Can the Use of Latent Heat Transport Mechanism Fulfill the Heat Extraction Function in a High Neutron Wall Load Fusion Device?
-Heat Pipe
-Gas/Droplet Mist Flow

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Design Integration of Heat Pipes into a Magnetic Fusion Device

- Werner, R. W., "The module approach to blanket design- A vacuum wall free blanket using heat pipes," proceedings of the International Conference on Nuclear Fusion Reactors, Culham, England, 1969
- V. Kovalenko et. al., "Heat-pipes-based first wall," Fusion engineering and Design 27 (1995) 544-549
- A. Makhankov et. al., "Liquid metal heat pipes for fusion application," ISFNT-4

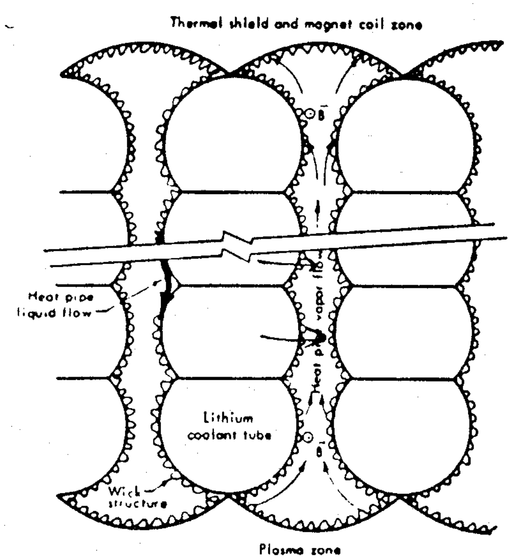


Fig. 2 Schematic of heat-pipe moderator blanket looking along axis of reactor (from Werner [1])

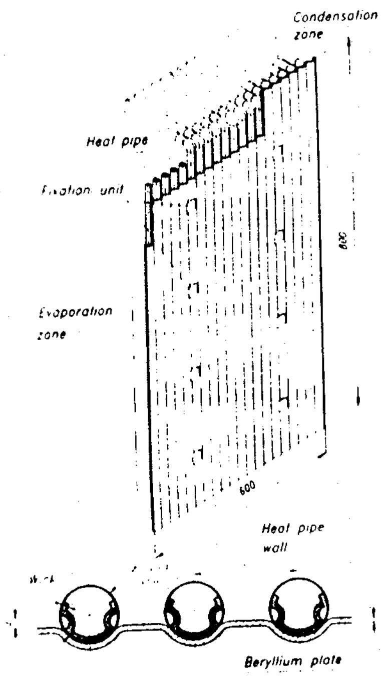


Fig. 1. First wall panel with heat pipes (multi-pipe first wall).

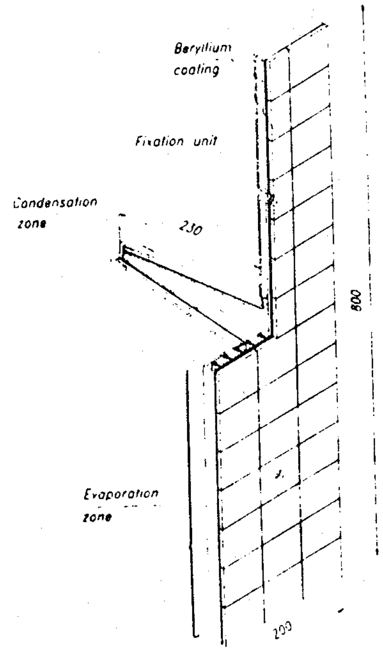
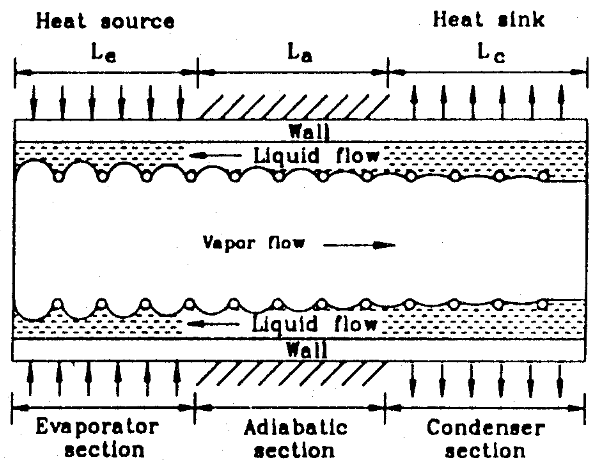


Fig. 2. First wall panel with heat pipes (vapor chamber first wall).

