# PHY524 Cryogenics-2

Thermal conduction w/ convection, radiation;

Thermal contact

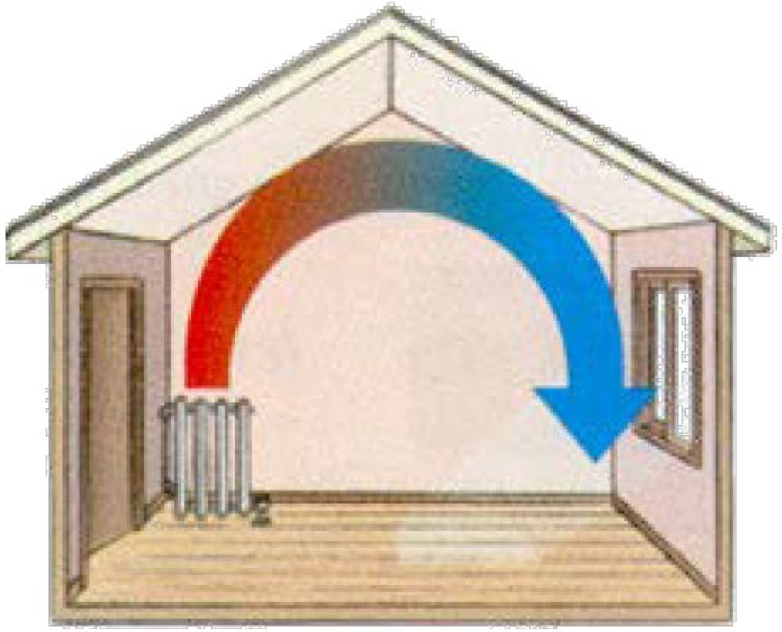
11/11/2025

Material adopted from

1. https://www.stonybrook.edu/commcms/case/courses/PHY695
2. http://cryocourse2016.aalto.fi/#program
3. http://cryocourse2011.grenoble.cnrs.fr/spip.php%3Frubrique13.html
4. USPAS | Materials | by Year | 21onlineSBU | Cryogenic Engineering
5. USPAS | Materials | by Year | 10MIT | Cryo Engineering

