Diego
La Jolla, CA 92093-0417

Subcontracting Work Performed by UCSD for Plasma Processes Inc. as Part of DoE SBIR Phase II Grant
"Advanced Heat Sink Material for Fusion Energy Devices"

Final Report

August 31, 2002

A. René Raffray, John Pulsifer, Mark S. Tillack

Summary of First Phase of Work

The interim report from the first phase of UCSD's effort as part of this subcontract summarized the bulk of the subcontract effort which was focused on a comparison of several potential fusion high heat flux concepts using liquid metal cooling as well as one porous configuration using helium cooling [1]. The major observations from the analysis results can be summarized as follows:

1. Single-Phase liquid metal flow in channels

   Channels with liquid metal coolant in conducting walls cannot be used for high heat flux fusion application with MHD effects due to the huge pressure losses. Insulated walls reduce the MHD pressure losses but do not necessarily improve the heat transfer performance for a given flow rate as, even in this case, MHD-flow laminarization is likely to occur. The presence of an insulating coating could even further increase the wall temperature. It is not clear what insulator material can be used. With a Li+Vanadium system AlN and CaO had been proposed but the integrity of the coating and the possibility of in-situ repair have yet to be demonstrated under relevant conditions in spite of many years of effort. For W as structural material, a good insulating coating candidate has not been identified. In general, refractory metals and W in particular, require a rather high operating temperature (>700-800°C for W) to avoid embrittlement under fusion conditions and the high temperature makes it even more difficult to find an adequate insulating material. It is possible to optimize the plasma-facing component geometry to flow the liquid metal coolant parallel to the magnetic field in the high heat flux region and to minimize the flow path length there. This helps in accommodating MHD effects and could significantly increase the effective heat transfer coefficient. However, an insulating channel is still required and the associated issues must still be resolved.

2. <u>Two-Phase liquid metal flow in channels</u>

   Boiling flow would increase to some extent the allowable heat flux in liquid metal system. However, the high operating temperature (equivalent to the boiling point, e.g. ~1340°C for Li at 0.1 MPa) and the need for an insulating wall make it extremely challenging to find a compatible insulator to interface with the liquid metal.

3. <u>Evaporation Cooling</u>

   A proposed evaporation cooling concept relying fully on the high latent heat of vaporization of Li and requiring lower flow rates could operate without insulator in the high heat flux region. However, the maximum heat flux that can be accommodated is limited to ~5-10 MW/m^2 based on the local superheat for a roughness of ~10 μm and film thickness of ~1 mm.

Overall, the liquid metal-based concepts tend to be limited in their application to fusion plasma-facing components in particular when considering the uncertainties associated with MHD effects and they would require a compatible insulator that would preserve its integrity and/or would be self-healing. This led to the consideration of an alternate concept, a helium-cooled porous medium configuration which seems to be potentially more attractive in good part due to its more predictable heat transfer performance. Such a concept appears to be able to comfortably accommodate heat fluxes of ~ 5 MW/m^2 and possibly higher heat fluxes of up to 20-30 MW/m^2 but at the cost of higher pressure drops

(~2 MPa in the latter case) and higher system pressure, and/or of lower coolant inlet temperature and lower-quality heat extraction.

The above observations were mostly based on analysis results and would need to be confirmed experimentally. It seems easier to confirm them for a He-cooled concept in a high heat flux facility than for a liquid-metal concept where MHD effects would have to be included and where any proposed insulator would have to be tested under prototypical conditions as to its integrity and lifetime.

The He-cooled porous concept configuration was further considered by PPI and is the focus of a new SBIR proposal under the same partnership (PPI and UCSD) due to start in 2002.

However, for completeness, it was agreed with PPI that UCSD would re-examined the possibility of 2-phase cooling of plasma facing components using liquid metals as part of the second phase of the subcontract. In particular, the previous analysis of boiling heat transfer focused on critical heat flux for pool boiling. It would be interesting to assess the critical heat flux for flowing liquid metals based on a combination of literature search and updated analysis. The next sections summarize the results of this effort.

Liquid Metal Flow Boiling

The phenomenon of boiling initiation in alkali metals is a very complicated one and the required superheat in a given situation depends on a large number of variables [2]. Most liquid metals, especially alkali metals such as lithium, show a greater change in saturation temperature, corresponding to a given change of pressure, than does an ordinary fluid (water for example). In a vertical system under gravitational force (or possibly for the fusion case under forces associated with MHD), the change of static pressure could appreciably alter the saturation temperature such that explosion-type flow oscillation could occur resulting in liquid expulsion and in flow instability, thereby adding to the complexity of the problem. In addition, alkali metals owing to their reduction power generally wet their containers very well, and, thus, also wet the larger cavities in heating surfaces and render then inactive. This tends to make the incipient-boiling superheats for alkali metals higher than those for ordinary liquids. Also, the capacity of liquid metals to dissolve inert gases increases rather than decreases with increase in temperatures, causing them to absorb gases from potential nucleating cavities (which typically contain gas impurities and promote the inception of boiling). This large superheat is beneficial when considered in the context of evaporation cooling. However, it also results in high surface temperature which limits the choice of possible insulator and structural material compatible with the liquid metal (lithium).