Heat Pipe Principles of Operation

- A heat pipe is a device used to transport heat from one location to another by means of the evaporation and subsequent condensation of an appropriate fluid, in which circulation of the fluid is maintained by capillary forces.



a) Liquid-vapor interface

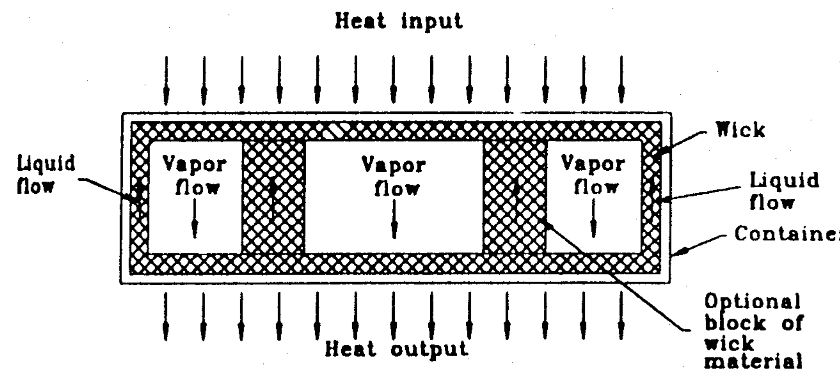


Figure 1.10: Flat-plate heat pipe

- The pressure inside the container is equal to the vapor pressure corresponding to the heat pipe temperature[low pressure operation]
- Possible to reduce the first wall heat loads by redistributing the heat into a larger surface area

[High thermal conducting extended surfaces allow the heat dissipated to a larger surface area.]

$$\text{Thermal admittance} = L(2hk\delta)^{1/2}\tanh(mb) \qquad \text{where } m = \left[\frac{2h}{k\delta}\right]^{1/2}$$

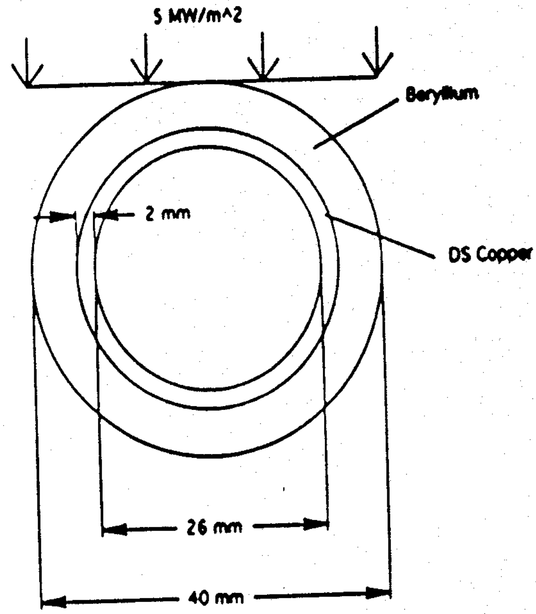
Helium-Cooled Divertor for ITER - by C. Baxi

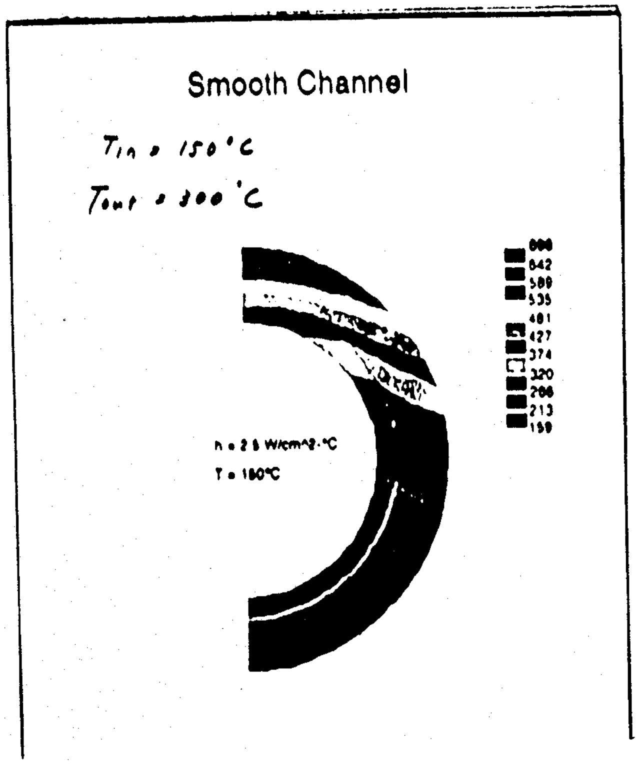
GENERAL ATOMICS

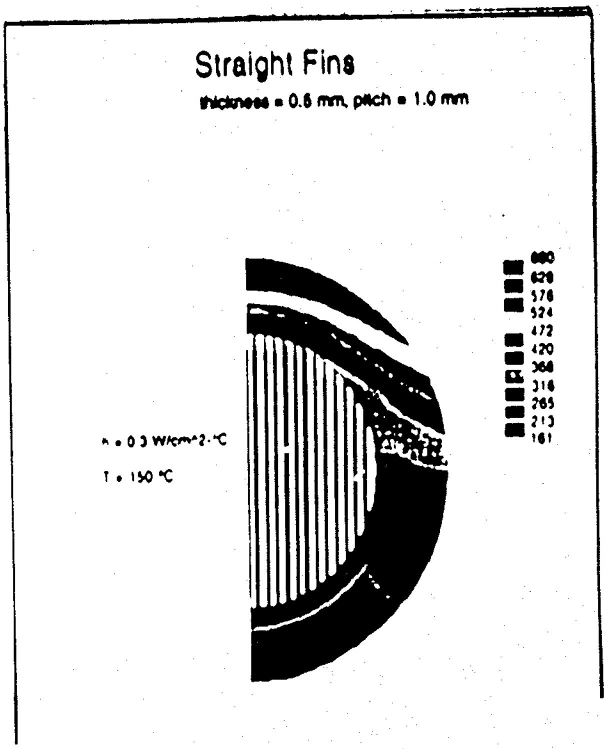
SUMMARY OF ANALYSIS

	Flow Required (kg/s)	Re #	VEL (m/s)	Dp (bar)	PP (MW)
Smooth	1840	2.7E06	490	9.0	220
2–D rough	1000	1.4E06	240	3.3	44
Twisted tape	840	1.1E06	197	2.0	23
3–D rough	630	8.8E05	150	1.6	14
Extended surface	270	4.6E05	110	1.0	4.0

