Thermal Analysis of Liquid First Wall

Dependence of Liquid Surface Temperature on Radiation Penetration and Turbulence Enhancement

Alice Ying

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Objectives

- To evaluate thermal response of the liquid jet/film and to help establish design windows for the liquid first wall concepts in MFE devices.

- The goal of thermal analysis is to achieve a minimum surface temperature facing the plasma side and a maximum exit temperature from the blanket.

  [Minimum surface temperature is determined by the maximum allowable evaporation rate for liquid that still insure stable plasma operation].

- The impact of photon radiation spectrum, the choice of the liquid, flow configuration, liquid velocity and thickness is under investigation.

  Candidate liquids- Li, Flibe and Pb-17Li

  Flow configurations considered are turbulent free jet and fast flowing film.

Methodology - Three-Dimensional Numerical Solution

The temperature profile of the liquid jet/film is calculated using a three-dimensional finite difference heat transfer code. The code solves the energy equation:

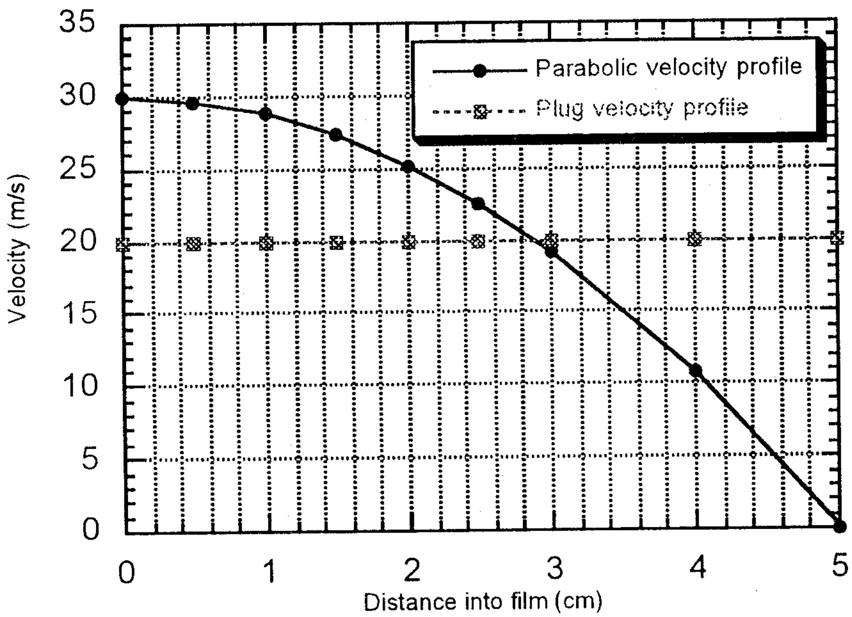
$$\rho C_p \left[v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} \right] = K\nabla^2 T + q'''$$

- Surface heat flux is applied as a boundary condition while heat deposition due to nuclear heating and x-ray penetration are accounted in the heat source term.
- To account for the sharp heat deposition gradient, finer meshes are used in the first 1 cm of the jet/film close to the plasma side.

Velocity Profile

- A plug velocity profile is used to simulate the turbulent jet velocity profile; while a parabolic velocity profile is used for the turbulent film.

- Turbulent "patches" are included in the analysis to estimate the turbulent heat transfer enhancement for flibe film.



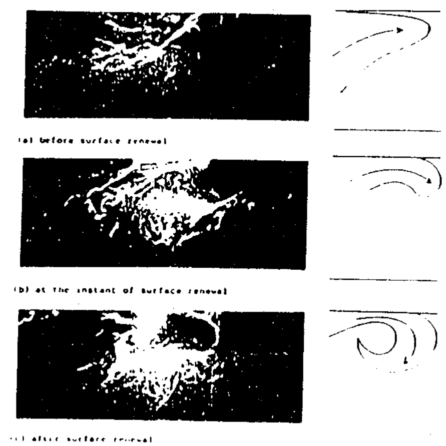


Figure 20. Flow patterns of the large-scale motions, visualized by the hydrogen bubble technique by Komori *et al* (1989a).

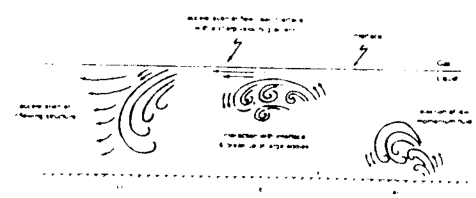


Figure 24. Sketch of burst evolution in a flowing liquid layer between a wall and a free surface. (a) Ejection from the wall; (b) Interaction with the interface; (c) Inflow from the interface.

