Cryostat Options and Heat Loads

Astronomy 525

Lecture 26

Outline

- Heat Loads
  - Conduction
    - Material Properties
    - Rigidizers and Thermal Standoffs
    - Neck Heat Load
    - Vapor Cooling
    - Mechanical Shafts
- Examples

Thermal Conduction

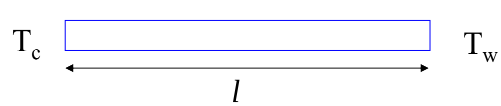
- A very important source of heat loading is thermal conduction through support structures
- Work surfaces, that support optics and the detectors are usually made of very good thermal conductors, such as copper or aluminum
- To make the thermal jump to different temperature stages, we must include low thermal conductivity support structures, often made of fiberglass, or Kevlar
- The support structures will have different temperature coefficients of thermal contraction, complicating the design.

Thermal Conduction

- The heat conduction equation is:

$$Q = A\kappa(T)\frac{dT}{dx}$$

- Where A is the cross-sectional area of the "heat pipe," $\kappa(T)$ is the (temperature dependent) thermal conductivity and Q is the "heat current" (Watts).



Thermal Conduction (cont'd)

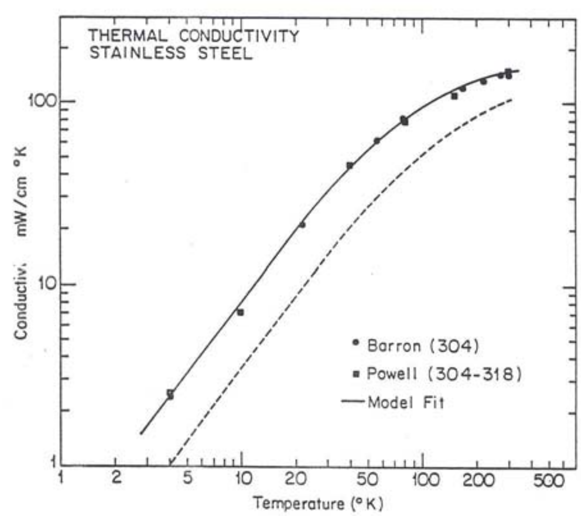
- Integrating we obtain $$Q = \frac{A}{l}\bar{\kappa}(T_w - T_c)$$

where

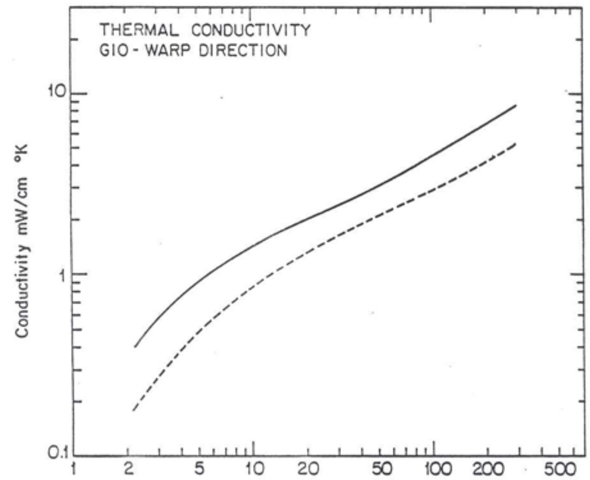
$$\bar{\kappa}(T_w - T_c) = \bar{\kappa}(T_w) - \bar{\kappa}(T_c) \qquad \bar{\kappa}(T_x) = \int_0^{T_x} \kappa(T)\,dT$$

	$\bar{\kappa}$(4–300K) (W/cm)	$\Delta l/l$ (4-300K) (10^{-5} cm/cm)
Cu	1600	339
Al (0.99 pure)	730	431
Stainless Steel	31	304
Titanium Alloy	17	155
Epoxy Fiberglass	1.5	225
0.8 mm Kevlar Thread		

