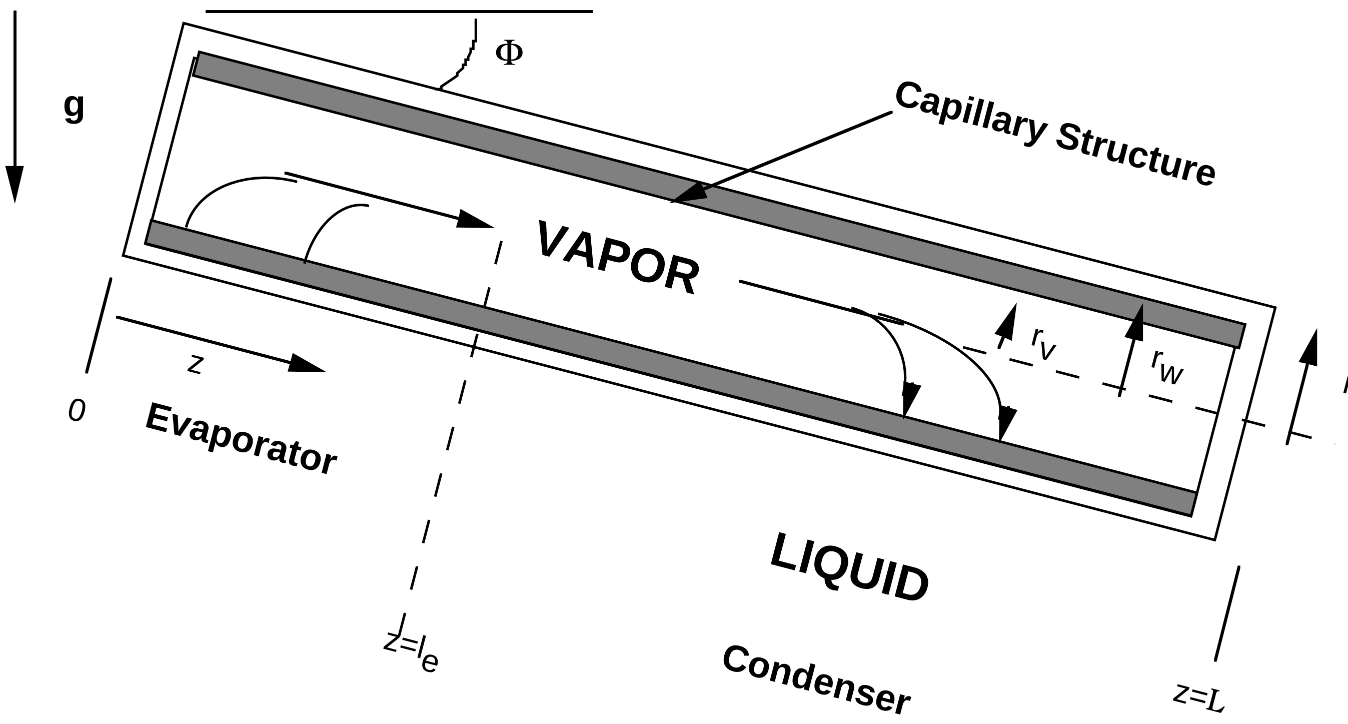
Heat Pipe Principles

Use 2 phase flow, latent heat of vaporization, and capillary action to circulate a working fluid between heated and cooled regions via a wick.