# Convection

- Convective heat transfer through *gases* and *liquids*



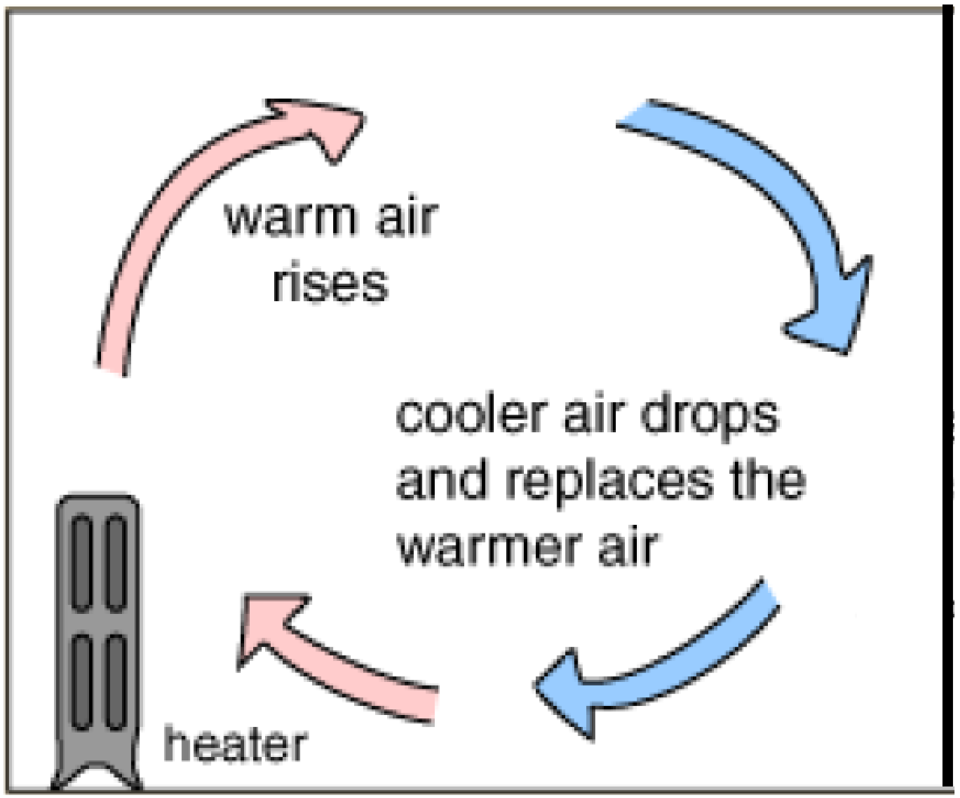
# Mechanism of Convection

ideal gas at constant pressure

$$\frac{V}{T} = \text{const}$$

$$\varrho = \frac{m}{V}$$

Temperature rise
→ volume rises
→ density decreases




https://www.facebook.com/watch/?v=1162378181625555

# Convective Heat Transfer through Gases and Liquids

two limiting cases: $\ell \ll d$ hydrodynamic regime

$\ell \gg d$ Knudsen regime (free molecule regime)

mean free path:

$$\ell = \frac{1}{\sqrt{2} n \sigma}$$

ideal gas:

$$\ell = \frac{RT}{\sqrt{2} \pi d^2 N_A \, p}$$

empirical law for real cryogenic gases:

$$\ell = 2.87 \times 10^{-3} \frac{T^{j+1}}{p}$$

[cm] [K] [Pa]

Helium: $j + 1 = 1.147$

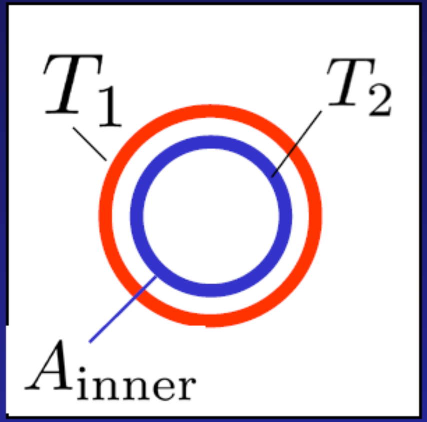
# Mean Free Path depends on pressure (Ideal Gas Law)

| Vacuum range | $p$ [mbar] | Molecules / $cm^3$ | mean free path |
|---|---|---|---|
| Ambient pressure | 1013 | $2.7 \times 10^{19}$.. | 68 nm |
| Low vacuum | 300..1 | $10^{19}..10^{16}$ | 0.1 ... 100 µm |
| Medium vacuum | $1..10^{-3}$ | $10^{16}..10^{13}$ | 0.1 ... 100 mm |
| High vacuum | $10^{-3}..10^{-7}$ | $10^{13}..10^{9}$ | 10 cm ...1 km |
| Ultra high vacuum | $10^{-7}..10^{-12}$ | $10^{9}..10^{4}$ | 1 km ... $10^5$ km |
| Extremely high vacuum | $<10^{-12}$ | $<10^{4}$ | $> 10^5$ km |

Mean free path $\sim \frac{1}{n\sigma}$

# Knudsen Regime $\ell \gg d$

Low density




material dependent constant

| | |
|---|---|
| air | 1.2 |
| helium | 2.1 |
| hydrogen | 4.4 |

$$\dot{Q}_{\text{gas}} = k\, a_0\, p\ A_{\text{inner}} \Delta T [W]$$

$p$: [$10^{-2}$ mBar] $A_{\text{inner}}$: [cm$^2$] $\Delta T$: [K]

$$a_0 = \frac{a_1 a_2}{[a_2 + (A_1/A_2)(1 - a_2)a_1]}$$

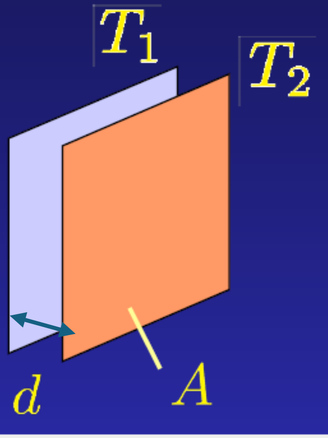
$$a_1 \approx a_2 \approx 0.5 \quad \rightarrow \quad a_0 = \frac{0.5}{1 + (A_1/A_2)0.5}$$