Critical Heat Flux for Flowing Liquid Metals

The critical heat flux condition involves complex phenomena. Experimental determination of CHF is often based on the sudden jump in wall temperature associated with the departure from nucleate boiling and the transition to film boiling. Even higher heat fluxes could be accommodated by film boiling albeit at very high surface temperatures until dry-out is reached.

For liquid metals, in addition to the complexity of predicting boiling phenomena due to the reasons outlined in the previous section, the relative scarcity of data has made it difficult to develop well tested CHF correlation over reasonable ranges of interest of liquids and parameters. For this reason, the initial estimates of CHF presented in the interim report were based on a saturated pool boiling CHF ($q''_{crit,sat,pool}$) correlation proposed by Noyes and Lurie [3]:

$$\frac{q''_{crit,sat,pool}}{\rho_g h_{fg}} = K_c\left(\frac{\sigma(\rho_l - \rho_g)g}{\rho_g^2}\right) + K_{NL} \qquad (1)$$

where h_{fg} is the latent heat of evaporation; ρ_g and ρ_l are the vapor and liquid densities, respectively; σ is the surface tension; g is gravity; and K_c and K_{NL} are parameters determined from previous experimental data (for the Li under a pressure of 1 atm, K_c and K_{NL} were assumed to be = 0.16 and 1 MW/m^2, respectively).

Noyes and Lurie also attempted to correlate experimental data of flowing sodium by the method of superposition neglecting any effect of interactions among various contributions:

$$CHF_{flow} = q''_{crit,sat,pool} + q''_{sub.pool} + q''_{non-boil.\,fc} \qquad (2)$$

where: CHF_{flow} = critical heat flux for flowing iquid;

$q''_{crit,sat,pool}$ = saturated pool; boiling CHF

$q''_{sub,pool}$ = subcooling effect on pool boiling

$q''_{non\text{-}boil.fc}$ = non-boiling forced convection heat flux

$q''_{crit,sat,pool}$ can be estimated from eq. (1). However, to be consistent with the formulation described in Ref. [4] for the different contributions to the CHF, the following correlation from Subbotin, et al., is used:

$$q''_{crit,\,sat,\,pool} = 0.14 h_{fg} \sqrt{\rho_g} \left[1 + \frac{4.5}{P_{cr}} \left(\frac{P_{cr}}{P_l} \right)^{0.4} \right] \left[g\sigma\left(\rho_l - \rho_g\right) \right]^{0.25} \qquad (3)$$

where P_{cr} and P_l are the critical and liquid pressures (MPa), respectively.

The subcooling effect on pool boiling and the non-boiling forced convection heat flux are estimated from the following expressions [4]:

$$q''_{sub.\,pool} = 0.15 h_{fg} \sqrt{\rho_g} \left[0.1 \left(\frac{\rho_l}{\rho_g} \right)^{0.75} + \frac{Cp_l}{h_{fg}} \left(T_{sat} - T_{bulk} \right) \right] \left[g\sigma\left(\rho_l - \rho_g\right) \right]^{0.25} \qquad (4)$$

$$q''_{non-boil.fc} = h_{non-boil.}\left(T_{sat} - T_{bulk}\right) \tag{5}$$

where Cp_l is the liquid specific heat, T_{sat} is the saturation temperature, T_{bulk} is the bulk liquid temperature, and $h_{non\text{-}boil.}$ is the convective heat transfer coefficient in the absence of boiling.

Ref. [4] reports that application of the above equations to estimate flowing liquid metal CHF showed large scatter when compared to existing experimental data. This highlights the difficulty of estimating CHF for liquid metals and cautions about inferring too much from application of these equations. However, they should be useful in showing rough values and in identifying trends.

The analysis was done for a simple geometry consistent with the prior analysis and shown in Fig. 1, with a. channel width of 3 cm, depth of 5 mm and length of 1 m. In the absence of data and of well-developed model, MHD effects were not included in calculating the boiling CHF. However, flow-laminarization was included when estimating the non-boiling convective heat transfer coefficient in Eq. (5) using the method reported in the interim report [1]. Pressure drop estimates were also carried out assuming MHD-effects in an insulated channels. As reported in Ref. [1], MHD pressure drop for conducting channels are so huge that such concepts are not applicable to fusion cases and the presence of an insulating layer must be assumed in the case of conducting walls.