Stainless Steel Thermal Conductivity

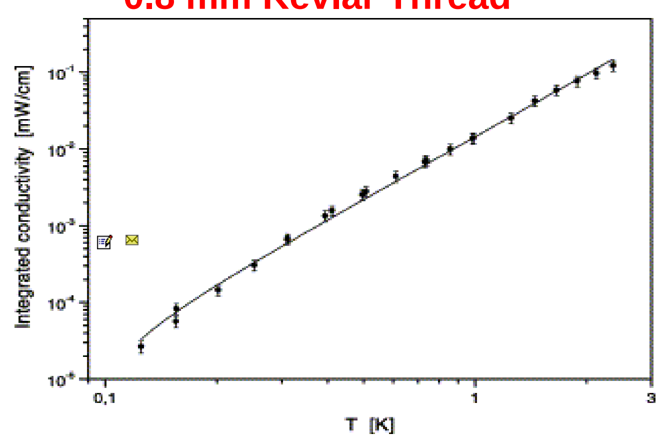


G10 Thermal Conductivity



$$\kappa_{G10}(T) = T \cdot 10\wedge\left\{-1.505 + 1.363\ln(T) - 0.284[\ln(T)]^2 + 0.033[\ln(T)]^3\right\} \quad mW/cm/K$$

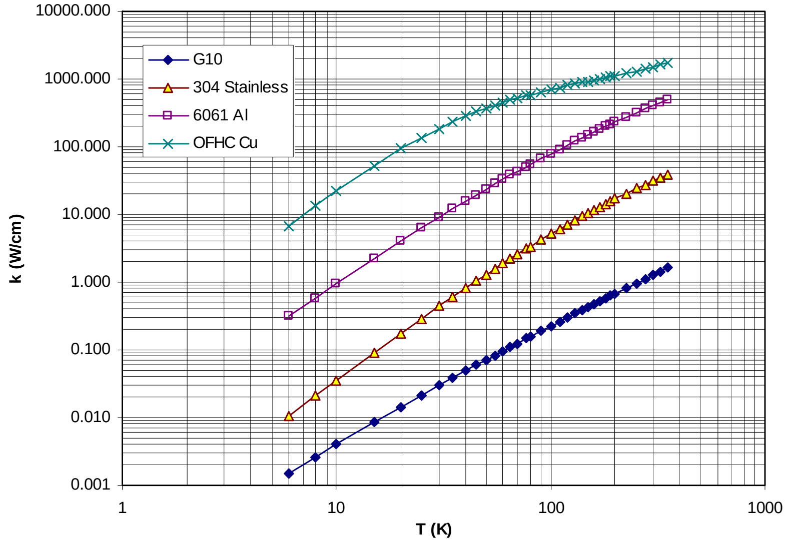
0.8 mm Kevlar Thread



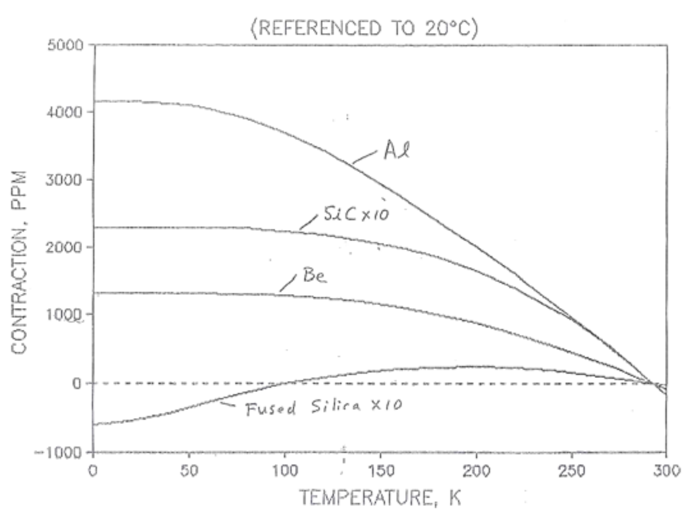
$$k(T) = (3.9 \pm 0.2) \times 10^{-2}\ T^{1.71 \pm 0.04}\ \text{mW/cm K}$$