r_o = outer radius

r_w = inner radius of wick

r_v = radius of free space in tube

l_e = length of evaporation regime

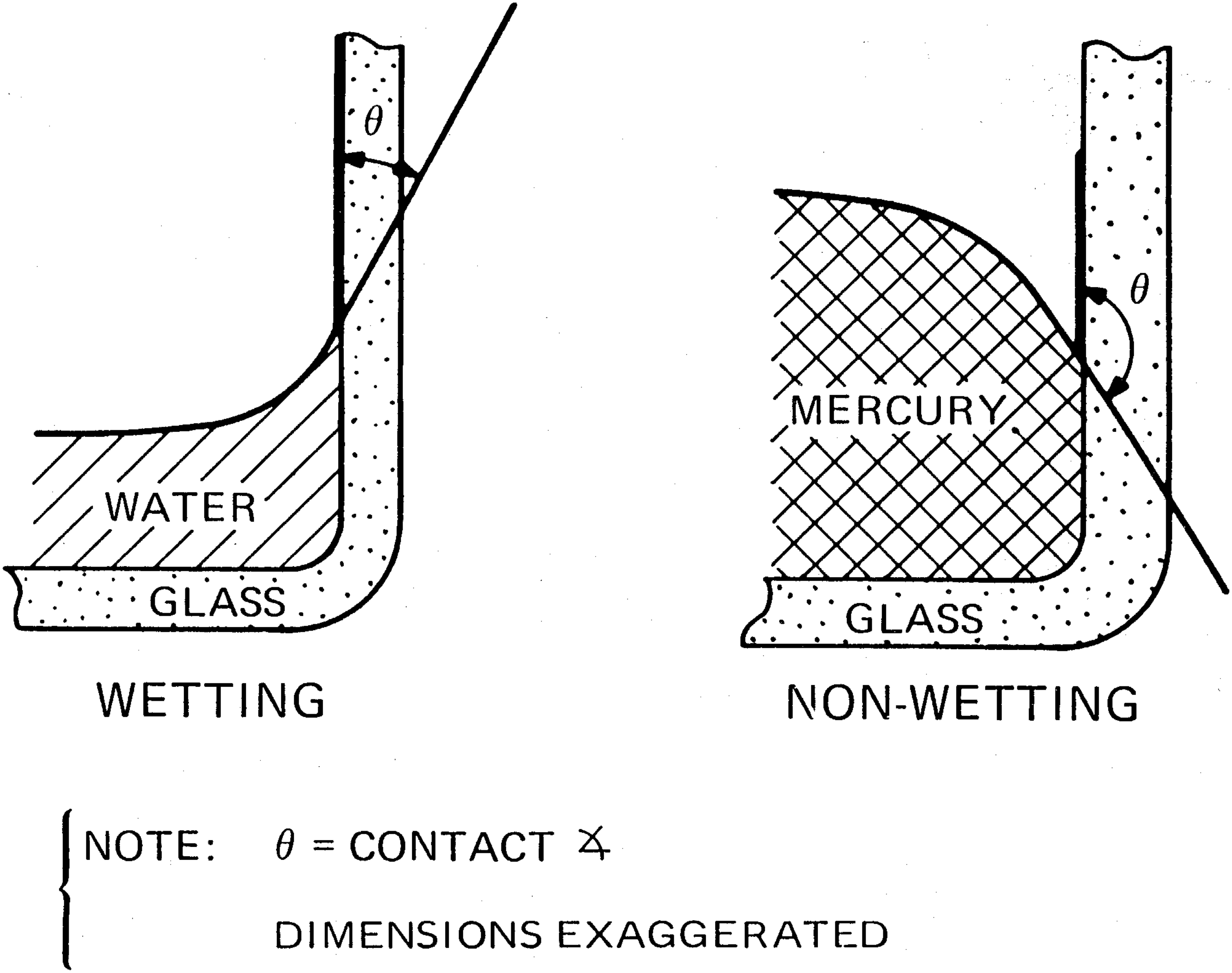


Fig. 4.9 Wetting of a solid surface. *Courtesy of Los Alamos National Laboratory.*

Capacity of Heat Pipe

- **I**ncrease in heat transfer must be consistent with capillary driven circulation of the working fluid.

Difference in pressure between the vapor phase, $\boxed{p_v(z)}$, and the liquid phase $\boxed{p_\ell(z)}$, must be balanced by the surface tension in the capillary structure.

$$\underbrace{p_v(z) - p_\ell(z)}_{\text{pushes down}} = \Delta p_v - \Delta p_\ell = \underbrace{\frac{2\gamma\cos\theta}{r_c}}_{\text{pulls up}}$$

radius of capillary pore

$$\Delta p_\ell = -p_\ell(L) + p_\ell(0)$$

Constant

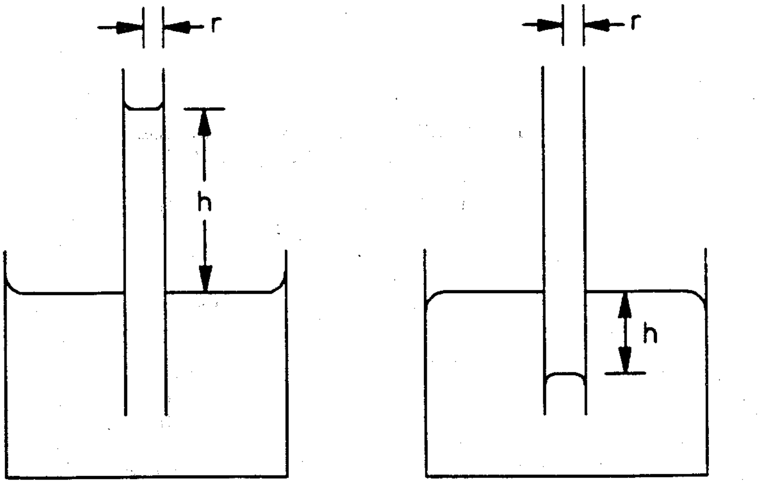
$$\Delta p_\ell = -\rho_\ell g L \sin\varphi - \frac{b\eta_\ell Q_e L}{2\pi\left(r_w^2 - r_v^2\right)\rho_\ell \varepsilon r_c^2 l}$$

Density of Liquid

Acceleration due to gravity

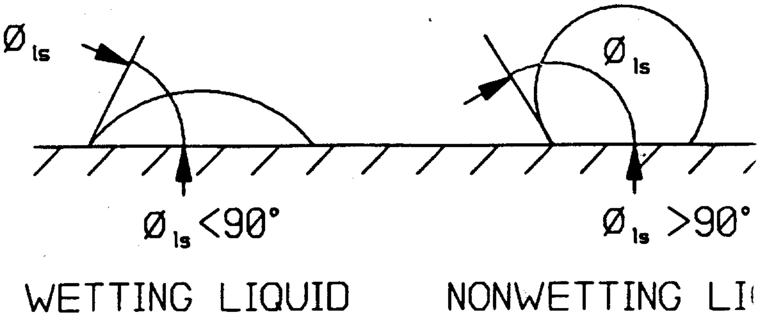
Angle to gravity
Φ=π/2 vertical
Φ=0 horizontal