The analysis proceeded by solving for a consistent set of values for the outlet temperature from the channel (based on the heat flux), the liquid velocity and the corresponding CHF. Temperature-dependent properties were used for Li consistent with the prior analysis [1]. The CHF results are summarized in Fig. 2 as a function of the lithium velocity for a Li inlet temperature of 550°C and pressure of 0.1 MPa. The corresponding Li outlet temperature and pressure drop in the channel are shown as a function of velocity in Fig.3.

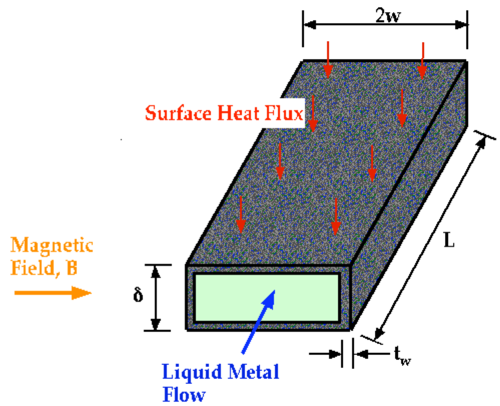


Figure 1 Example liquid metal channel configuration

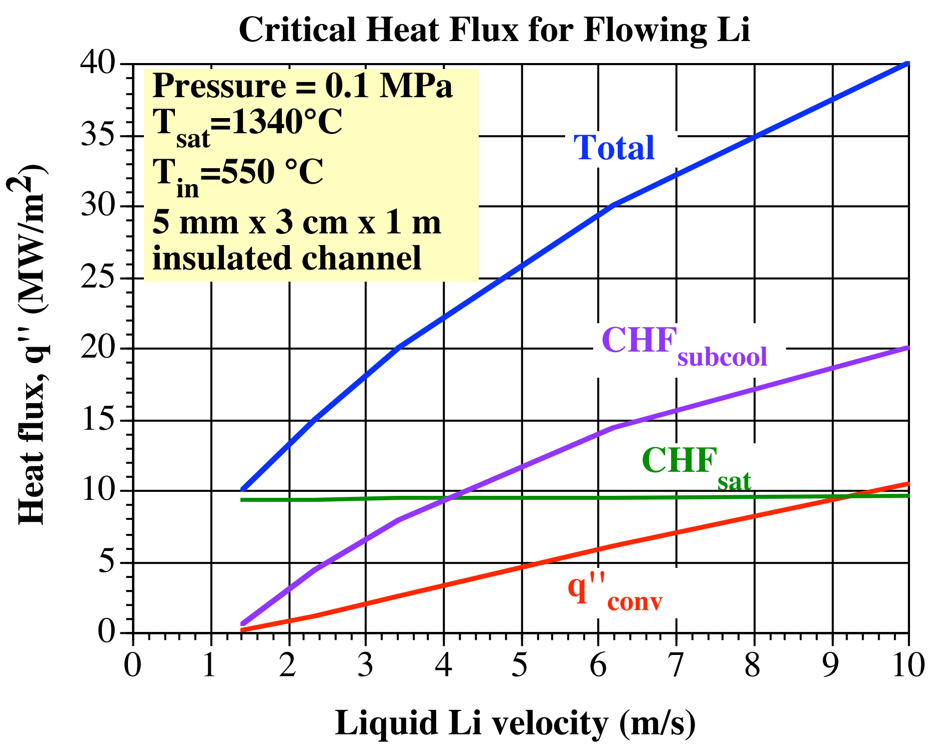


Figure 2 CHF contributions for lithium flowing in a 1-m long insulated channel with an inlet temperature of 550'C and pressure of 0.1 MPa shown as a function of lithium velocity.

The subcooling and non-boiling heat transfer contributions increase as the outlet temperature is decreased (i.e. as the velocity is increased). The saturated pool boiling contribution does not vary much with the velocity and the associated temperature changes and is about 9 MW/m^2 which is higher than the prior value obtained from Eq. [1] but of the same order. This is not inconsistent with CHF estimated for liquid metal which tend to have large uncertainties.

Based solely on the CHF performance shown in Fig. 2, a high velocity (~10 m/s) would accommodate large heat fluxes (up to 40 MW/m^2 based on the model used). Due to the uncertainty in the prediction and in line with common practice in using CHF estimates a safety factor would have to be used of at least 2 or more in this case(as a guestimate). In other words for a design velocity of 10 m/s the allowable heat flux would be about 20 MW/m^2.