G. Ventura, M. Barucci, E. Gottardi and I. Peroni, Cryogenics 40, 489 (2000)

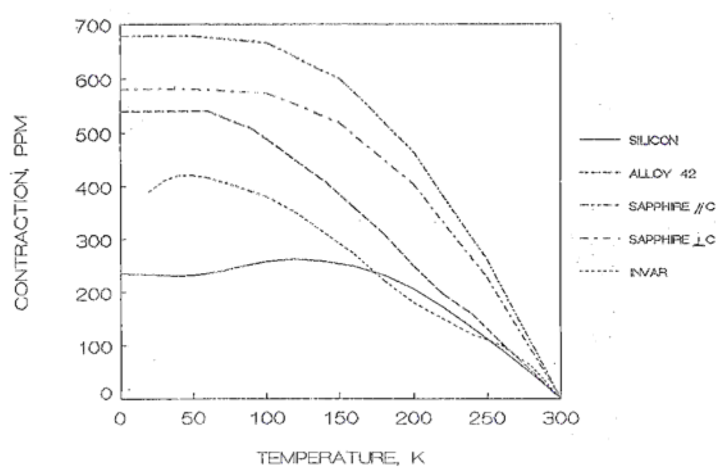
Integrated Thermal Conductivities



Thermal Contraction (Mirror Materials)



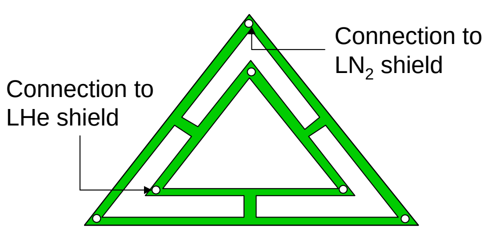
Thermal Contraction (Focal Plane Materials)



Heat Loads 11 A525 - Lecture 26

Rigidizers and Thermal Standoffs

- There is a need to mechanically strengthen the cryogen cans to
  - Prevent stress on the neck(s)
  - Prevent shifts in optical alignment with changes in dewar orientation.
- Example: G10 "triangle" attached to LN_2 & LHe shields



Typical $A/l \sim 0.022$ cm

$Q_{Triangles} \sim 3.1$ mW

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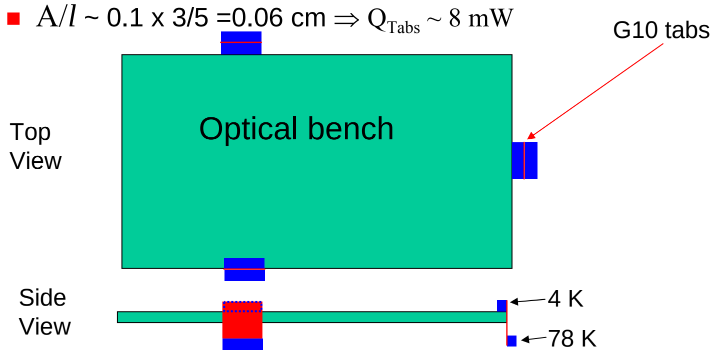
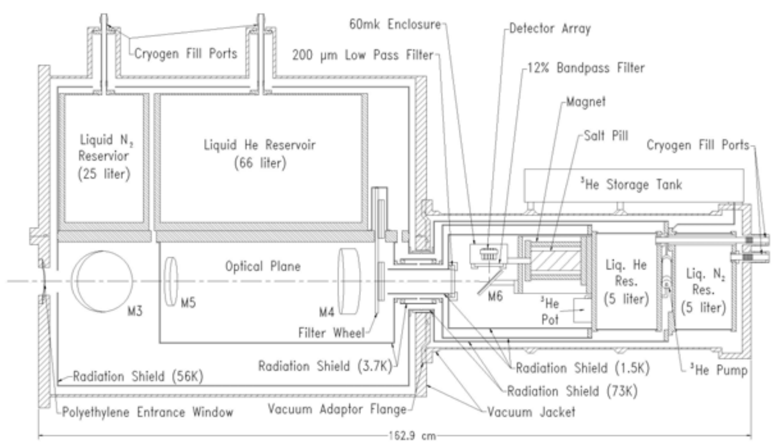
Rigidizers and Thermal Standoffs

- Another way: flexible G10 tabs
  - Can be placed at center of gravity
  - Support structure: can have “floppy necks
  - Very rigid, small thermal loads
  - A/l ~ 0.1 x 3/5 =0.06 cm $\Rightarrow Q_{Tabs} \sim 8$ mW