Frac. of Wick Vol. Occ. by Liquid



WETTING LIQUID

NONWETTING LIQUID



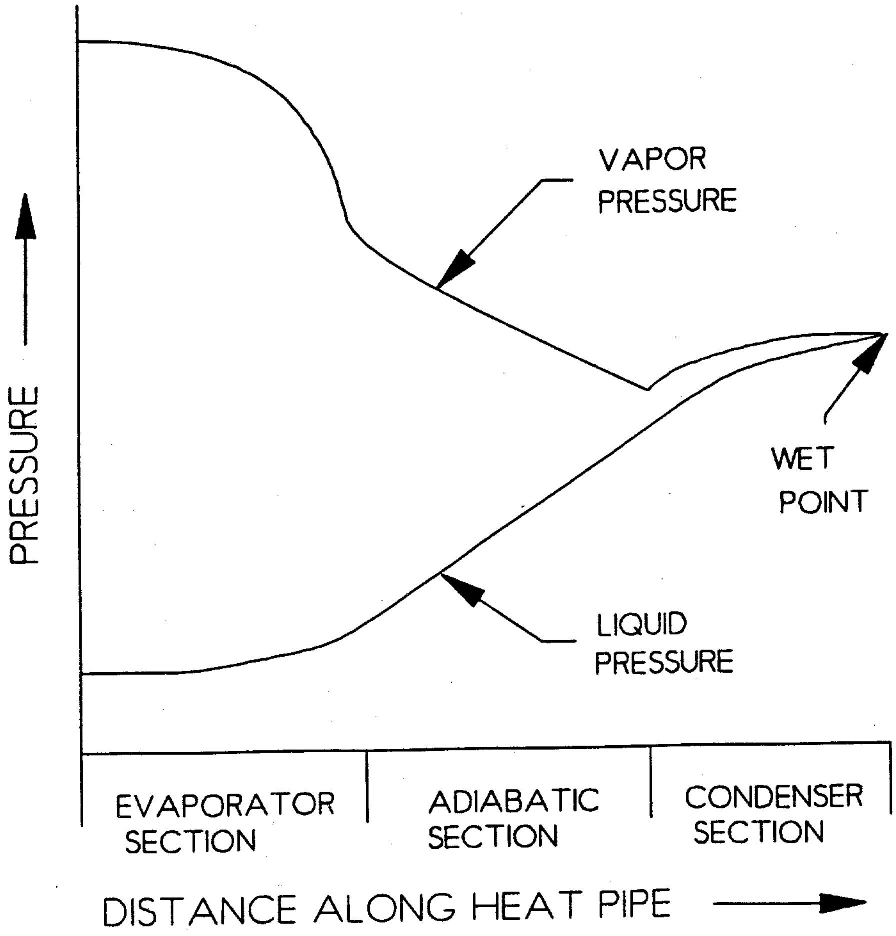


Figure 2.5. Liquid and vapor pressure distributions in a heat pipe (wet point at condenser end).

Value of Constant 'b'

If pores are not interconnected, then b≈8

If the pores are interconnected, then b≈10-20

Optimum Pore Size (see Ref 10 Book by Silverstein)

Viscosity of liquid

$$r_c = \frac{b\eta_l Q_e L}{4\pi\left(r_w^2 - r_v^2\right)\rho_l \varepsilon l \gamma \cos\theta}$$

Maximum Heat Transport

$$Q_e = \frac{\pi r_w^2 l \gamma \cos\theta}{3L}\sqrt{\frac{\varepsilon\rho_v\rho_l}{3b\eta_v\eta_l}}$$

(Reynolds #<<1)

$$Q_e = \frac{4\pi r_w^2 l}{3}\left[\frac{2\rho_v\rho_l\varepsilon\gamma^2 \cos^2\theta}{\left(\pi^2 - 4\right)bL\eta}\right]^{\frac{1}{3}}$$

(Reynolds #>>1)

Surface Tension of Some Heat Pipe Liquids

	T-°C	Gamma-N/cm
Methyl Alcohol	50	2.01
Ammonia	11	2.35
Water	20	7.28
Na	816	12.1
Li	1204	26

Key Features of High Temperature Heat Pipes

- Extremely high heat transfer in a simple container
- Allows many heat transfer loops, avoiding a single point failure
- Smaller units avoid bulky pressure vessel (implications for reentry)
- Avoids the use of valves, pumps or compressors
- Ability to start up 'cold' avoids the need for preheat
- Nearly isothermal temperature transfer and high temperatures allows very high efficiency operation

Typical Performance Parameters for Space Reactor Heat Pipe

Working Fluid	***Li***	
Op. Temp. ° C	***1200***	
Axial Power Density		
Normal	***8***	***kW/cm2***
Contingency	***10.5***	***kW/cm2***
Max. Radial Power		
Evaporator	***105***	***W/cm2***
Condensor	***6.5***	***W/cm2***
Reliability		
7 y normal	***98 %***	
7 y contingency	***96 %***	

Transport Limitations

- **Sonic Limits**

  - Choked Vapor Flow
  - Typically occurs when pipe operates near the freezing point where vapor pressures and densities are very low.