Problem Illustration

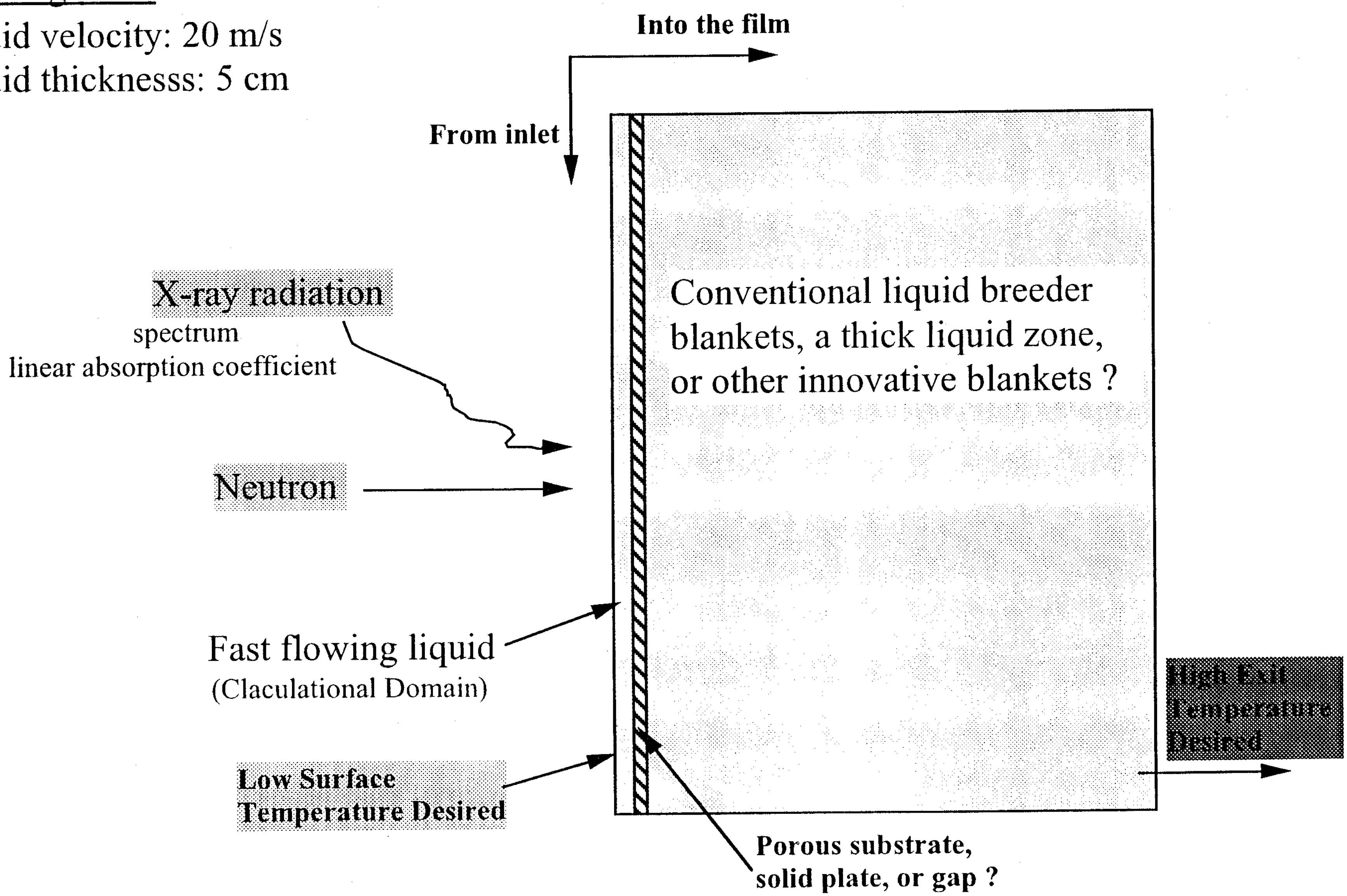
Surface heat load = 2 MW/m^2

Neutron wall load = 7 MW/m^2

Starting Point

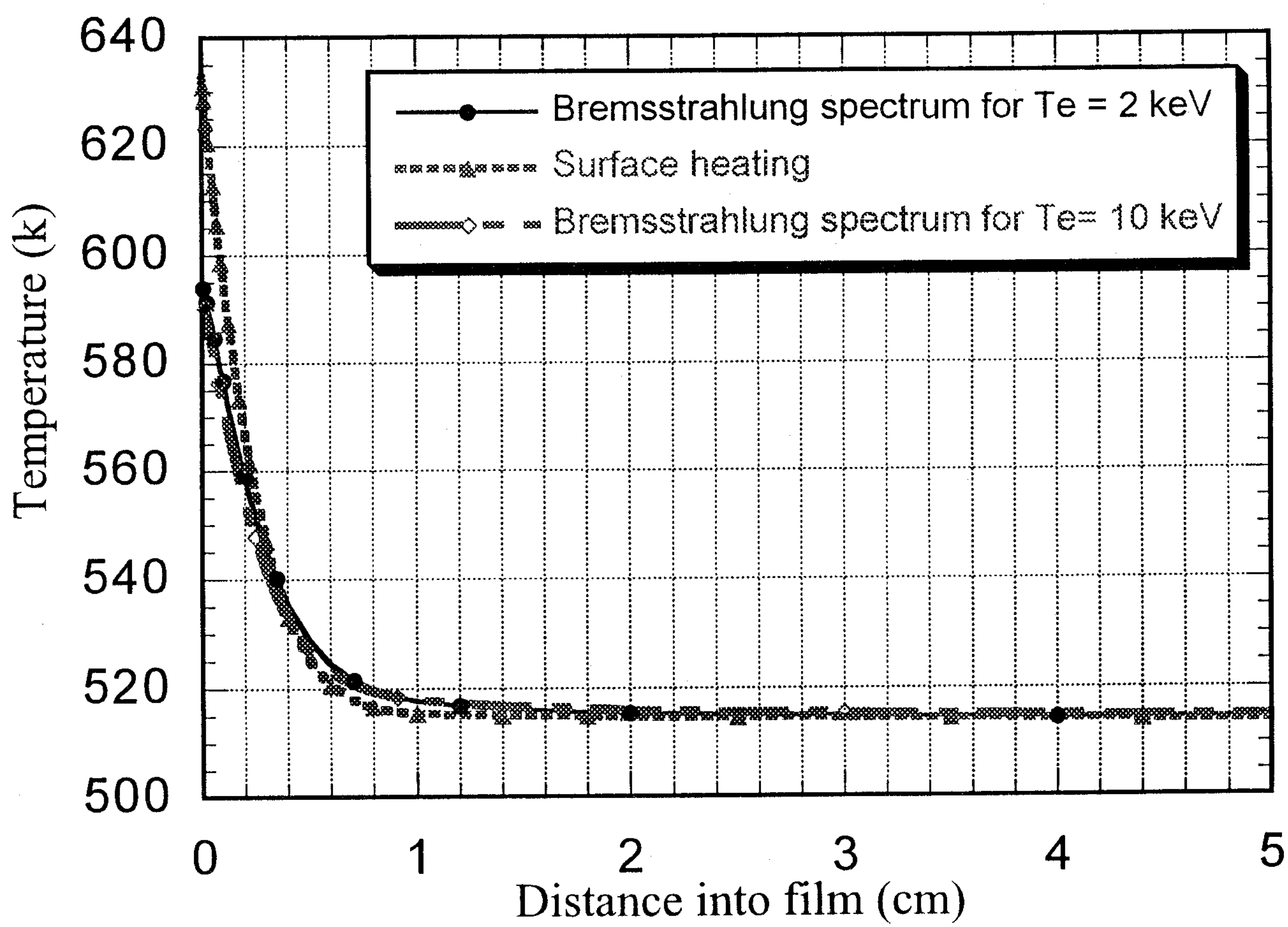
liquid velocity: 20 m/s

liquid thicknesss: 5 cm

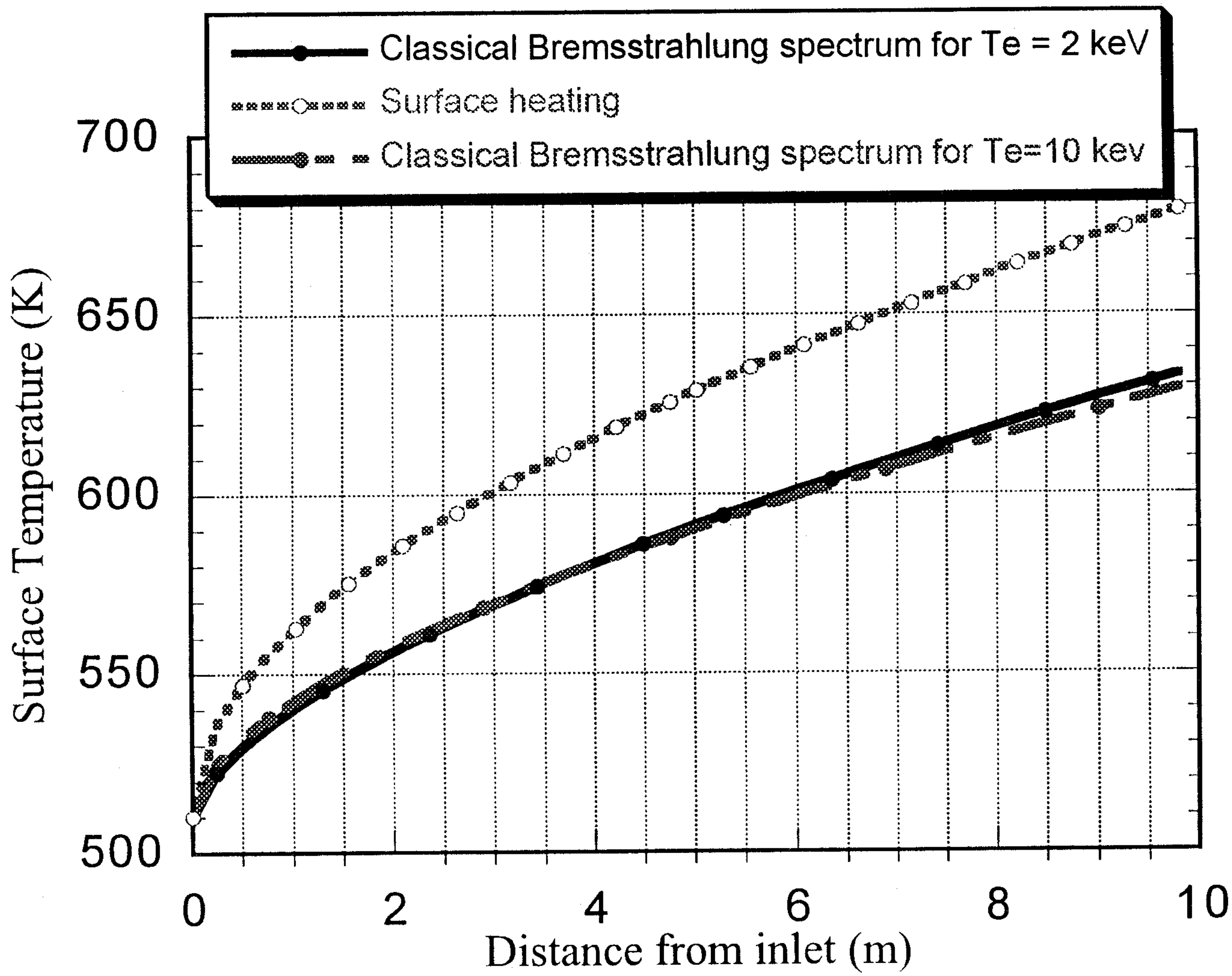


Impace of Incident Photon Energy Spectrum on Lithium Film Temperature Profile (Plug velocity profile of 20 m/s; mid-plane location)