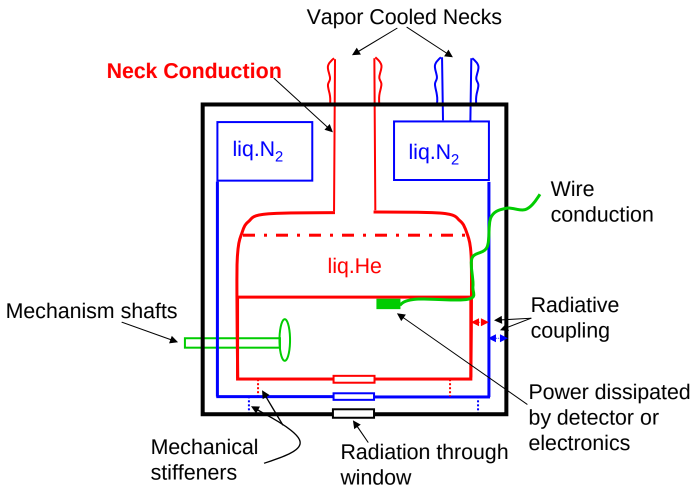


Rigidizers and Thermal Standoffs

- SPIFI Cryostat: Side view



Cryostat Heat Loads



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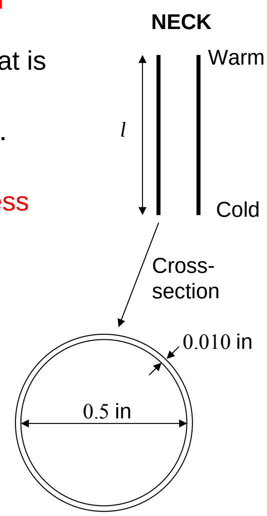
Neck Conduction

- A main consideration in the design of a cryostat is the neck tube since this cannot be avoided.
- A typical neck might be 5 in. long with a 0.5 in. diameter and a wall thickness of 0.010 in.
- Because of its low thermal conductivity stainless steel is used.
- The heat conduction through the neck will be

$$Q_n = \frac{A}{l}\bar{\kappa}(T_w - T_c) = 247\ mW$$

This would boil off 1 liter of LHe in ~2.9 hrs!

Fortunately this answer is incomplete!



Heat Loads 16 A525 - Lecture 26

Gas Cooling Power

- Since the He vapor rises and cools the neck, the thermal conduction through the neck is greatly reduced.
- Note:
  - The energy required to boil 1 g of LHe at 4.2 K is ~21 J.
  - The energy required to warm the resulting 1 g of vapor from 4.2 to 77 K and from 4.2 to 293 K are 385 and 1540 J respectively. (specific heat, C_p ~ 5.2 J/K/g)
- Clearly, the enthalpy (cooling power) of the gas is enormous compared to the latent heat of vaporization of the liquid.

Computing the Neck Heat Load

- The heat flow in the neck at any point is given by:

$$Q_n = \frac{A}{l}\kappa(T_n)\frac{dT_n}{dx} \qquad (0 \le x \le 1) \qquad (1)$$

- Where the tube length is l and x is the normalized distance.
- Due to the cooling power of the escaping gas, the net heat current in the neck tube decreases as the gas warms.
- The rate of change of Q_n is

$$\frac{dQ_n}{dx} = \dot{M}C_p \frac{dT_g(x)}{dx} \qquad (2)$$

$\dot{M}$ = mass flow rate of the gas
C_p = specific heat of the gas
$T_g(x)$ = temperature of the gas
T_g = exit gas temperature at x =1
T_c = cryogen temperature at x = 0

Neck Heat Load (cont'd)

- Equation (2) is integrated to obtain [$Q_c = Q_n(x=0)$]

$$Q_n = Q_c + \dot{M} C_p \left(T_g - T_c\right) \qquad (3)$$

- The rate at which gas is boiled off is given by

$$Q_c + P_h = \dot{M} L \qquad (4)$$

L = latent heat of vaporization
P_h = parasitic heat (all sources except the neck)

- Combining equations 1, 3, and 4 gives

$$\frac{A}{l}\kappa(T_n)\frac{dT_n}{dx} = Q_c + \frac{P_h + Q_c}{L} C_p \left(T_g - T_c\right) \qquad (5)$$

Heat Loads 19 A525 - Lecture 26

Neck Heat Load (cont'd)