- **Entrainment Limit**

  - High velocity vapor flow strips and entrains liquid droplets thereby impeding liquid flow to evaporator
  - Occurs at high loads and near freeze point

- **Capillary Pumping**

  - Hydrodynamic balance between capillary forces and liquid/vapor viscous pressure drops
  - Usually determines limiting performance

- **Boiling Heat Flux**

  - High local heat fluxes that cause nucleate boiling and interupts liquid flow in evaporator

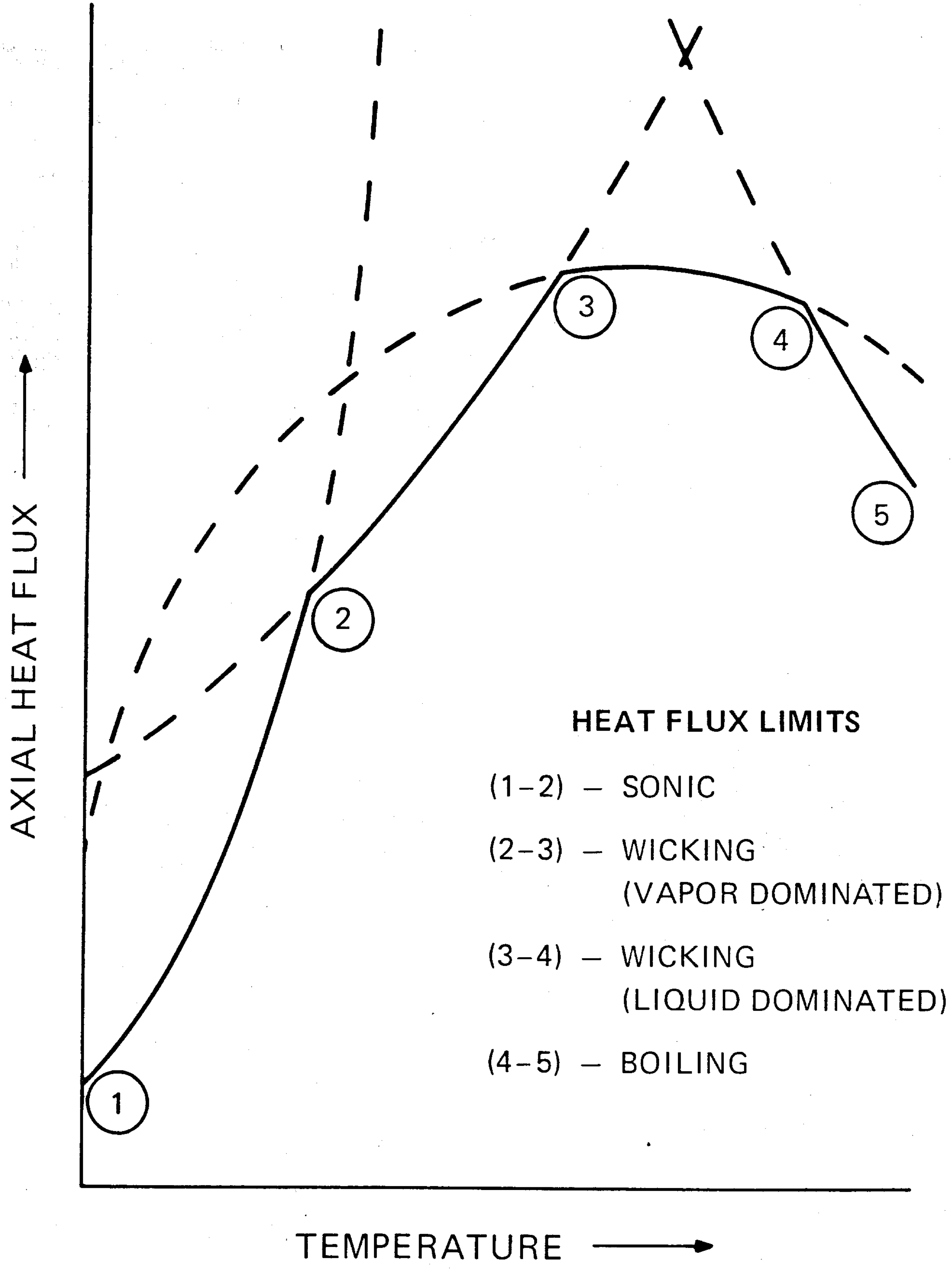


Fig. 4.11 Phenomena limiting heat pipe performance. *Courtesy of Los Alamos National Laboratory.*