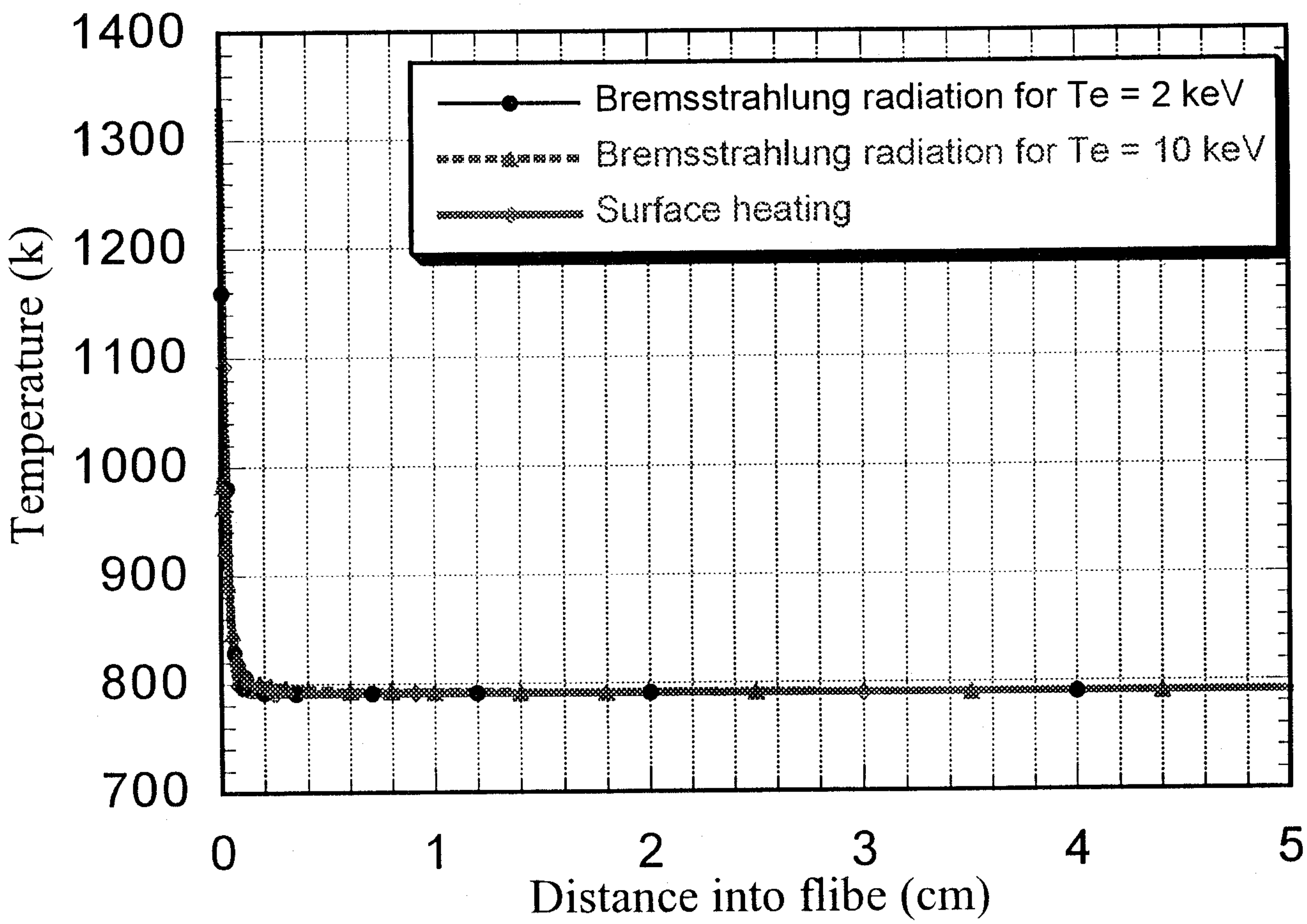
Surface temperature at mid-plane drops about 40 K under the assumed spectra



Total Fractional Power of Low Energy Tails are about the Same for 2 Spectra Investigated



Flibe Surface Temperature Drops about 340 K if the Incident Surface Heat Load Follows a Classical Bremsstrahlung Radiation of Te= 10 keV