parallel plates $\quad A_1 = A_2 \quad \rightarrow \quad a_0 = 0.33$

# Hydrodynamic Regime $\ell \ll d$

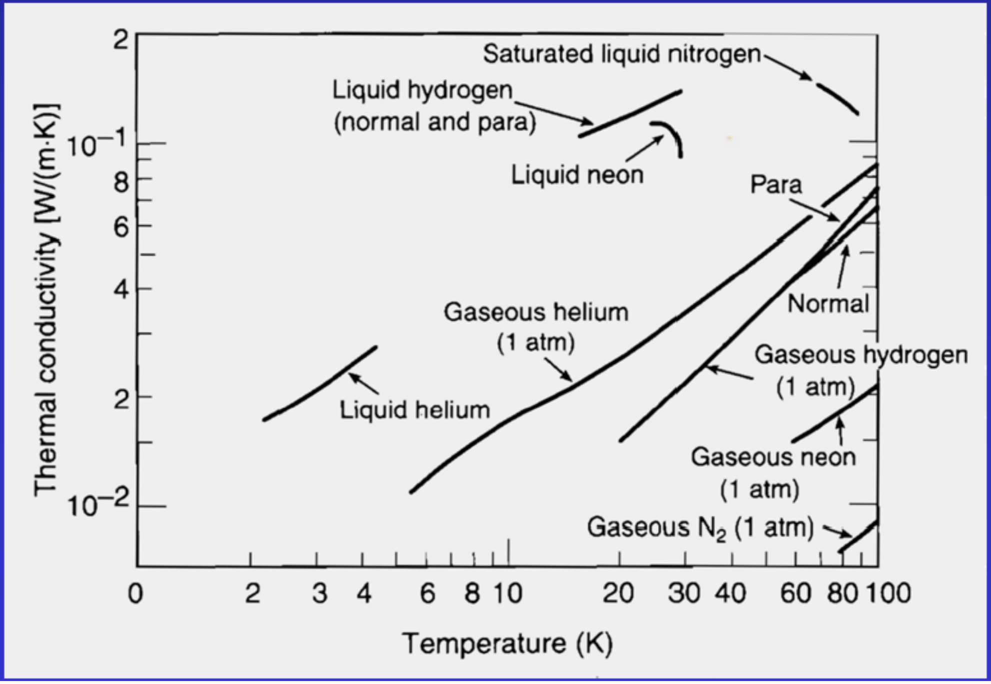
High density

thermal conductivity independent of pressure: $\lambda \propto \ell n\,, \quad \ell \propto \dfrac{1}{n}$




$$\dot{Q}_{\rm gas} = \frac{\bar{\lambda}\, A\, (T_1 - T_2)}{d} = \frac{\bar{\lambda}\, A\, \Delta T}{d}$$

mean thermal conductivity




for gases: $\lambda = c\, C_V$

constant 1.5 ... 2.5

Ekin 2005

# Fluid dynamics

Continuity $\nabla.\mathbf{v} = 0$

Navier–Stokes $\rho\mathbf{v}.\nabla\mathbf{v} = -\nabla p + \mu\nabla^2\mathbf{v} + \cancel{\mathbf{f}}$