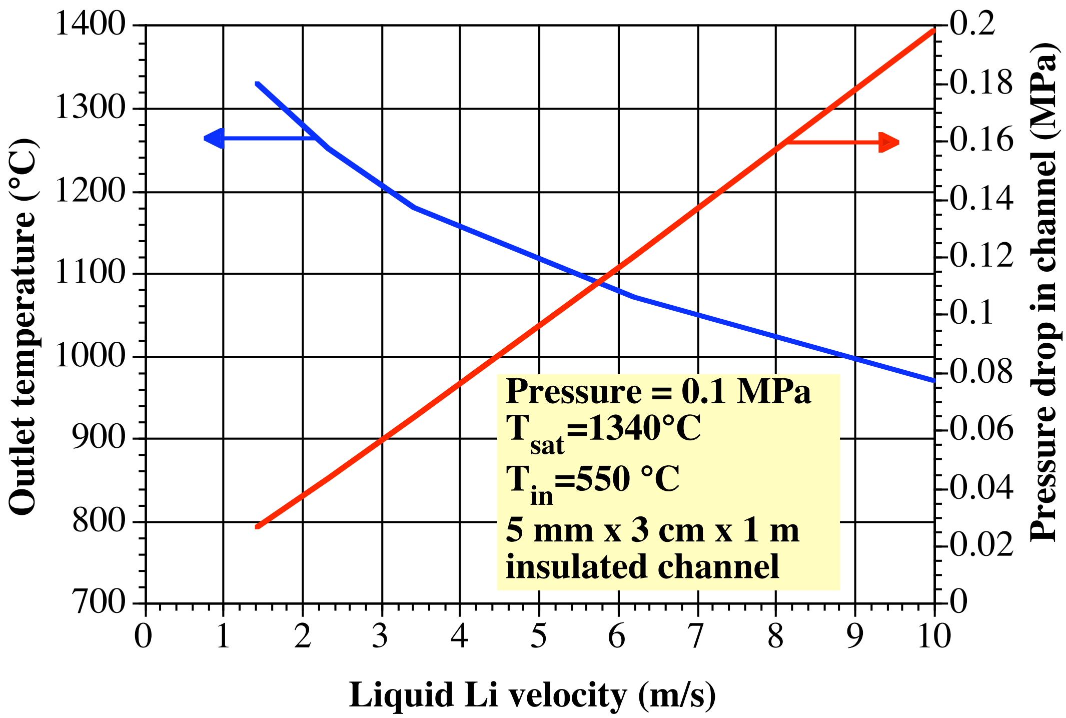


Figure 3 Li outlet temperature and pressure drop in a 1-m long insulated channel as a function of velocity for a Li inlet temperature of 550'C and pressure of 0.1 MPa.

The results shown in Figure 3 illustrates the limits imposed by pressure drop consideration. For a 0.1 MPa system, the pressure drop in the 1-m high heat flux channel only cannot be more than a few % of the total pressure drop, limiting the velocity in this case to about 3 m/s. The corresponding CHF would still be >15 MW/m^2 or about 8 MW/m^2 of allowable heat flux including the safety factor. However, the outlet temperature is about 1200°C, raising severe concerns as to the compatibility and reliability of any insulating material with lithium as coolant, not to mention of the structural material itself.

In addition to compatibility with lithium, other criteria such as strength and embrittlement would limit the maximum temperature of the materials including the temperature rises through the different material layers. Even if the film drop is neglected (optimistically) the temperature rises through the insulator and structural material can be appreciable. For example, Figure 4 shows the temperature rises through a 0.2-mm thick SiC insulating layer and through a 3-mm W wall, respectively as a function of surface heat flux. For a 20 MW/m^2 heat flux, these temperature rises are about 200 °C and 600°C, respectively.

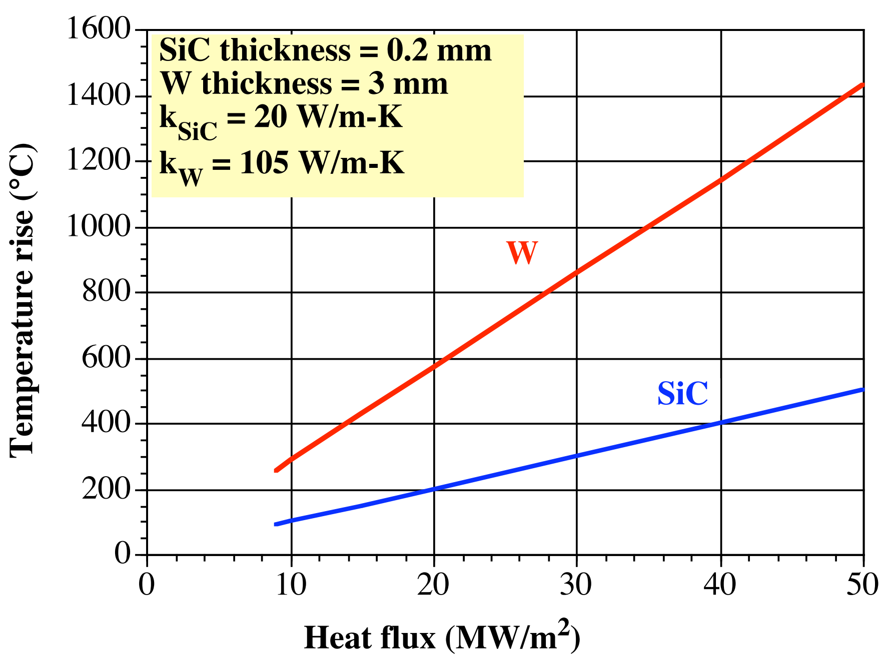


Figure 4 Temperature rises through a 0.2-mm thick SiC insulating layer and through a 3-mm W wall as a function of surface heat flux.