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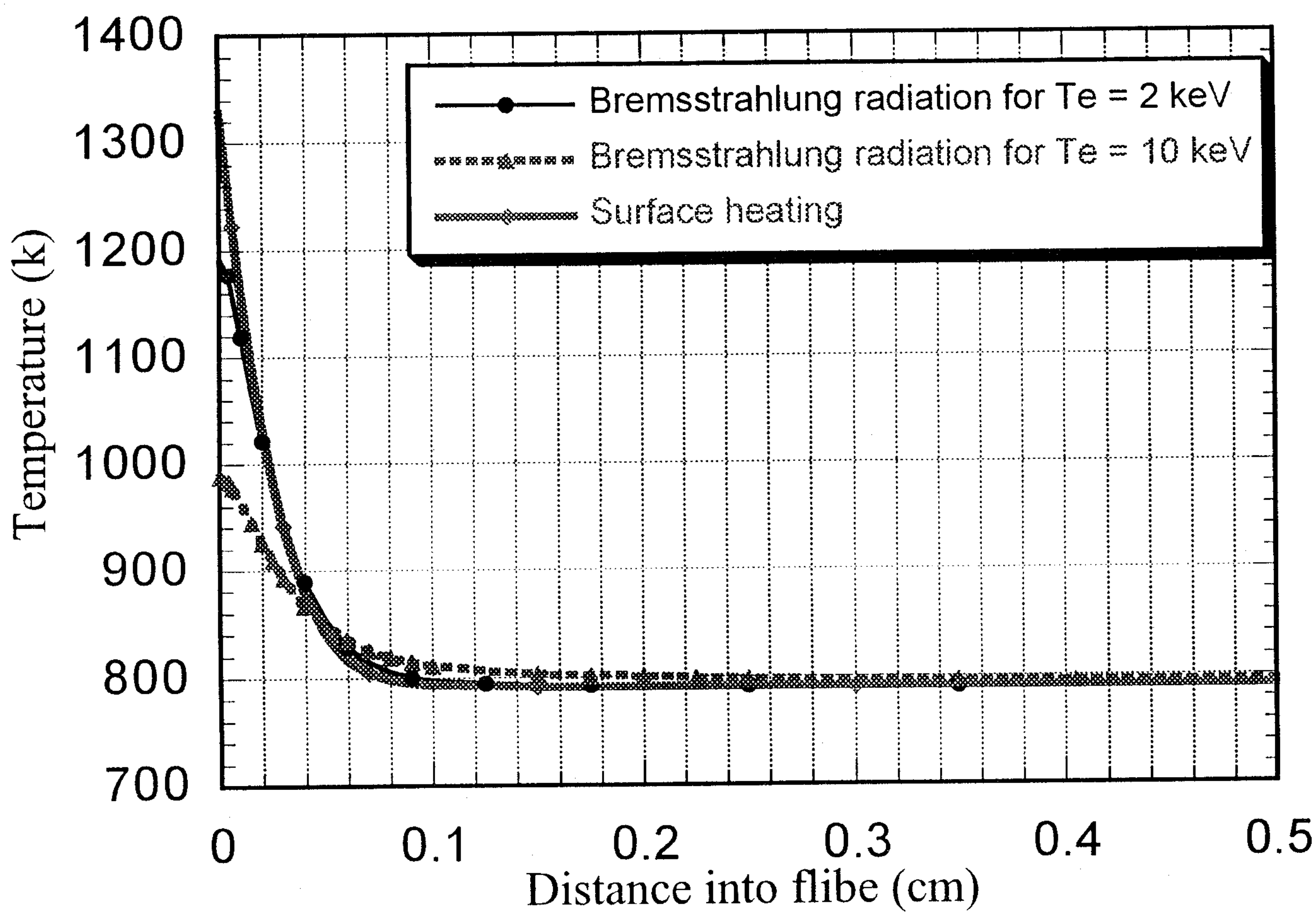
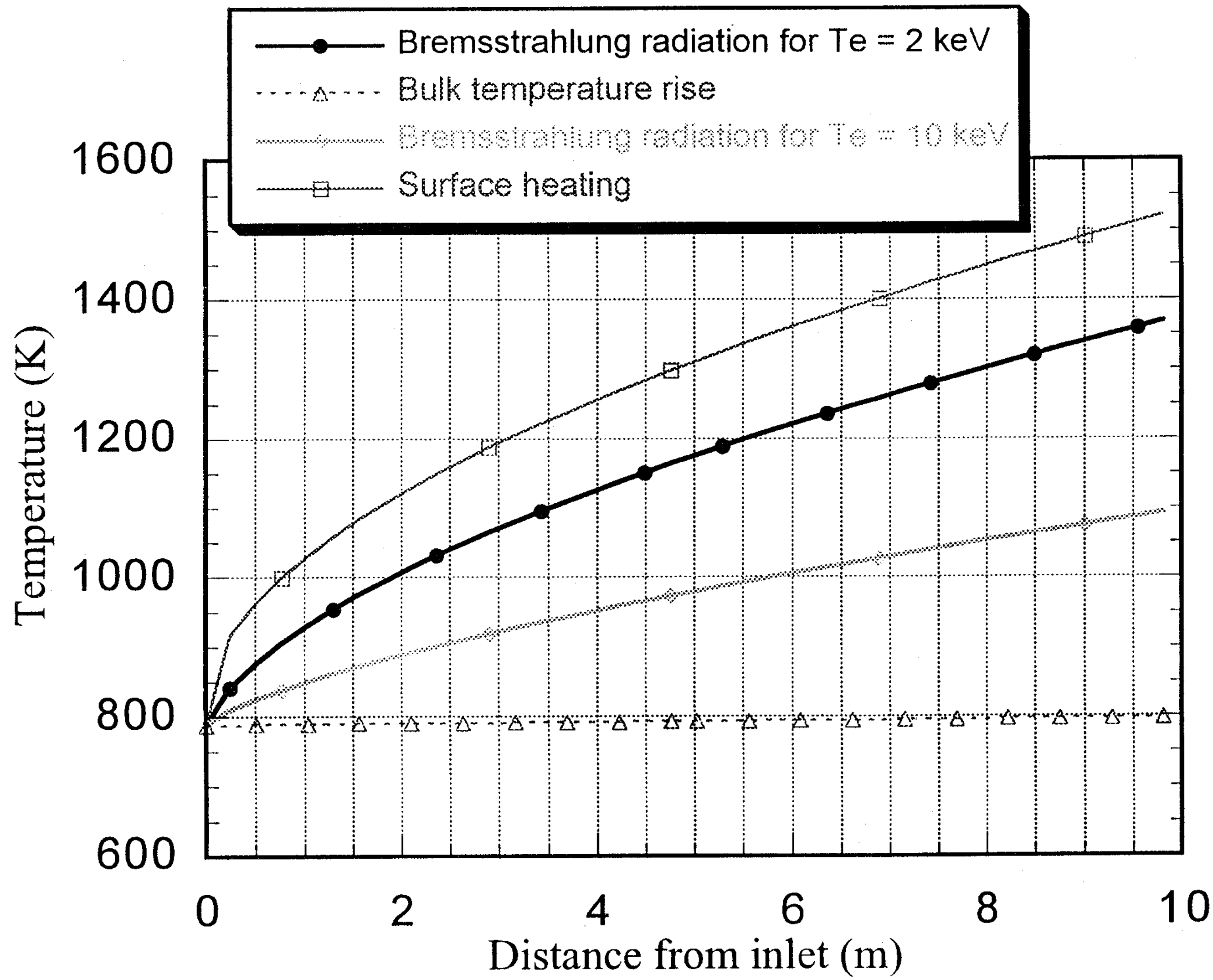
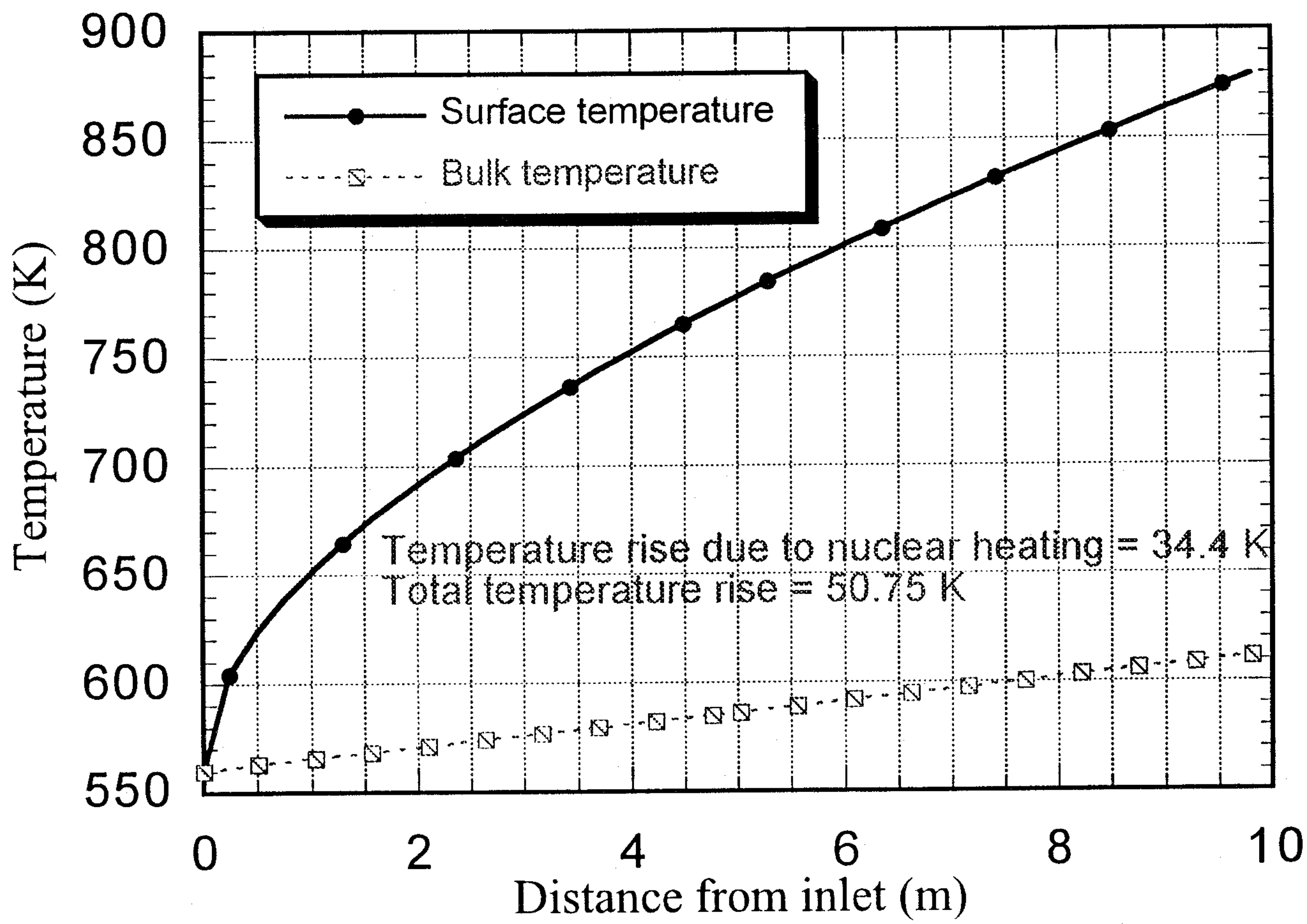
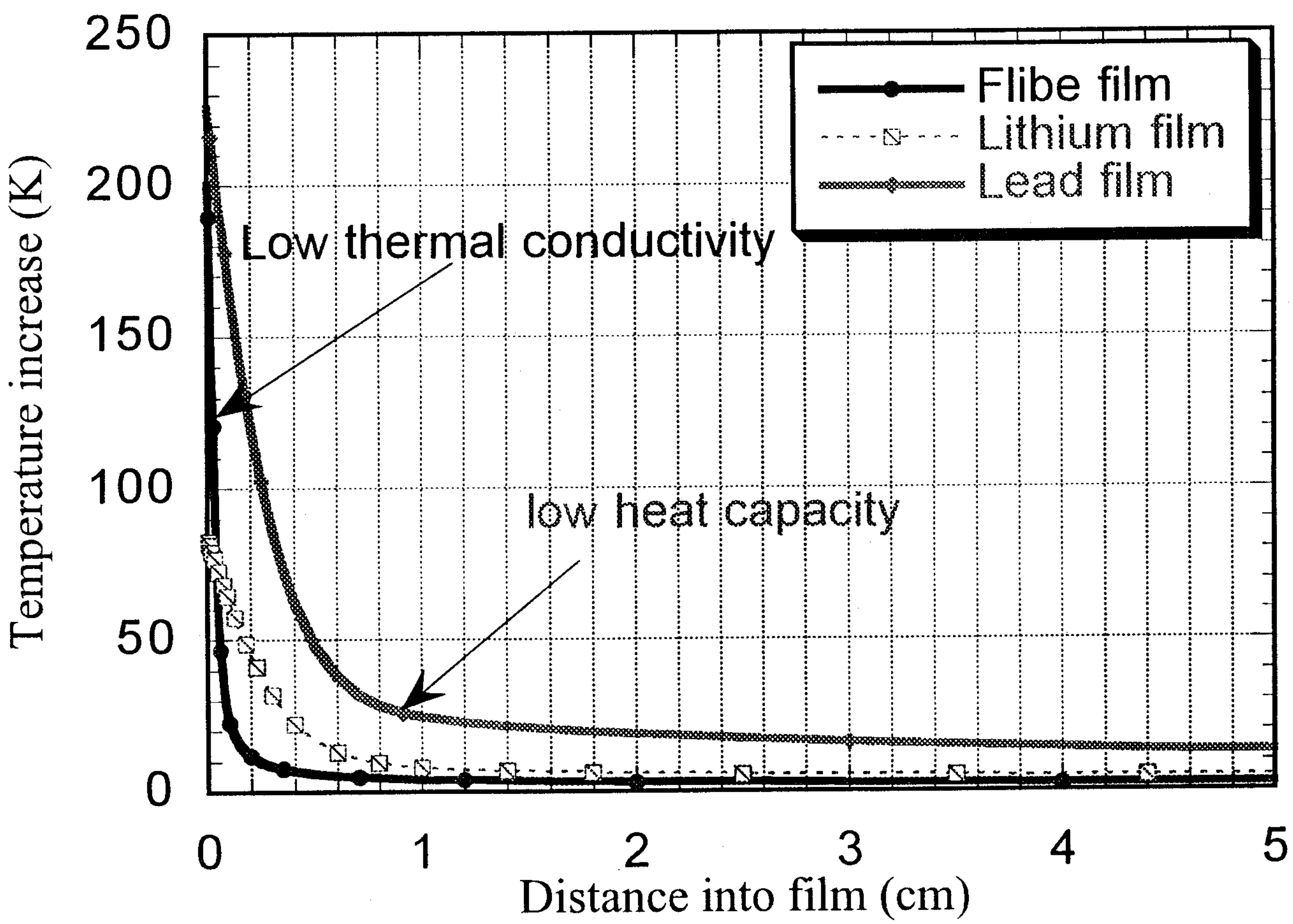