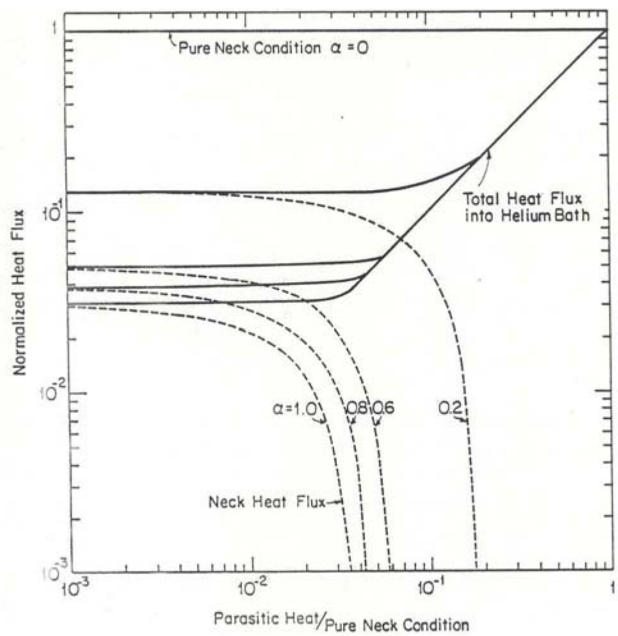
- In general, the gas temperature lags behind the tube temperature as it warms. We model this assuming

$$T_g - T_c = \alpha\left(T_n - T_c\right) \qquad (6)$$

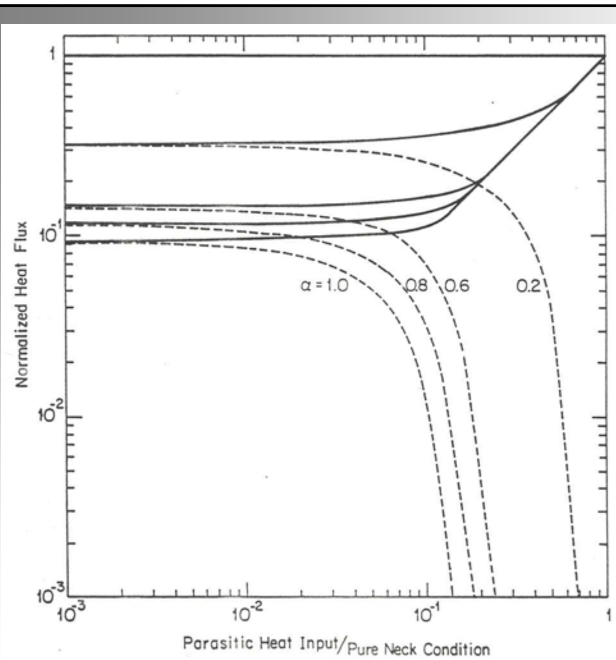
- The case $\alpha = 0$ corresponds to no gas cooling with the vapor leaving the neck tube at the cryogen boiling temp.
- The case $\alpha = 1$ corresponds to perfect thermal contact between the neck tube and the gas (very slow gas flow rate).
- With assumption of equation 6, equation 5 becomes

$$\frac{A}{l}\kappa(T_n)\frac{dT_n}{dx} = Q_c + \frac{\alpha C_p \left(P_h + Q_c\right)\left(T_n - T_c\right)}{L} \qquad (7)$$

Heat Loads 20 A525 - Lecture 26

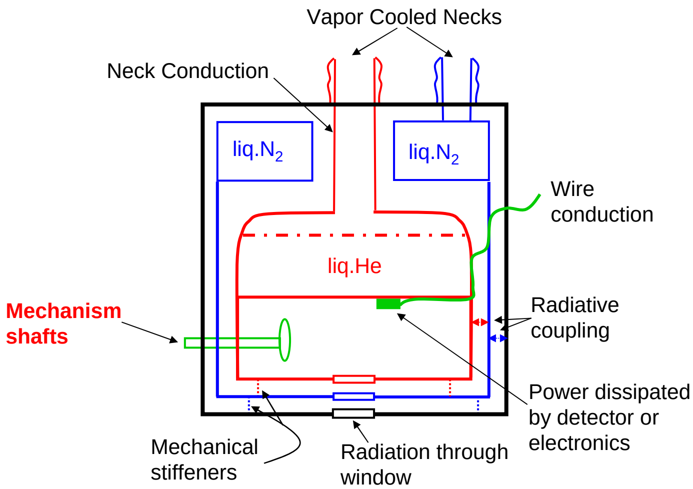


Neck Conduction (4.2-300K)