Increasing the system pressure would help in increasing the subcooling effect if the overall flow configuration can be designed to handle the higher pressure stresses. An analysis of this case was also performed and the results are shown in Figures 5 and 6. A CHF of 40 MW/m^2 (allowable heat flux ~ 20 MW/m^2) can be achieved with a velocity of about 4 m/s (based on this model). The corresponding pressure drop is about 0.07 MPa which could be acceptable. However, the outlet temperature is now >1400°C raising even bigger concerns as to the choice of insulating and structural material that could accommodate this temperature and be compatible with lithium. Reducing the outlet temperature even to the still high value of 1100-1200°C would require a velocity of about 10 m/s with a corresponding pressure drop of ~0.2 MPa which is probably not acceptable. Still, it appears that based on these criteria increasing the system pressure would be beneficial provided again that the pressure stresses are acceptable.

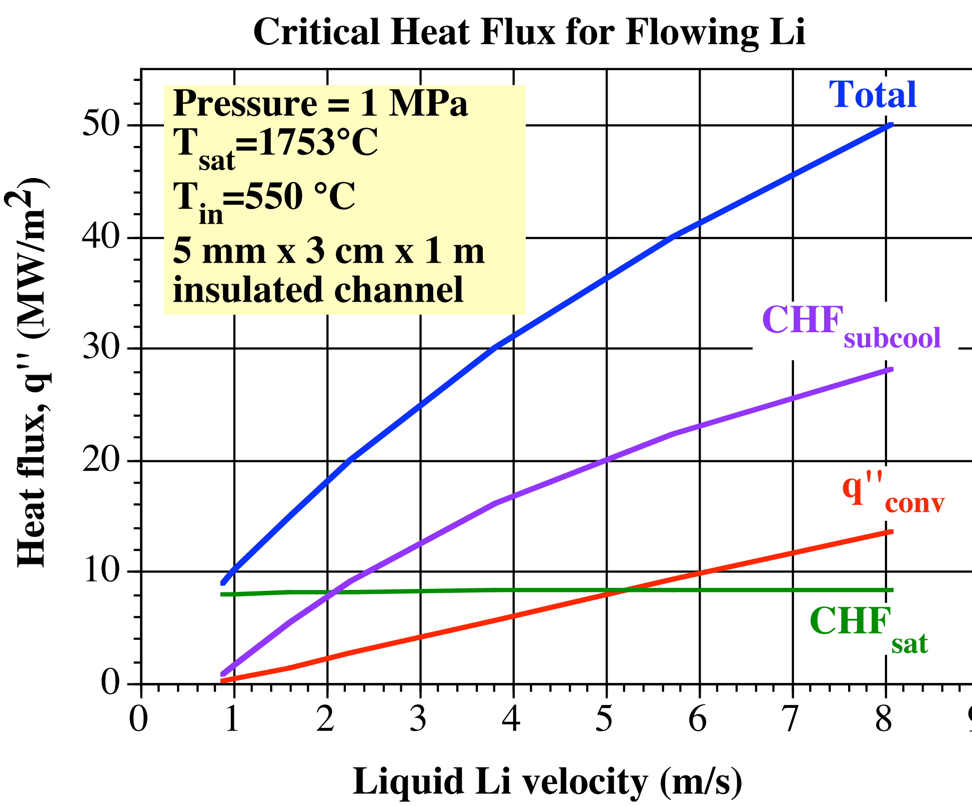


Figure 5 CHF contributions for lithium flowing in a 1-m long channel with an inlet temperature of 550'C and pressure of 1 MPa shown as a function of lithium velocity.