Cross section of Channel







How much capillary pressure is needed? Will the MHD pressure drop retard the return flow?

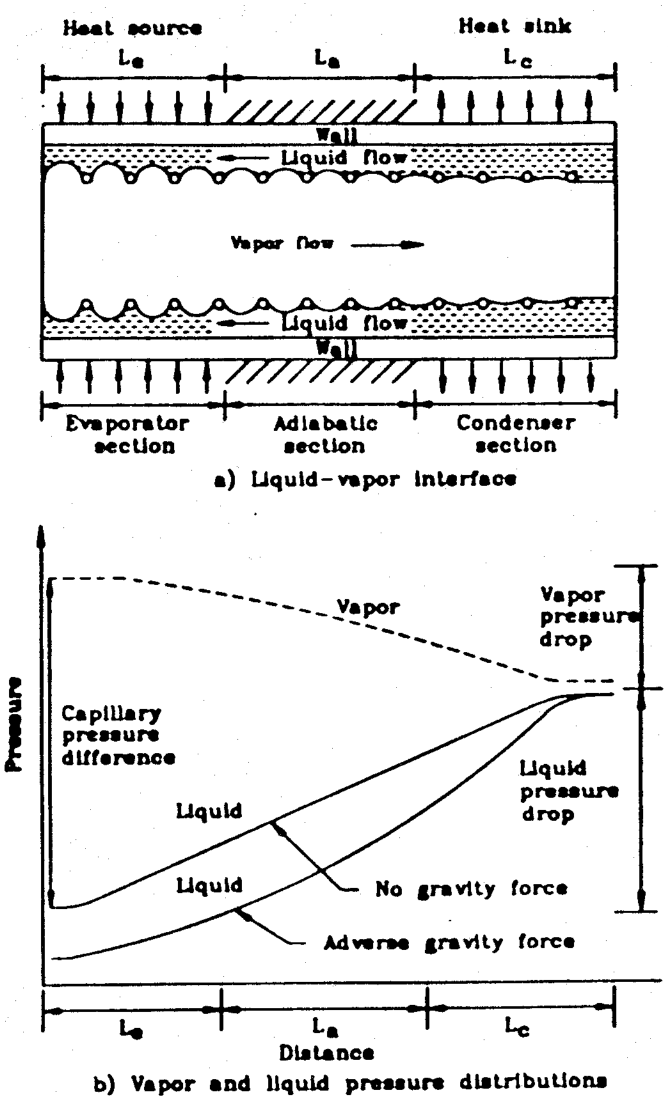
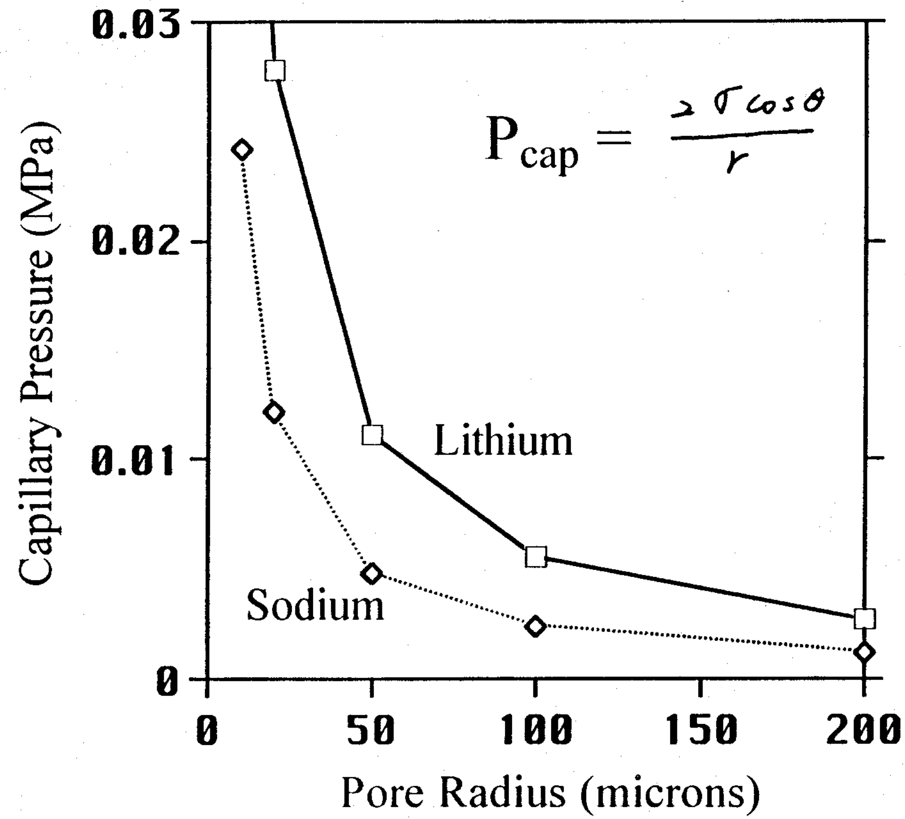
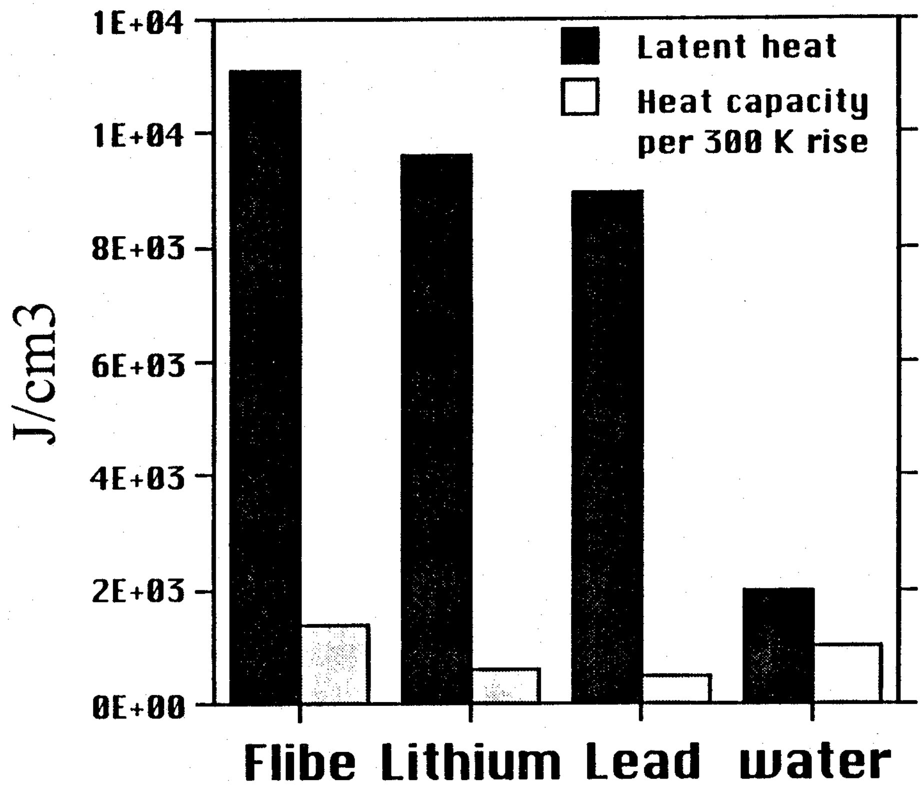