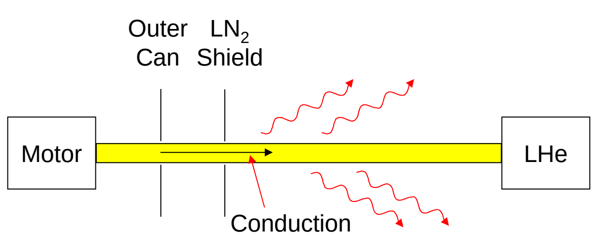


Neck Conduction (4.2-77K)

Cryostat Heat Loads



Mechanical Shafts



- If the shaft (rod) is not heat sunk to the LN2 shield it will act as a “hot poker” radiating into the helium cryostat.
- As before $$Q_r = \frac{A}{l}\kappa(T_r)\frac{dT_r}{dx}$$

Mechanical Shafts

- But radiative cooling/heating changes the heat flow in the rod

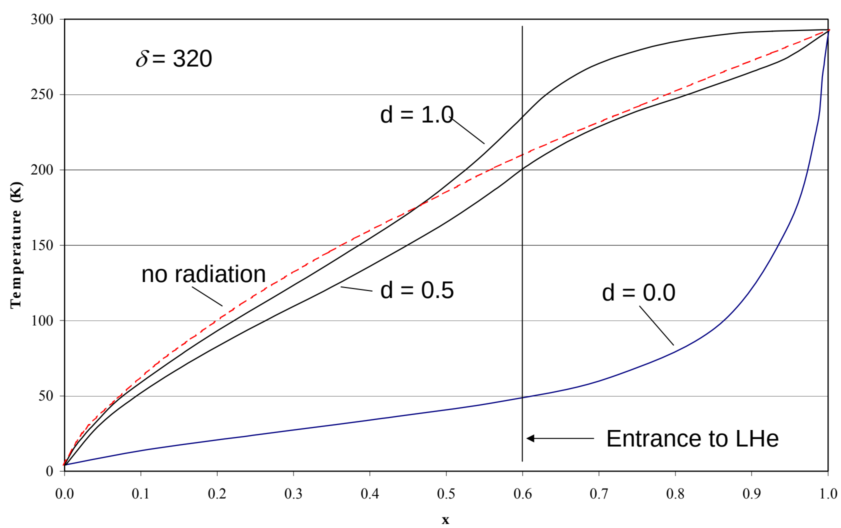
$$\frac{dQ_r}{dx} = Sl\varepsilon\sigma\left(T_r^4 - T_b^4 d\right)$$

- Where S = surface area of rod per unit length, ε = effective emissivity, and d is the dilution factor for the background radiation. Combining our two equations gives

$$\frac{d}{dx}\left[\kappa(T_n)\frac{dT_n}{dx}\right] = 4\delta\sigma\left(T_r^4 - T_b^4 d\right) \qquad \delta = \varepsilon\frac{Sl^2}{4A}$$

- For a fixed thermal conductivity, δ measures the relative importance of radiative vs. conductive heat input.

Radiating-Conducting Shaft



Example Dewar Hold-time Estimates

	Heat Load (mW)				
Item/Case	1	2	3	4	5
Rigidizers	4.6	4.6	-	4.6	4.6
Radiation	9	9	9	9	9
Window	24	24	24	24	24
Grating Shaft	18	7.7	-	-	7.7
Filter Shaft	23	14.7	-	23	23
Neck Tube	< 1	< 1	< 1	< 1	< 1
Total Heat Input	79	60	33	61	68
Expected Hold Time (hr/l)	9.1	11.9	21.6	11.7	10.4
Observed Hold Time (hr/l)	10	12.5	20.5	13	11

A"-" denotes item not present
Case 2, both grating and filter shaft aluminized
Case 3, no grating or filter shafts
Case 4, no grating shaft
Case 5, grating shaft aluminized