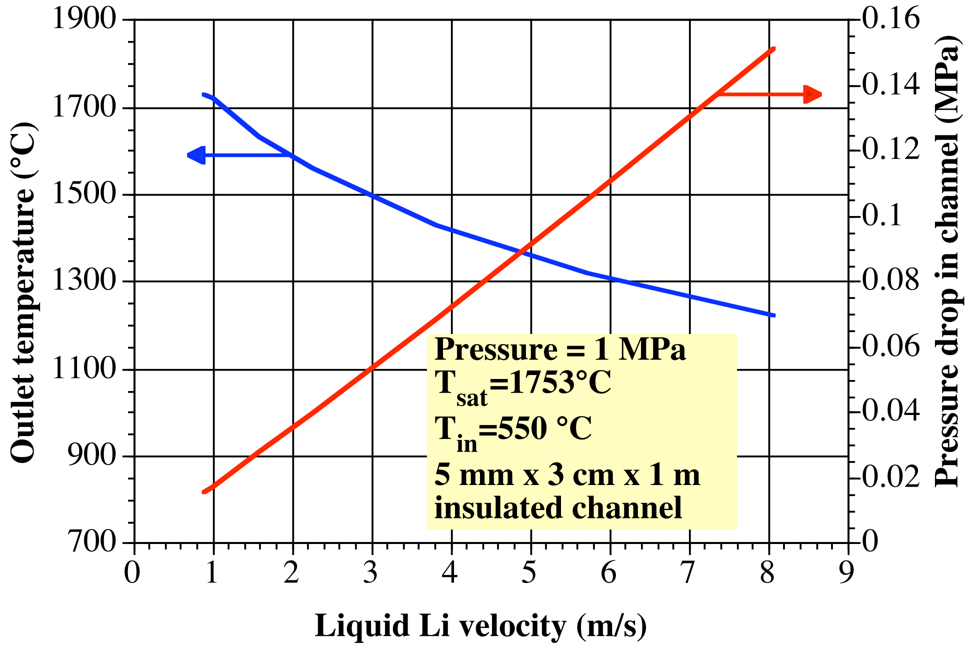
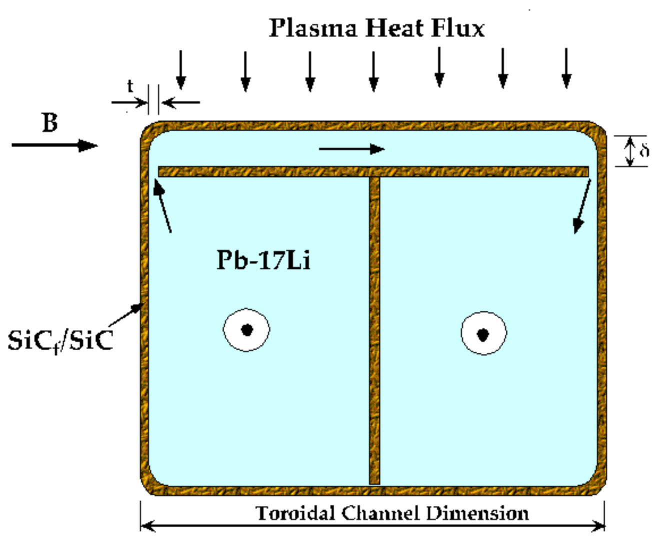


Figure 6 Li outlet temperature and pressure drop in a 1-m long channel as a function of velocity for a Li inlet temperature of 550'C and pressure of 1 MPa.

It is possible to design the high heat flux configuration such that the lithium flow path through the high heat flux region is minimized, and the pressure drop reduce accordingly. This would be the case for a configuration based on the ARIES-AT divertor (see Fig. 7) described in the interim report [1]

The example analysis was done for a similar design with Li as coolant and a 3-mm thick W wall with a thin 0.2 mm SiC-like insulating insert. The channel thickness, width and length were set as 0.2 mm, 1 m and 3 cm, respectively.

The results are summarized in Figures 8 and 9. A CHF of about 50 MW/m^2 can be obtained with a velocity of about 1 m/s. The corresponding pressure drop is very small. The outlet temperature is about 950°C which could cause some thermal stress concern since the temperature would change from the inlet value of 550°C to ~950°C over a 3-cm distance. Of more concern though is the enormous temperature rises in the SiC and W as illustrated in Fig. 4. This is a key constraint. For example, assuming an outlet Li temperature of 1000°C and maximum temperature limits of 1200°C and 1500°C for SiC and W, respectively (as illustration only as these limits have not been clearly defined yet), the maximum allowable heat flux is limited to ~20 MW/m^2 and ~17 MW/m^2, respectively.