Bremsstrahlung radiation for Te = 2 keV
Bulk temperature rise
Bremsstrahlung radiation for Te = 10 keV
Surface heating
1600
1400
1200
1000
800
600
Temperature (K)
0
2
4
6
8
10
Distance from inlet (m)

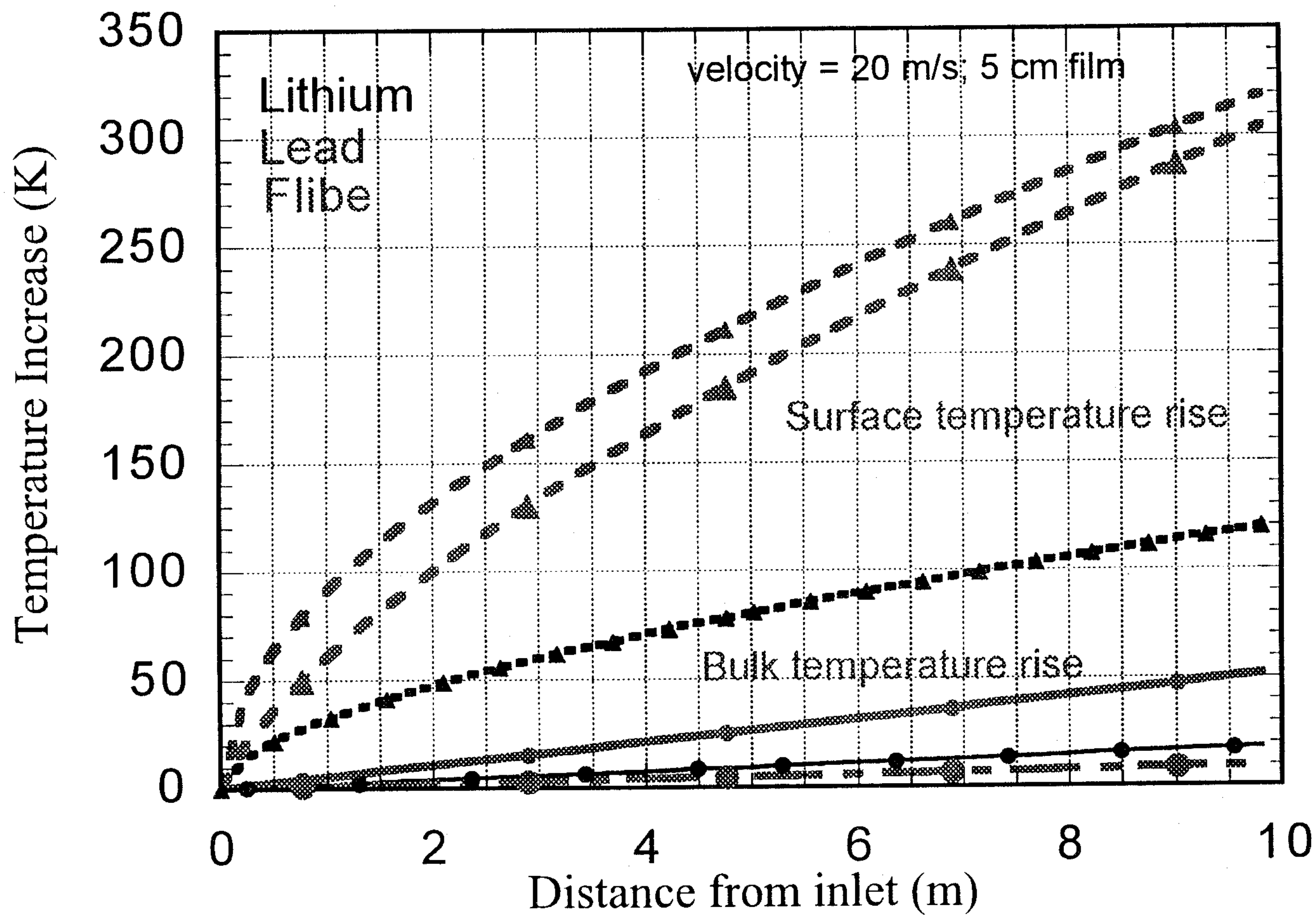
Characteristics of Temperature Increase as Lead Proceeds Downstream (lead velocity = 20 m/s, film thickness = 5 cm)



Impact of Liquid Thermal-physical Properties on Temperature Gradient Across the Film

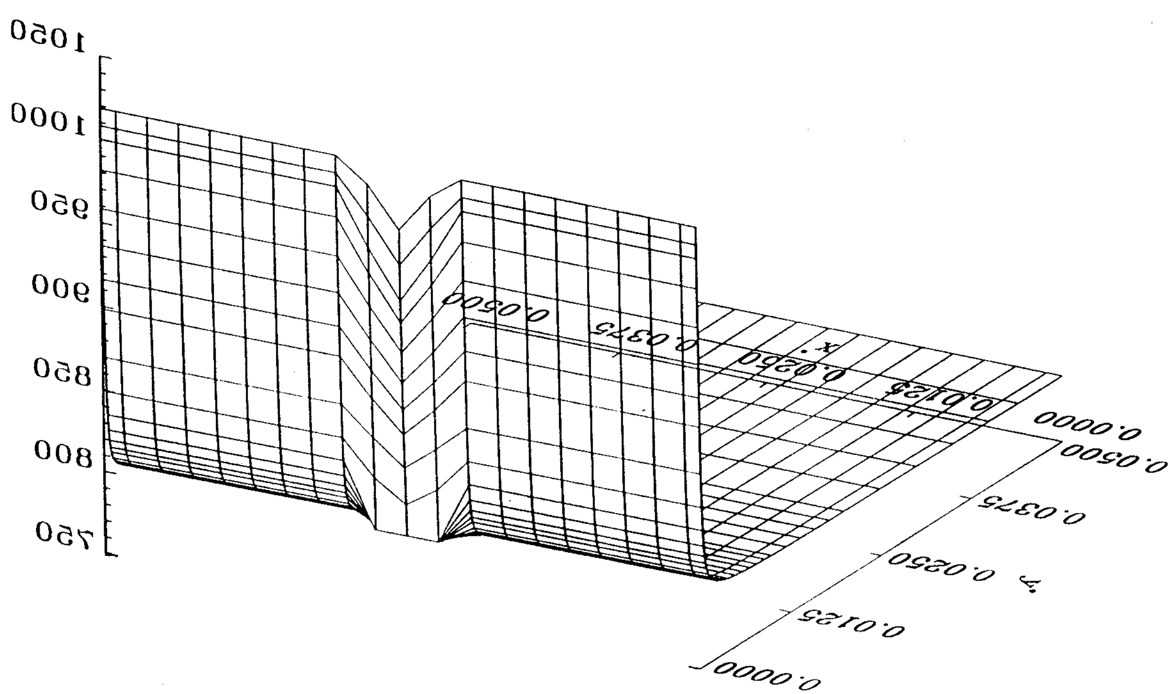


Lithium has the lowest surface temperature rise while Li-Pb has both the highest surface and bulk temperature rises