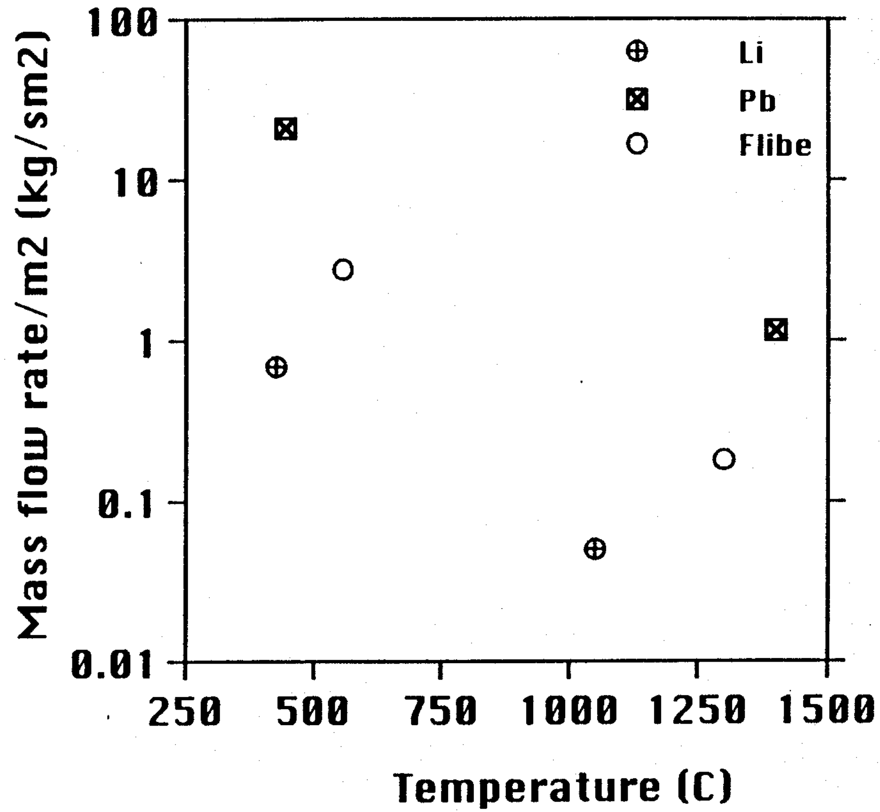
Figure 1.2: Axial variation of the liquid-vapor interface, and the vapor and liquid pressures along the heat pipe at low vapor flow rates