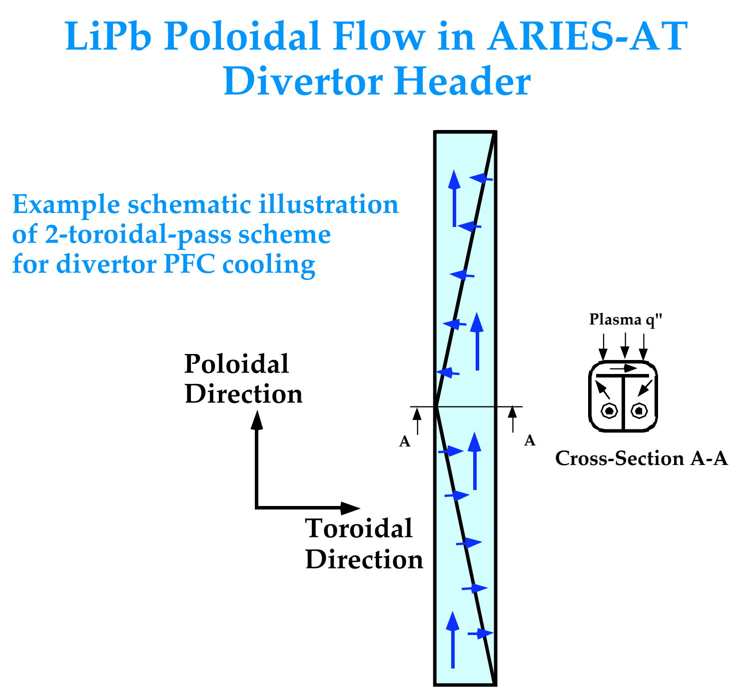


Figure 7 (a) and (b) ARIES-AT divertor configuration and Pb-17Li cooling scheme using 2-toroidal pass scheme and minimizing path length through heated section [5]

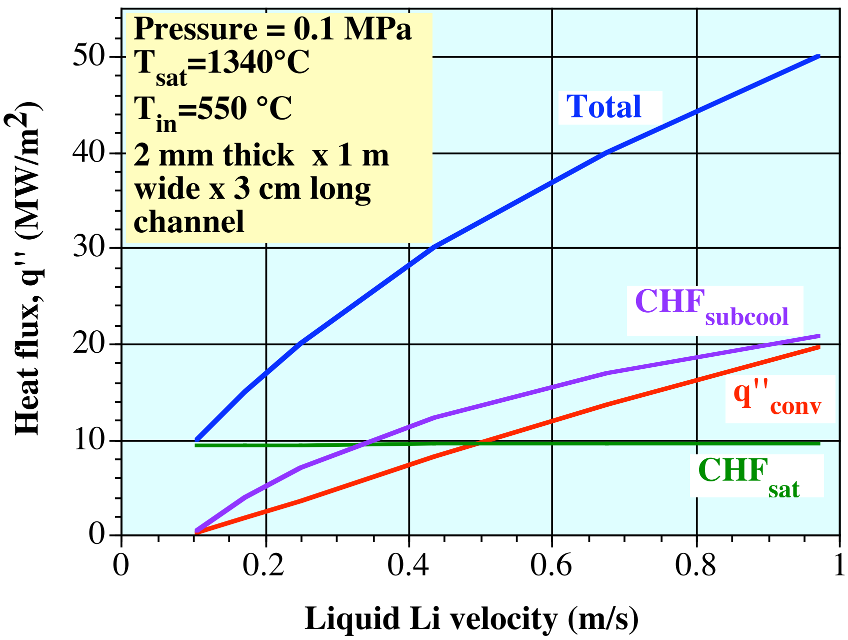


Figure 8 CHF contributions for lithium flowing in a 3-cm long channel with an inlet temperature of 550'C and pressure of 0.1 MPa shown as a function of lithium velocity.

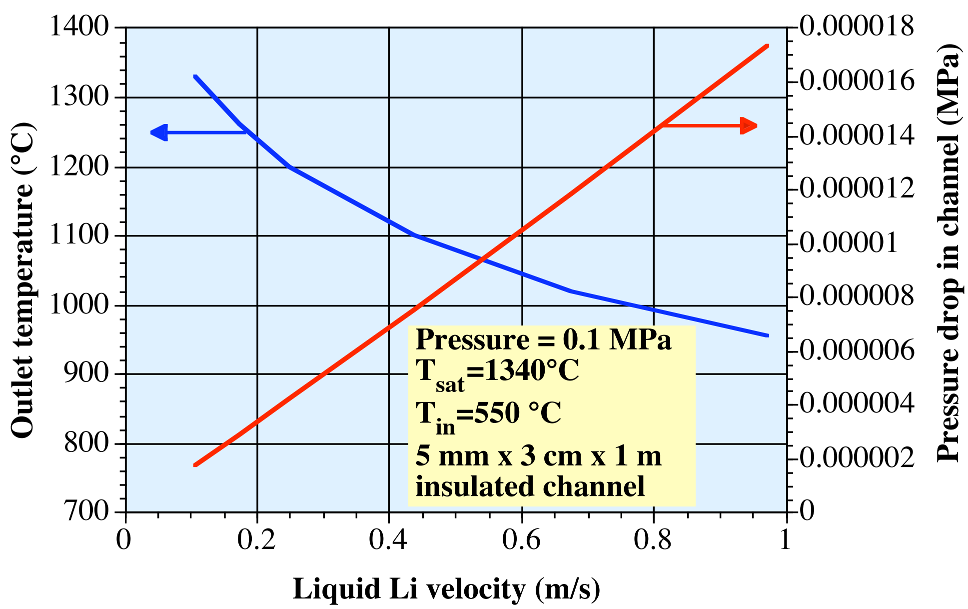


Figure 9 Li outlet temperature and pressure drop in a 3-cm long channel as a function of velocity for a Li inlet temperature of 550'C and pressure of 0.1 MPa.