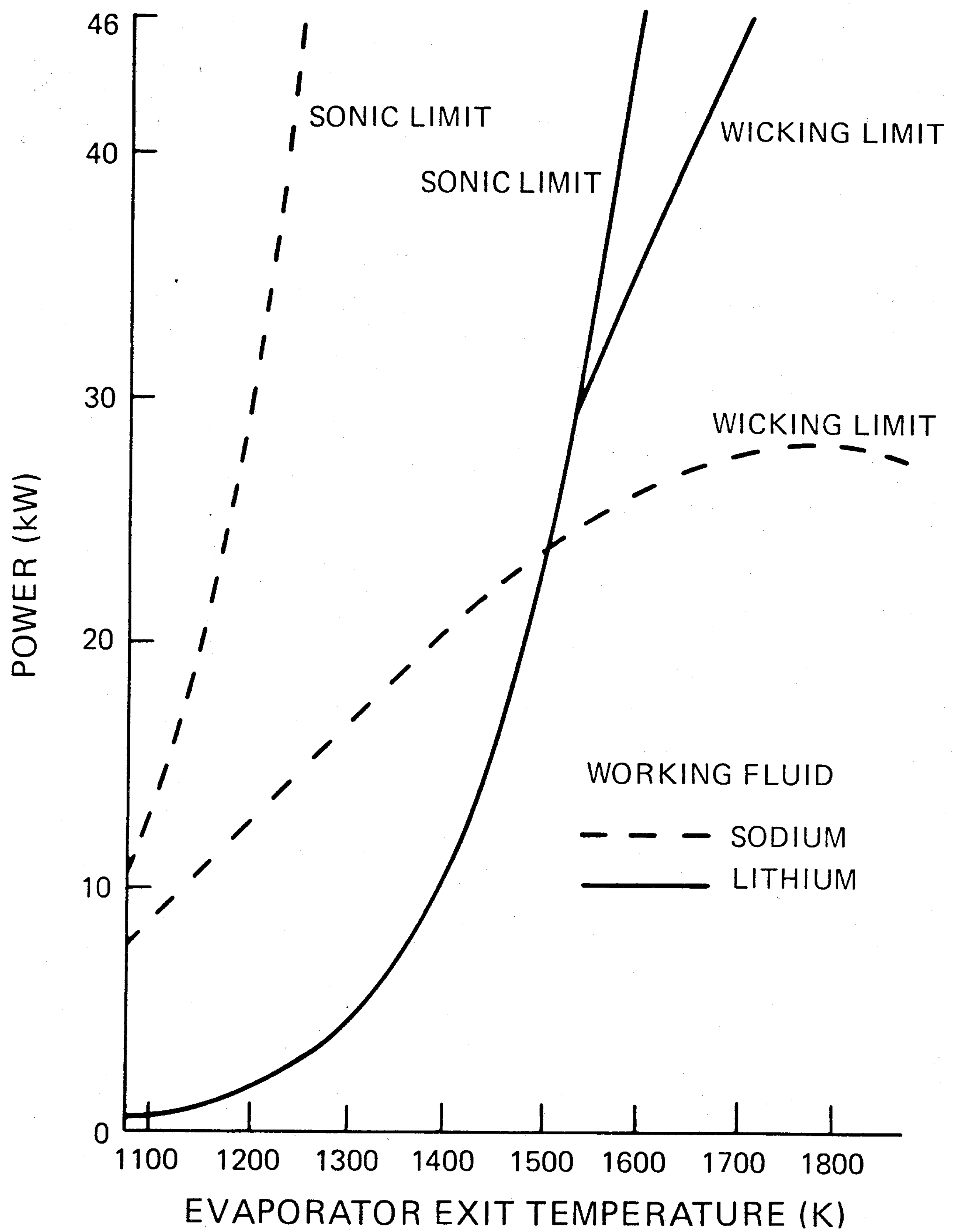


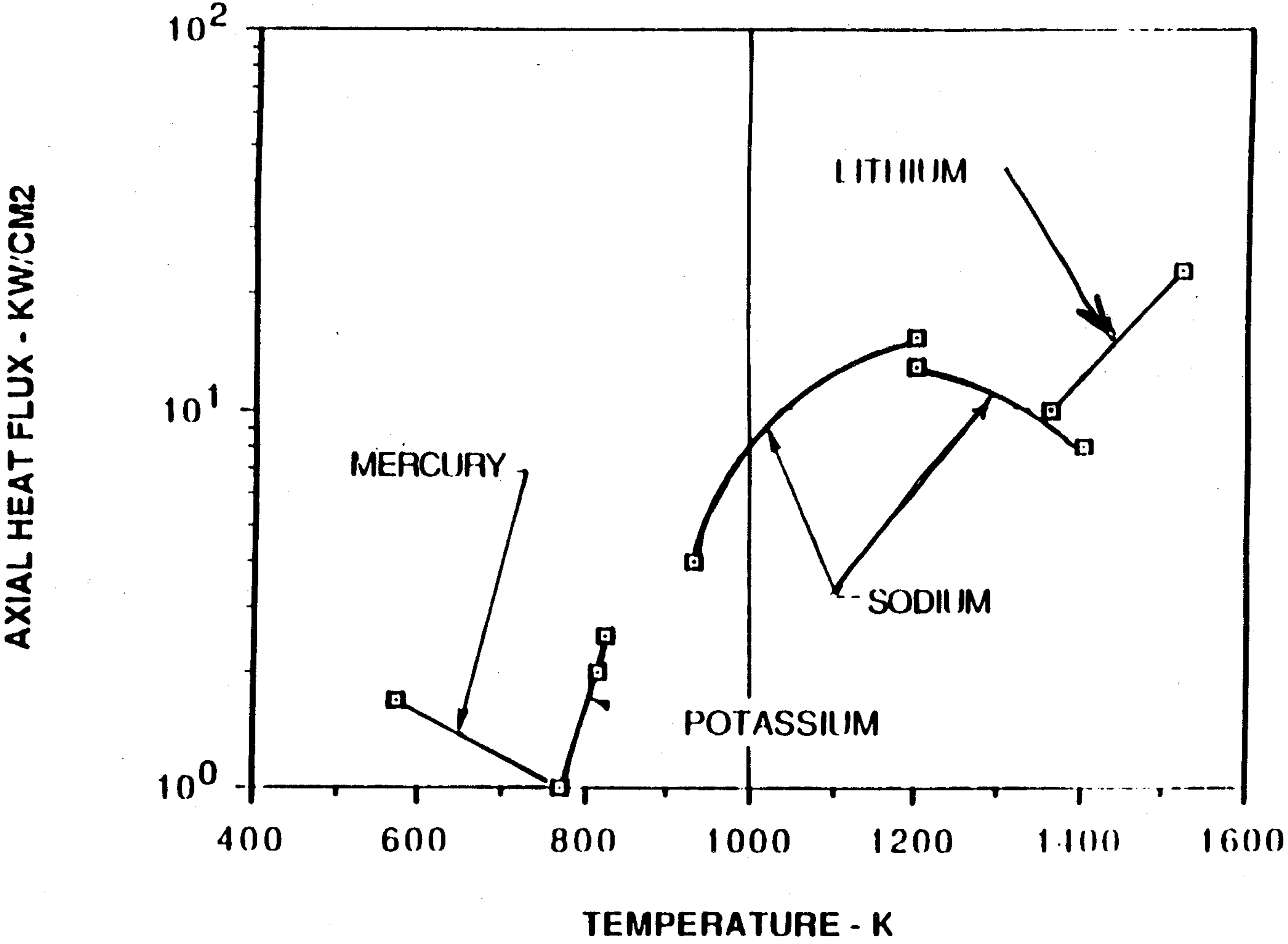
Fig. 4.12 A comparison of lithium and sodium heat pipe performance. *Courtesy of Los Alamos National Laboratory.*