Estimated MHD pressure drop = 0.0012 MPa (0.01 m/s Li for a flow path of 0.1 m under a 10 T and c= 0.0033)

Heat transfer is enhanced by the evaporation of the liquid (The required mass flow rate in a heat pipe device is much smaller than that in a convective flow)

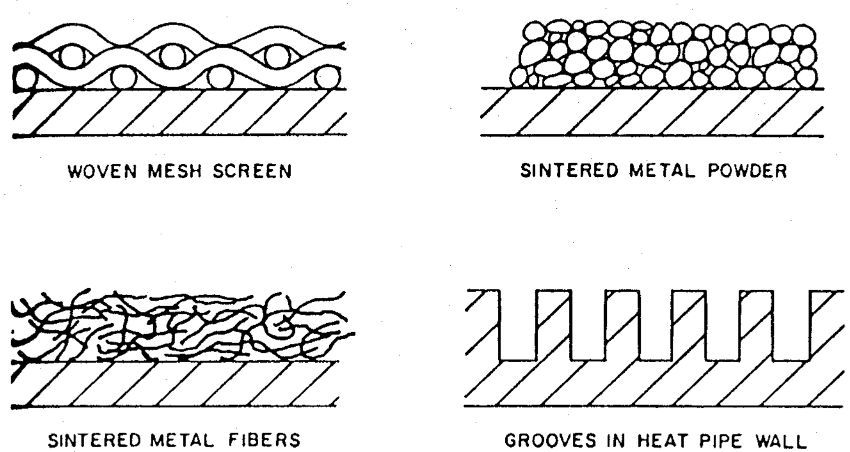


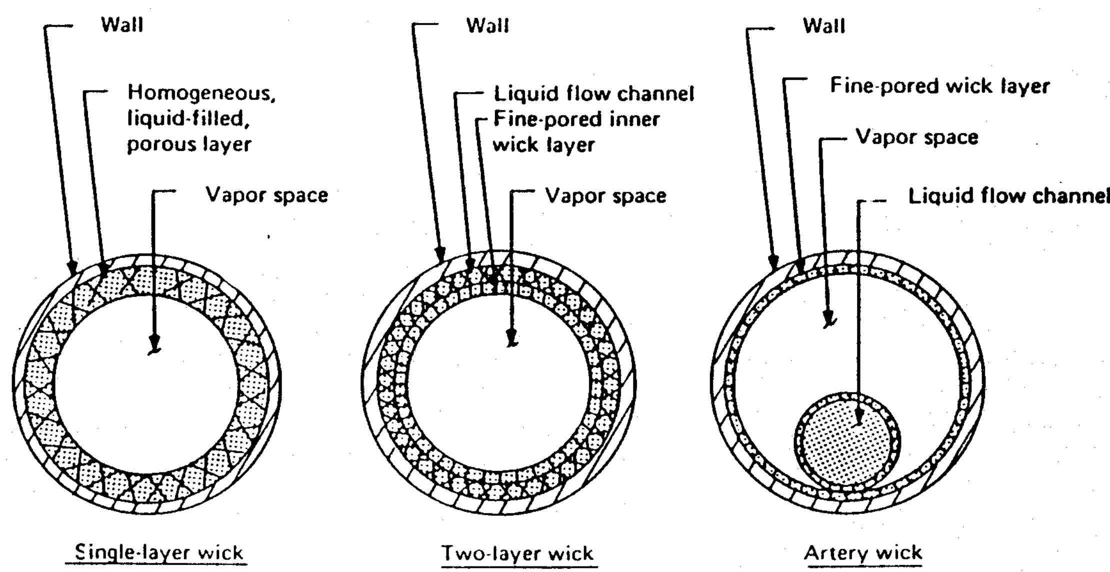


Important Design Parameters that Impact Heat Pipe Performance

Heat pipe fluid
Wall and wick material
Vapor temperature
Wick type
Evaporator length
Condenser length
Vapor space radius

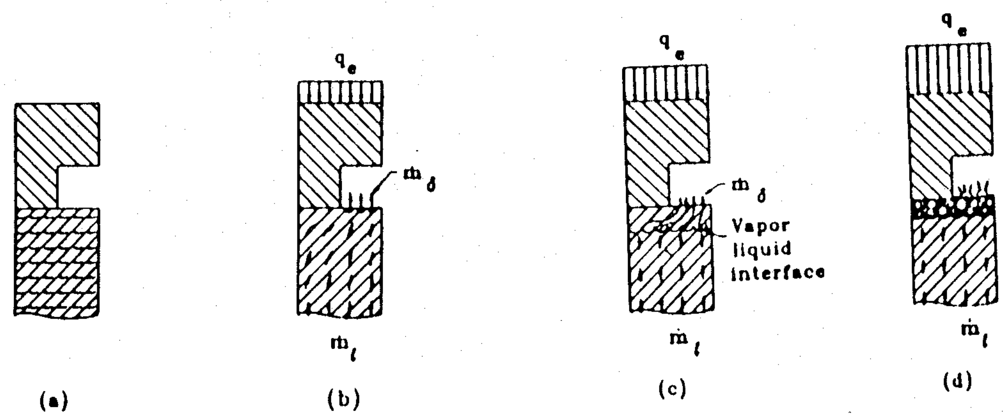
Heat Pipe Liquid	Recommended Materials
Lithium [1273-2073 K]	Tungsten TZM molybdenum Tantalum Niobium
Sodium [873-1473 K]	Stainless steel Inconel 800 Hastelloy X Molybdenum