Conclusions

In general, the observations and conclusions from the first phase are still valid. A more detailed assessment of 2-phase cooling with liquid metals in a fusion environment shows the possibility of increasing the critical heat flux by considering flowing lithium and by increasing the system pressure.

The database on critical heat flux for flowing liquid metals is still limited and no well-developed and well-tested correlation ad/or model was found in the literature. A correlation based on the method of superposition was found but its previous application showed large scatters in the predicted data compared to some available experimental data on sodium CHF. In the absence of better models and with the understanding that this model would only be used to provide a rough guidance for the case of flowing lithium in a fusion-relevant configuration, an analysis was made to provide some insight in the trade-off between achieving higher CHF and the velocity (and associated pressure drop) required.

The results indicated that for a conventional channel, CHF values of ~ 40 MW/m^2 could be obtained with high lithium velocities (~10 m/s) for a 0.1 MPa system. However, the corresponding pressure drop is too high and a reduction in velocity would reduce the CHF to just over 15 MW/m^2. When taking into account the typical safety factor used in such CHF cases (assumed to be 2 here), the maximum allowable heat flux is about 8 MW/m^2.

By increasing the system pressure to 1 MPa, a CHF of 40 MW/m^2 (allowable heat flux ~ 20 MW/m^2) can be achieved with a velocity of about 4 m/s (based on this model). The corresponding pressure drop is about 0.07 MPa which could be acceptable. However, the outlet temperature is >1400°C raising major concerns as to the choice of insulating and structural materials that could accommodate this temperature and be compatible with lithium. Still, it appears that based on these criteria increasing the system pressure would be beneficial provided that the pressure stresses are acceptable.

It is possible to design the high heat flux configuration such that the lithium flow path through the high heat flux region is minimized, and the pressure drop reduce accordingly. For an ARIES-AT divertor type of configuration, a CHF of about 50 MW/m^2 (allowable heat flux ~ 25 MW/m^2) can be obtained with a velocity of about 1 m/s for a 0.1 MPa system. The corresponding pressure drop is very small. The outlet temperature is ~950°C which could cause some thermal stress concern since the temperature would change from the inlet value of 550°C to ~950°C over a short distance (~3 cm). Of more concern though is the enormous temperature rises in the SiC and W which in all cases are directly dependent on the surface heat flux.

In summary, consideration of CHF for flowing lithium would probably increase the allowable heat flux in particular in a design minimizing the flow path in the high heat flux region and with higher system pressure. An overall evaluation must consider the allowable heat fluxes in conjunction with the pressure drop and the temperature limits for insulator and/or structural materials in contact with lithium as well as the overall temperature limits of these materials based on other requirements (e.g. strength, embrittlement under irradiation etc..). The initial analysis indicates that the heat fluxes for this kind of system (2-phase flowing lithium) are probably limited to ~10-15 MW/m^2 or lower depending on the material maximum temperature limits. However, these are very approximate results given the many uncertainties in the correlations used as well as in the understanding of the different phenomena involved in particular when considering the added complexity of MHD effects in a fusion environment. A final assessment should only be based on experimental results in a prototypical environment.

As a word of caution to the use of boiling liquid metal in a fusion reactor, it should be noted that for a liquid metal-cooled nuclear reactor (e.g. sodium-cooled reactor) boiling is considered an accident condition and a reactor design should include considerable margin to prevent initiation of boiling [4].

References

1. A. René Raffray, John Pulsifer, Mark S. Tillack , "Subcontracting Work Performed by UCSD for Plasma Processes Inc. as Part of DoE SBIR Phase II Grant: "Advanced Heat Sink Material for Fusion Energy Devices", Interim Report, 2001.

2. O. E. Dwyer, "On incipient-boiling wall superheats in liquid metals," Int. J. heat mass Transfer, Vol. 12, pp1403-1419, 1969.

3. "Handbook of Heat Transfer Fundamentals," Editors: W. M. Rohsenow, J. P. Hartnett, E. N. Granic´, 2nd Edition, Mc Graw-Hill Book Co., New York, 1985.

4. L. S. Tong and Y. S. Tang, "Boiling Heat Transfer and Two-Phase Flow," second edition, Taylor & Francis, Washington, D.C., 1997.

5. A. R. Raffray, L. El-Guebaly, S. Malang, I. Sviatoslavsky, M. S. Tillack, X. Wang, and the ARIES Team, "ARIES-AT Blanket and Divertor," 14th ANS Topical Meeting on Technology of Fusion Energy, October 15-19, 2000, Park City Utah.