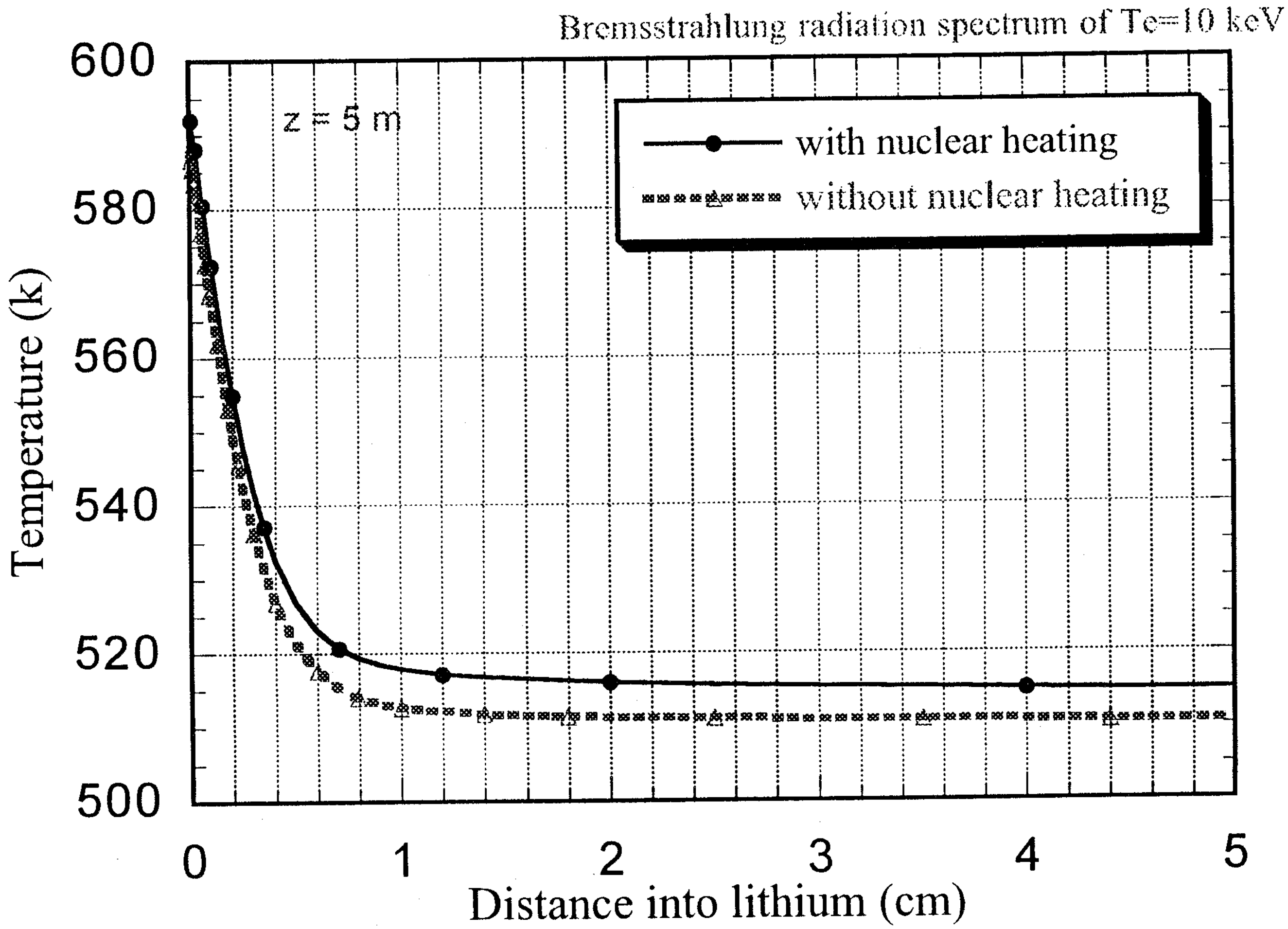


The Magnitude of Surface Temperature Drop Depends on the Size of the Velocity Fluctuation (which Characterizes the Turbulent Patch)

The calculation assumes Vy = 4% of Vz. Vx is determined based on mass balance and the size of the eddy. Flibe surface temperature drops about 20 to 40 K.

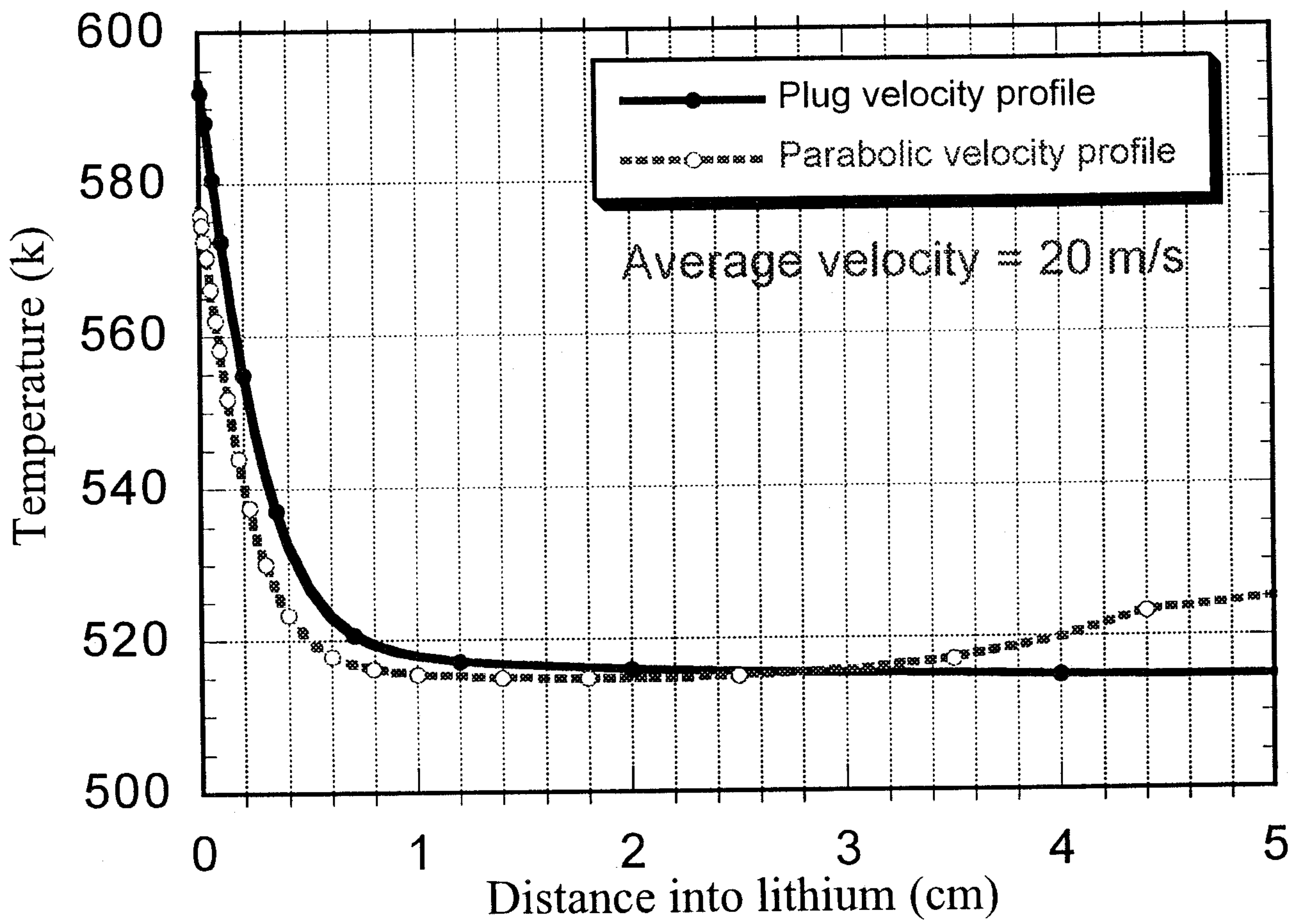


Lithium Surface Temperature Increases Slightly due to Additional Nuclear Heating (about 6 K)