HEAT PIPE APPLICATIONS IN SPACE NUCLEAR POWER

DEMONSTRATED RADIAL FLUX DENSITIES

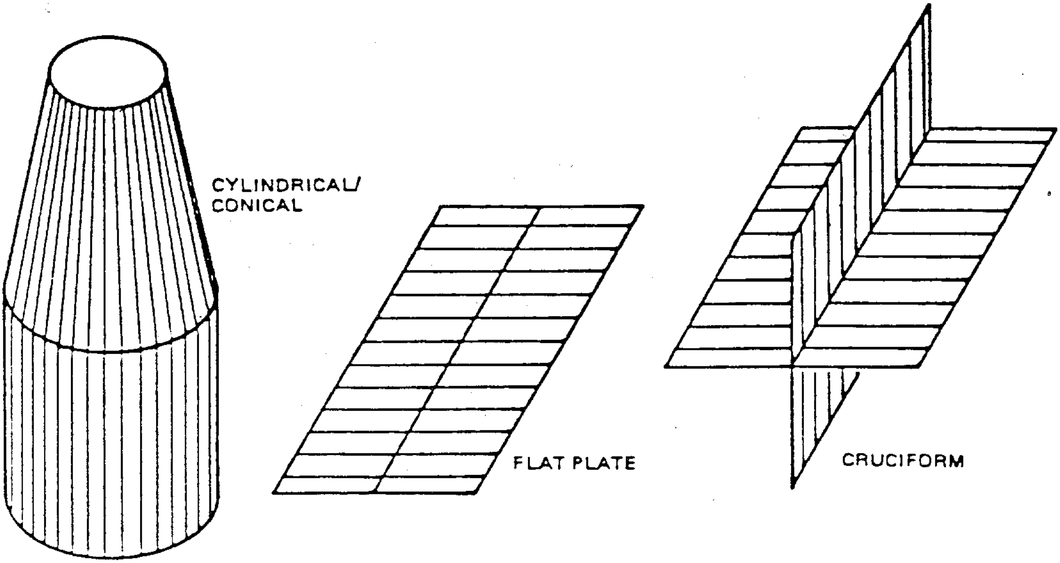
POTASSIUM	40 TO 50 W/CM^2
SODIUM	TO 1000 W/CM^2
LITHIUM	TO 300 W/CM^2
MERCURY	150-200 W/CM^2