Heat Pipe Theory Consists of Fundamental Analyses Related to Hydrodynamic and Heat Transfer Processes

- Hydrodynamic
  - liquid pressure drop in the wick structure
  - maximum capillary pumping head
  - vapor flow in the vapor channel
- Heat Transfer
  - conjugate heat conduction in the wall and wick
  - evaporation and condensation at the liquid-vapor interface
  - forced convection in the vapor channel and wick structure
  - transient behavior



Theoretical Heat Transfer Limitations for Liquid Metal Heat Pipes

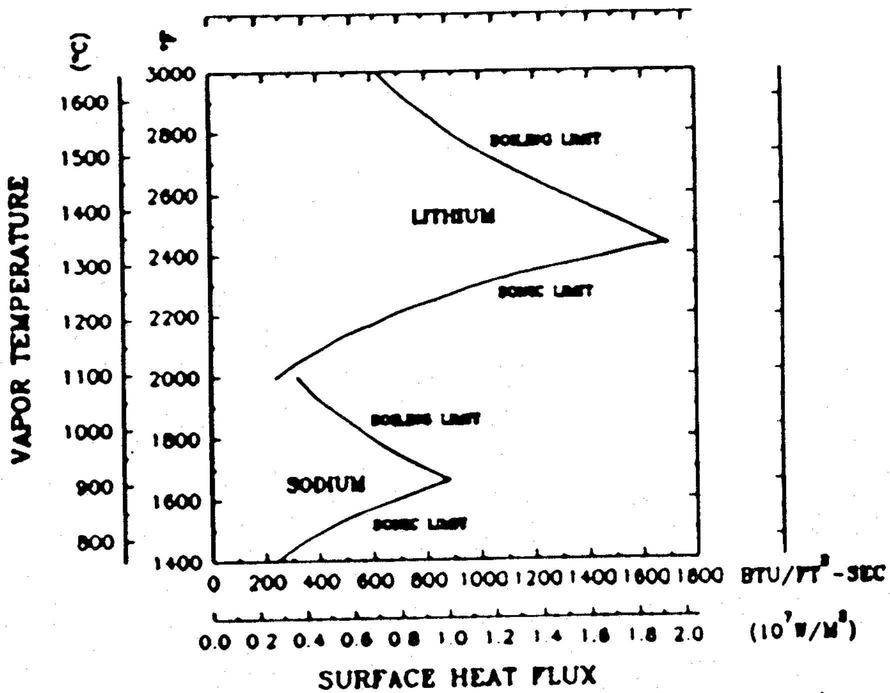


Figure 5.23. Operating temperature range versus surface heat flux for sodium and lithium cylindrical heat pipes.

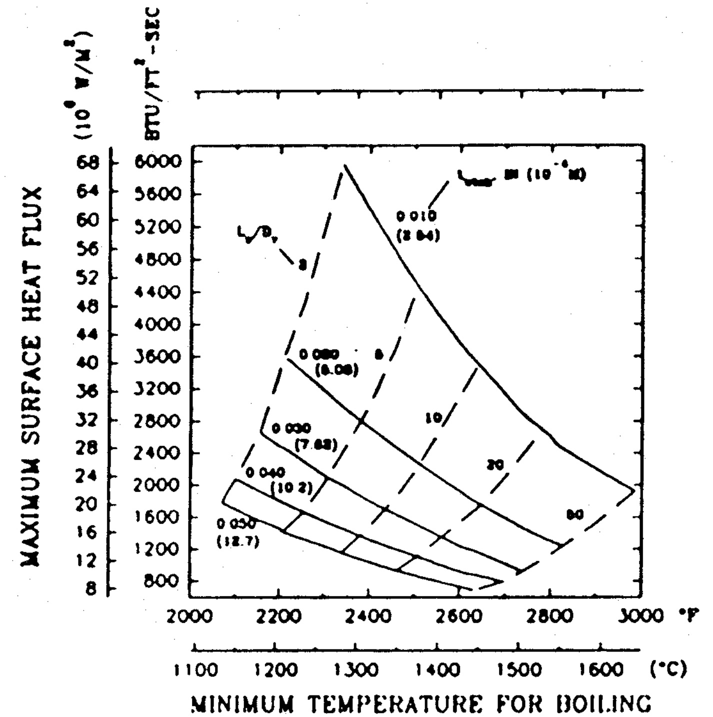


Figure 5.25. Maximum surface heat flux and minimum boiling temperature for a lithium heat pipe.