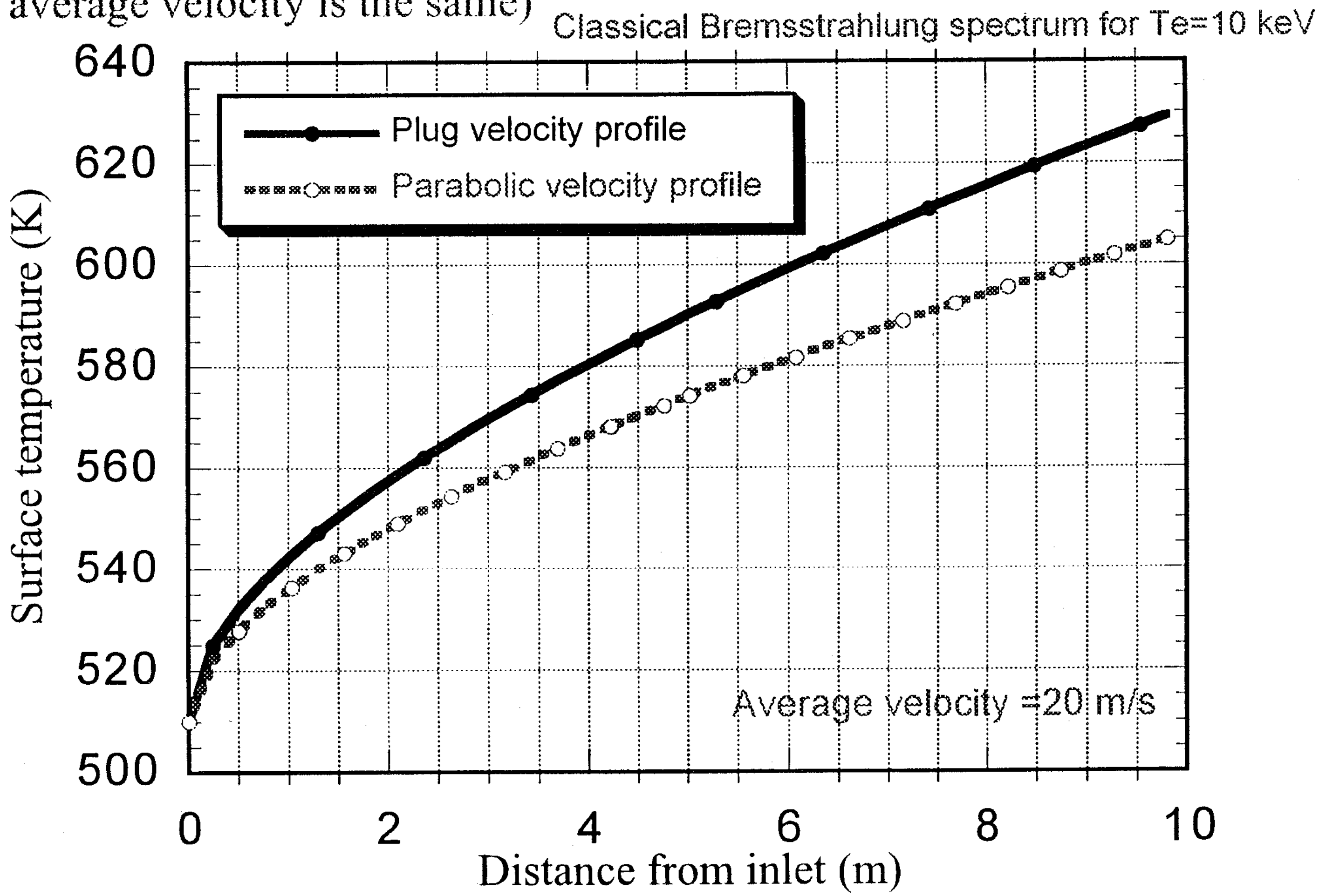
Impact of Velocity Profile on Lithium Film Temperature Profile

Surface temperature drops about 17 K due to a higher velocity on the free surface side in a parabolic velocity profile

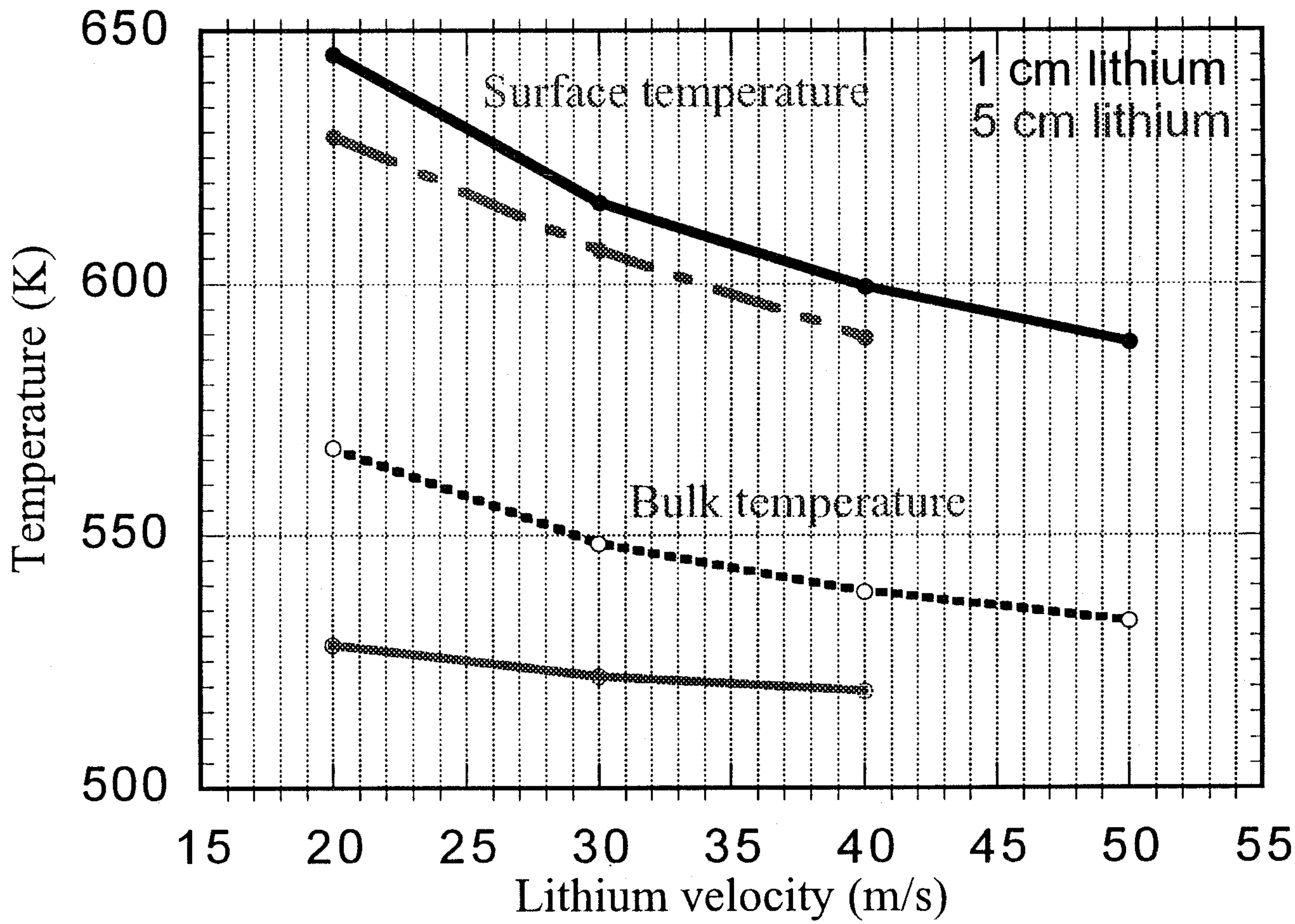


Impact of Velocity Profile on Lithium Film Surface Temperature

A higher surface velocity helps to reduce the surface temperature (even the average velocity is the same)