DEMONSTRATED AXIAL HEAT FLUX

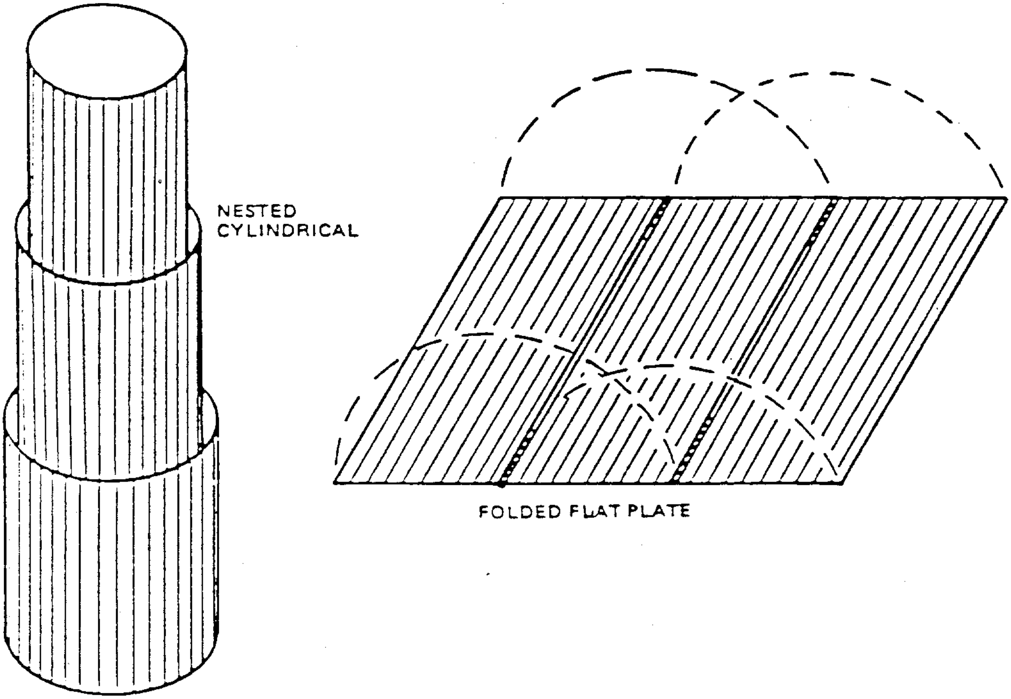


DEMONSTRATED OPERATING LIFE FOR HIGH TEMPERATURE HEAT PIPES (LOS ALAMOS)

LITHIUM-MOLYBDENUM	25,000 HR @ 1700K
SODIUM-MOLYBDENUM	45,000 HR @ 1400K
SODIUM-300 SERIES SS	23,000 HR @ 920K
POTASSIUM-NB-1ZR (SP-100 TESTS)	10,000 HR @ 1350K
POTASSIUM-300 SERIES SS	5,300 HR @ 920K
POTASSIUM-TITANIUM (REFLUXING CAPSULE)	5,000 HR @ 800K
MERCURY-300 SERIES SS	10,000 HR @ 600K