State-of-the-Art Liquid Metal Heat Pipe Performance

- Fusion application- Heat Flux Experiments on Heat Pipes for Plasma Facing Applications- H. Bolt et. al. Fusion Technology 1994
  - Na/Nb[steady state heat flux up to 1.8 MW/m^2]

- Space and Aerospace Programs
  - Na/SS heat pipe operating near 775 ^oC achieving heat fluxes up to 12.5 MW/m^2 - Vinz and Busse, 1973.
  - Li/W heat pipe operating up to 1650 ^oC achieving interface surface heat fluxes of nearly 200 MW/m^2 -
  - Li/Nb heat pipe operating at 1037 ^oC achieving a heat flux of 13.8 MW/m^2 - Wojcik and Clark 1991.

Other Possible Fusion Heat Pipe Configurations

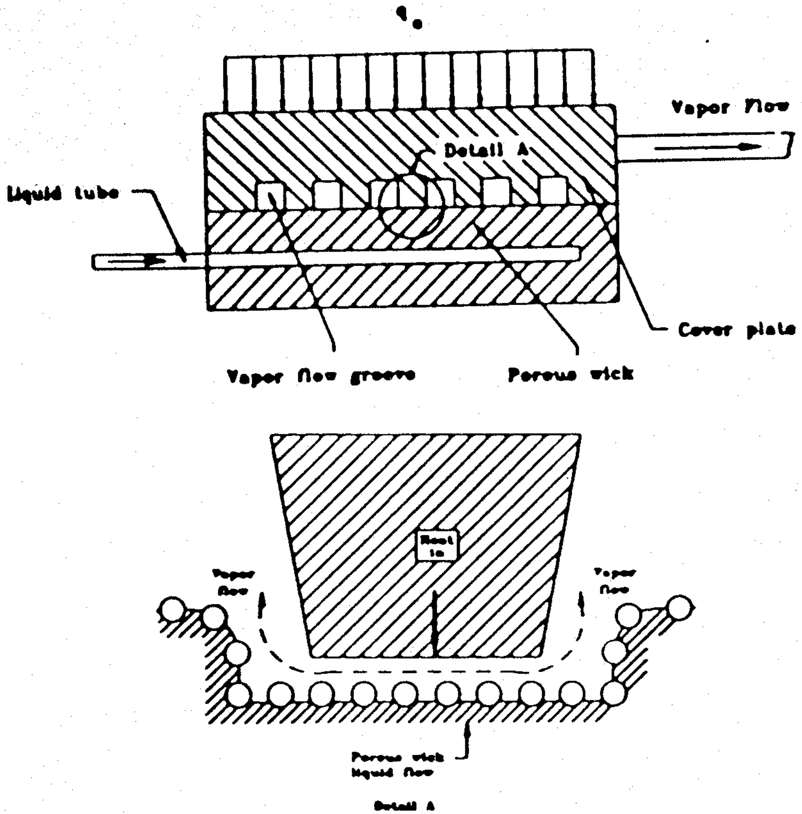
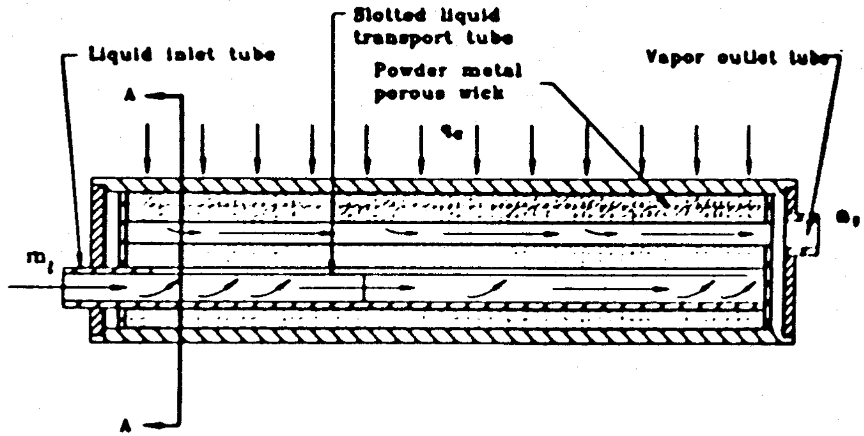


Figure 9.7: Configuration of a flat-plate-type CPL evaporator



Proposed near term tasks

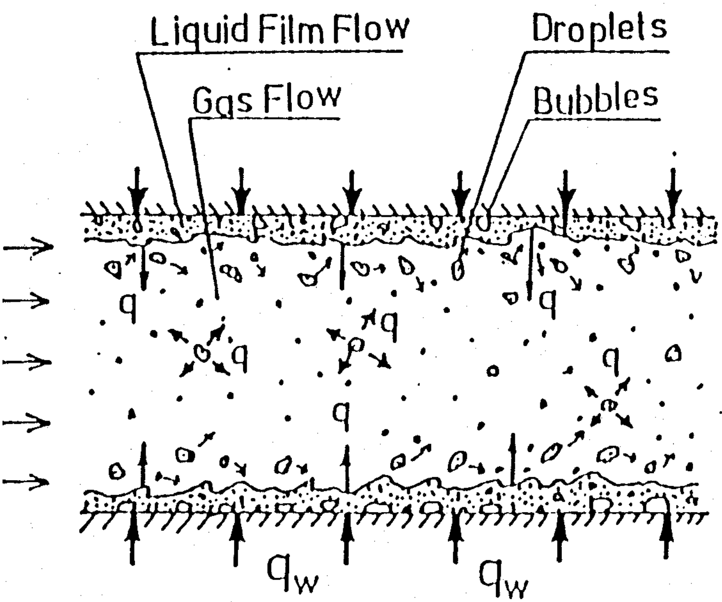
- Identification of HP material systems suitable for fusion relevant configurations
- Estimation of heat removal capabilities for such systems