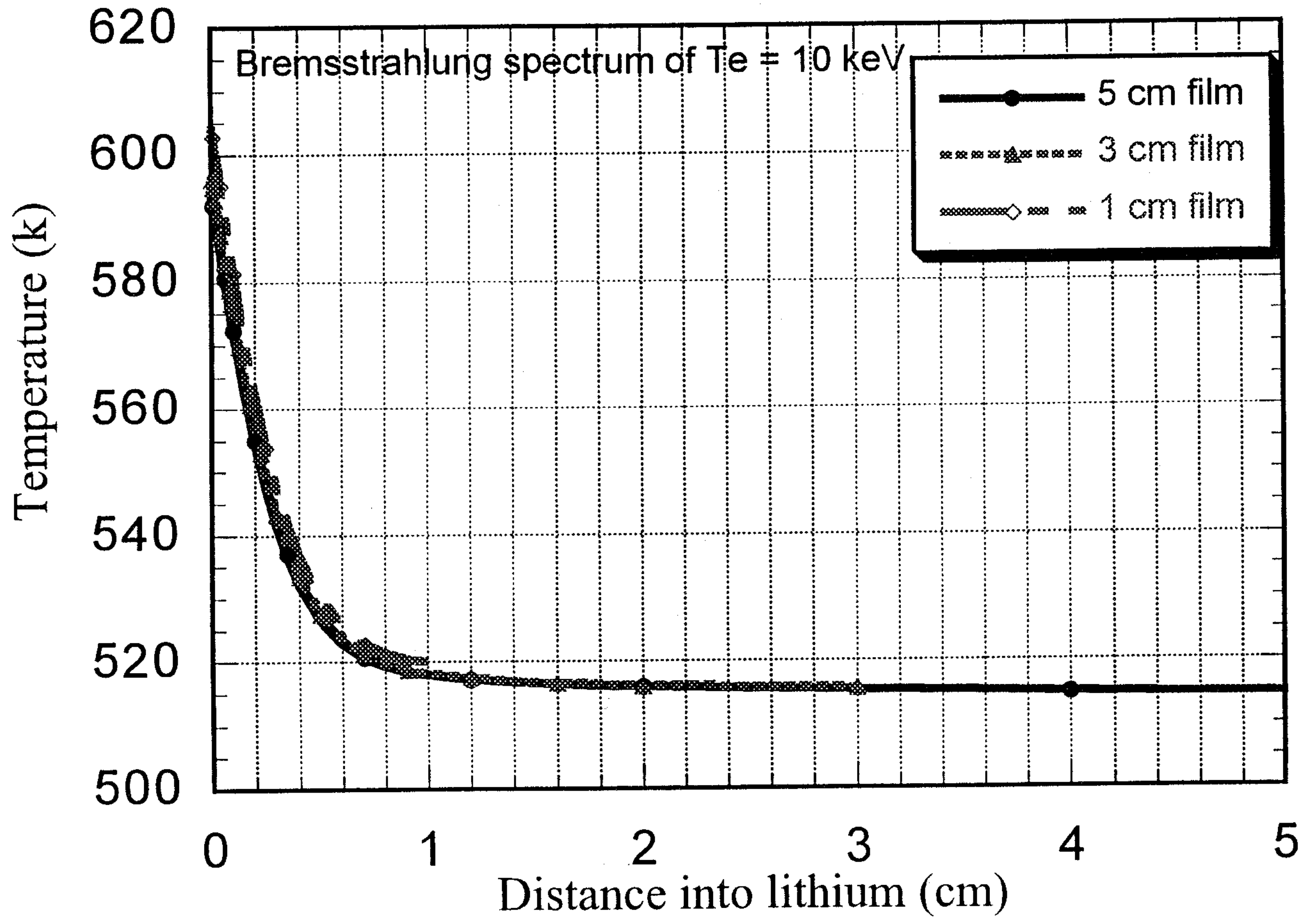


Increasing Lithium Flow Velocity Helps Smooth out the Temperature Gradient Across the Jet; Meanwhile Reduces the Surface Temperature

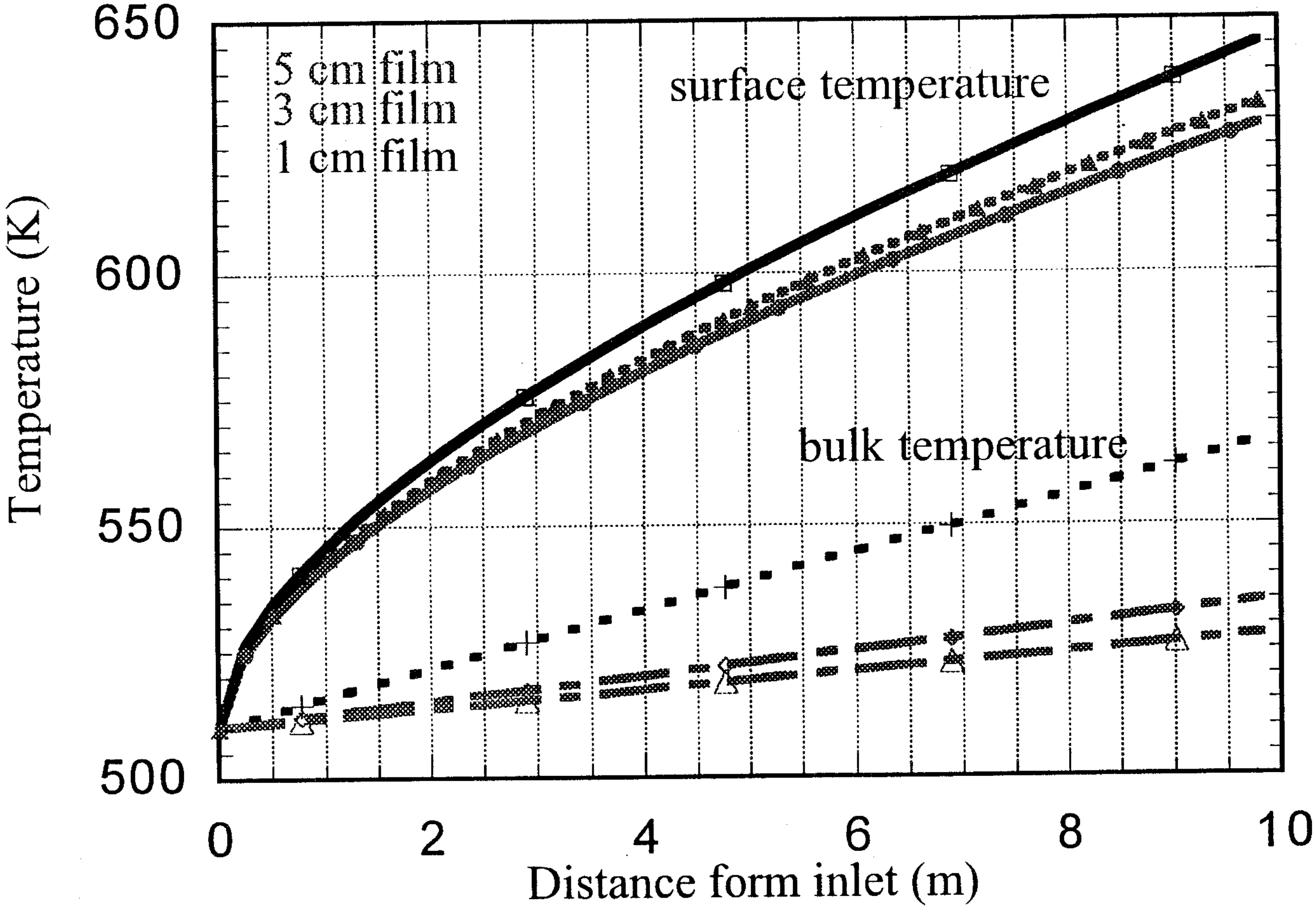


Impact of Lithium Film/Jet Thickness on Temperature Profile [About 10 K increases on surface temperature if jet thickness decreases from 5 to 1 cm]

(velocity = 20 m/s, z= 5 m)



About a 57 K Increase on the Bulk for a 1 cm Lithium Film as Compared with that of 18 K for a 5 cm Film meanwhile the Surface Temperature Increases about 16 K (v= 20 m/s)



x-ray spectrum effect [Bremsstrahlung radiation spectra of Te = 2 and 10 keV]	- about 40 degree drop in lithium surface temperature under the assumed x-ray spectra - a large surface temperature reduction of couple hundred degrees (for example 400 K) for flibe film striken by a hard photon spectrum - insignificant surface temperature reduction for Pb-17Li film within 10 keV photon energy
nuclear heating	- Liquid surface temperature increases ~8% for lithium and about 20% for lead due to addiational nuclear heating
liquid velocity	- For lithium, liquid velocity of about 30 m/s is needed to maintain a low evaporation rate of 10^{19} $/m^2s$. Higher velocities are needed for other fluids to achieve the the same rate.
liquid thickness	- Liquid layer can be as thin as 1 cm for "surface heat" removal.

Conclusions

- Lithium appears to have the lowest surface temperature increase due to its high thermal conductivity and long x-ray mean free path among the three liquid options
    - For a combined surface heat load of 2 MW/m^2 and neutron wall load of 7 MW/m^2, if the incident surface heat load follows a classical Bremsstrahlung radiation spectrum for a Te of 2 keV or above, the surface temperature, can be maintained below 325 °C [corresponding to an evaporation rate of 10^{19} $/m^2s$] over a 10 m long flow path with velocities of 30 m/s or higher.

- The analysis shows that 2 liquid layers should be used for the liquid lithium first wall/blanket: a high speed (of > 30 m/s) liquid layer to minimize the evaporation rate and a much lower speed (< 0.1 m/s) zone behind it to maximize the bulk exit temperature for a high thermal efficiency.

Conclusions (Cont'd)

- Flibe first wall has the steepest temperature profile across the film mainly due to its low thermal conductivity (1.06 W/mK compared to 47.6 W/mK of lithium).

- If the incident surface heat load follows a classical Bremsstrahlung radiation spectrum corresponding to a Te of 10 keV or above, the flibe surface temperature drops significantly (about 400 K at the 10 m exit as compared to that from the radiative surface heat load).

- Further surface temperature drop can be induced by the turbulent patches. All these factors would reduce the flibe first wall surface temperature.

- Pb-17Li liquid first wall has the highest temperature increases, both surface and bulk even under a classical Bremsstrahlung radiation spectrum of Te= 10 keV, due to the mean free path of Pb-17Li being too short to redistribute the heat to the bulk.

- Furthermore, being an electrical conducting medium there might be no turbulent heat transfer enhancement because of the MHD effect.

Thermal Related R&D Issues

- Effect of flow stability on liquid thermal performance
- Impact of turbulent flow structure on heat transfer enhancement
- Impact of MHD effects