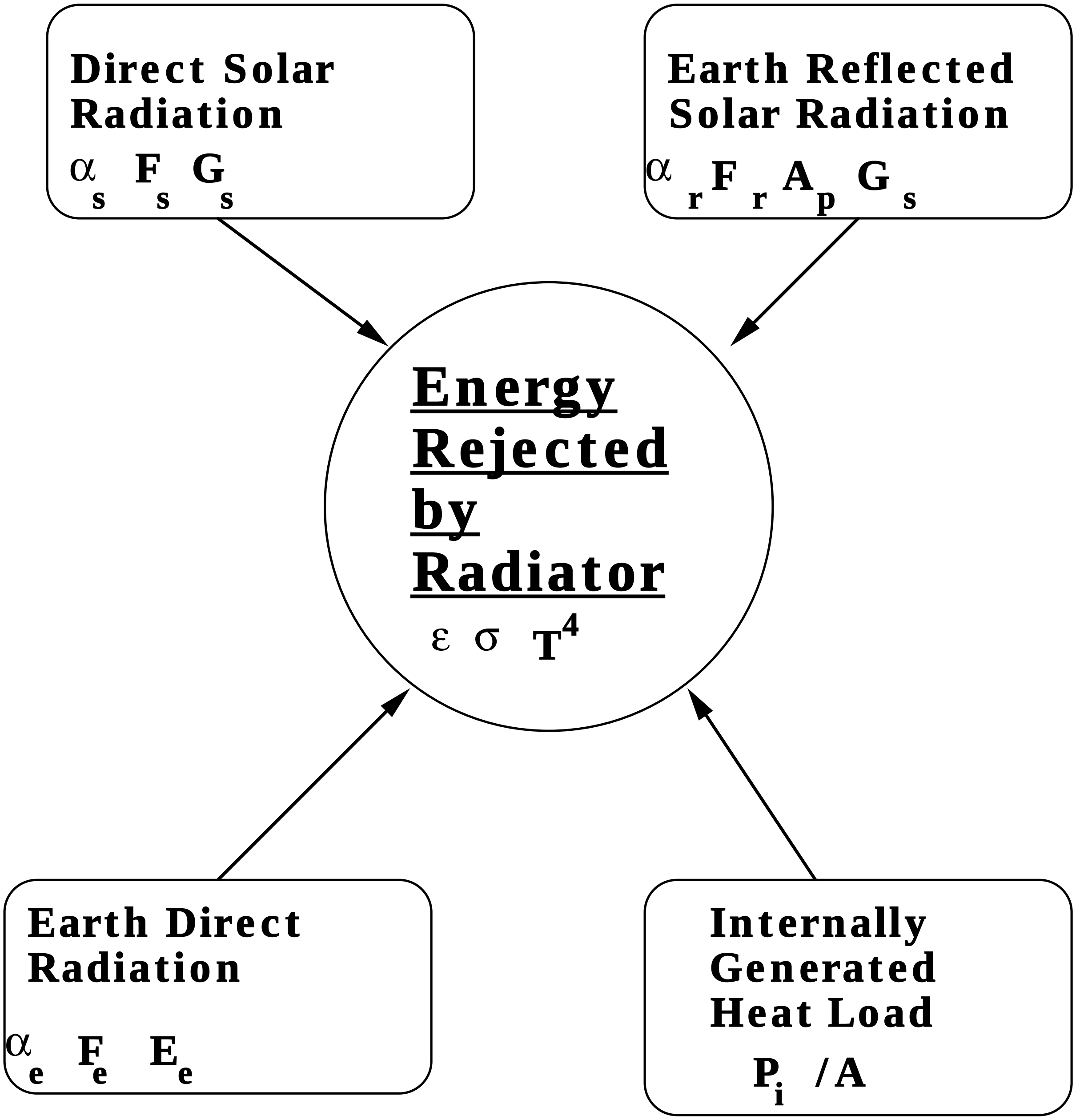
FIXED RADIATORS



DEPLOYABLE RADIATORS

Fig. 6.3 Typical radiator configurations [*2*].

Radiator Thermal Design



Direct Solar Radiation

$\alpha_s \ F_s \ G_s$

Earth Reflected Solar Radiation

$\alpha_r F_r A_p \ G_s$

Energy Rejected by Radiator

$\varepsilon \ \sigma \ T^4$

Earth Direct Radiation

$\alpha_e \ F_e \ E_e$

Internally Generated Heat Load

$P_i \ /A$

α=solar absorptivity= 0-1.0 (direct or reflected from the Earth)
F_s=cosine of angle to sun = 0-1.0
G_s=solar constant= 1371 W/m^2 at 1 AU
F_r=view factor $\approx$ 0.1 from low Earth orbit, 0.02 from GEO
A_p=Earth's albedo $\approx$ 0.3
F_e=view factor of radiation emitted from the Earth to radiator $\approx$ 0.3
E_e=Earthshine radiation $\approx$ 240 W/m^2

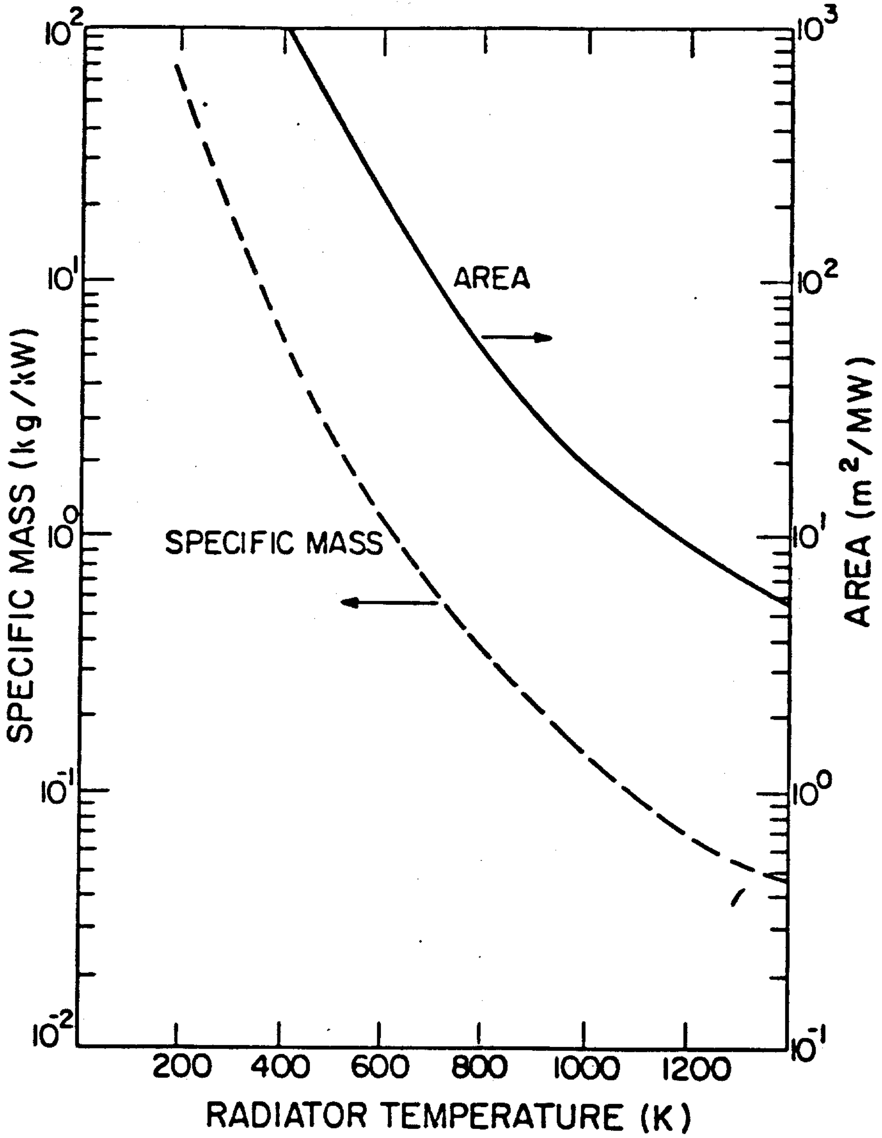


Fig. 6.1 Radiator area and mass as a function of temperature.

RADIATOR WEIGHT DOMINATES LARGE SYSTEMS