Summary of Heat-Pipes Based Concepts for MFE

- Available data from two-sided evaporators indicates that heat fluxes of more than 10 MW/m^2 can be removed using Li as heat pipe working fluid
- Data is needed for a more fusion relevant geometry - heat pipes with one sided evaporators
- Flibe appears to be a favorable working fluid for fusion heat pipe applications; one possible structural material could be tantalum
- <u>Additional Merits</u>
  - low pressure system
    - thin wall possible
    - leakage tolerant [no immediate reactor shutdown is required, thus prolongs MTBF]
  - the coolant container can be made out of tungsten (with Li as a working fluid) which is one of the candidate plasma facing materials; no additional armor is needed
  - can be designed as a separable component

Mist Flow Cooling

- When liquid droplets are added to a flowing gas stream, heat transfer is enhanced by sensible heating of the two-phase mixture, evaporation of the liquid and disturbance of the boundary layer.



Gas : He , vapor of liquid metal

Liquid metal : Li ,K

Gas-liquid metal annular-mist flow cooling

Expected advantage points:

1. Low MHD pressure drop
2. No supplement heating system
3. High heat transfer coeff.
4. High heat capacity
5. Low system pressure
6. Reasonable breeding ratio of tritium

Disadvantage points:

1. Poor data bases for the two phase MHD flow
2. Separation system between gas and droplets
3. Possibility of flow instability under a magnetic field

The best performance of the liquid metal mist cooling is achieved when used in an impinging jet profile.

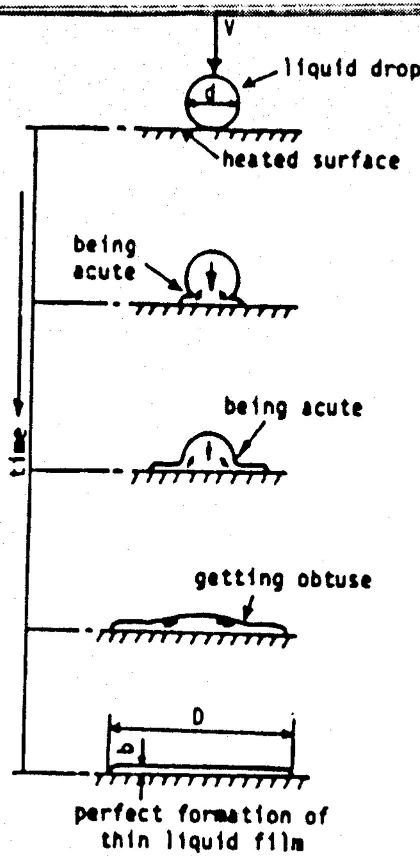


図13. 液体金属ミスト滴の高温面上での変形ダイナミックス[23-25].

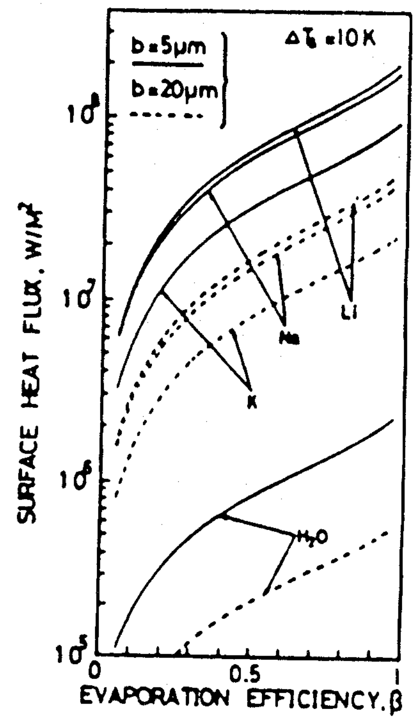


図14. 液体金属ミスト衝突噴流冷却の超高熱流束熱除去特性[26].

<u>Issues</u>

Bulk of research on mist cooling flow was done at Japan universities. The subject can be explored further through participation of Japanese scientists.

Key Technical Issues

- Experimental investigation of fluid flow (Li and Flibe) in wick structures with and without MHD effects
- Experimental evaluation of heat transfer limits for heat pipes with one sided evaporators using different transport lengths
- Identification of the most favorable heat pipe geometry for use in a magnetic fusion configuration
- Design integration/optimization of heat-pipe based advnaced power exteaction concepts

Proposed Near Term Tasks

- Identification of HP material systems suitable for fusion relevant configurations
- Estimation of heat removal capabilities for such systems
- To invite Japanese scientists' participation in the APEX study, particularly on the subject of mist flow cooling concepts