Energy $\rho C\mathbf{v}.\nabla T = k\nabla^2 T + \text{Q}$

Dimensionless $\longrightarrow$

$$\nabla.\mathbf{v}^* = 0$$

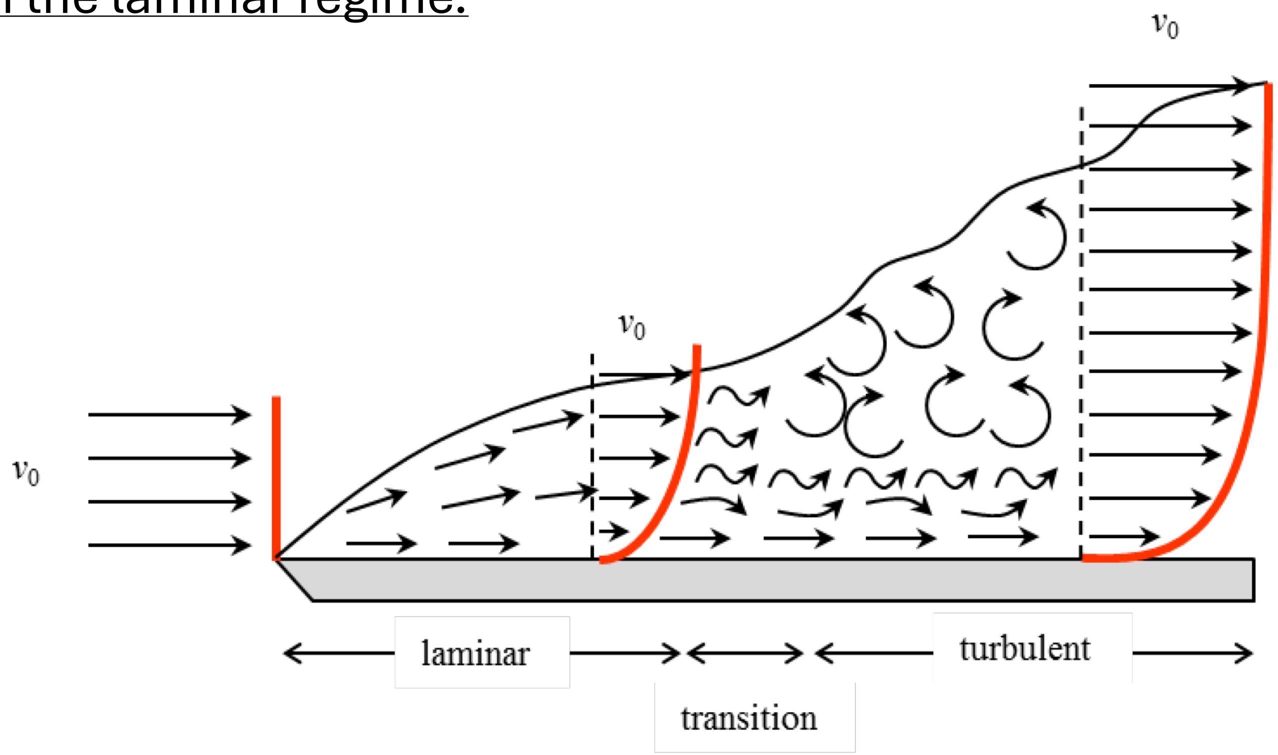
$$\mathbf{v}^*.\nabla\mathbf{v}^* = -\nabla p^* + \text{Re}^{-1}\nabla^2\mathbf{v}^*$$

$$\mathbf{v}^*.\nabla T^* = \text{Re}^{-1}\,\text{Pr}^{-1}\,\nabla^2 T^*$$

- Reynolds number, $\text{Re} = \frac{\rho L v}{\mu}$
  - ratio of the inertia to the viscous forces
- Prandtl number, $\text{Pr} = \frac{\mu C}{k}$
  - ratio of the momentum to the thermal diffusivity

# Laminar vs turbulent flow

- Re < 2300: laminar regime
  - the **viscous forces dominate**, creating an 'ordered' flow with streamlines. In this regime, the surface heat transfer is low and so is the surface friction.
- $Re_L > 5 \times 10^5$ : turbulent regime
  - $Re_D > 4000$ for a plate and a tube-shaped geometry, respectively.
  - **the inertia forces dominate**, and the flow becomes highly irregular (velocity fluctuation), as shown below. The surface heat transfer and the friction are higher than those in the laminar regime.



# Newton's law

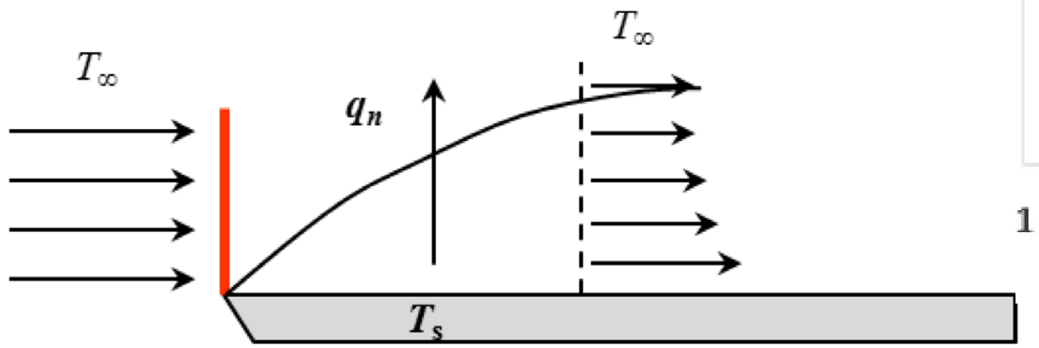
- When there is an interaction with solid surfaces in convection, the heat transferred in (or out) of the fluid to solids is evaluated by the Newton's law:

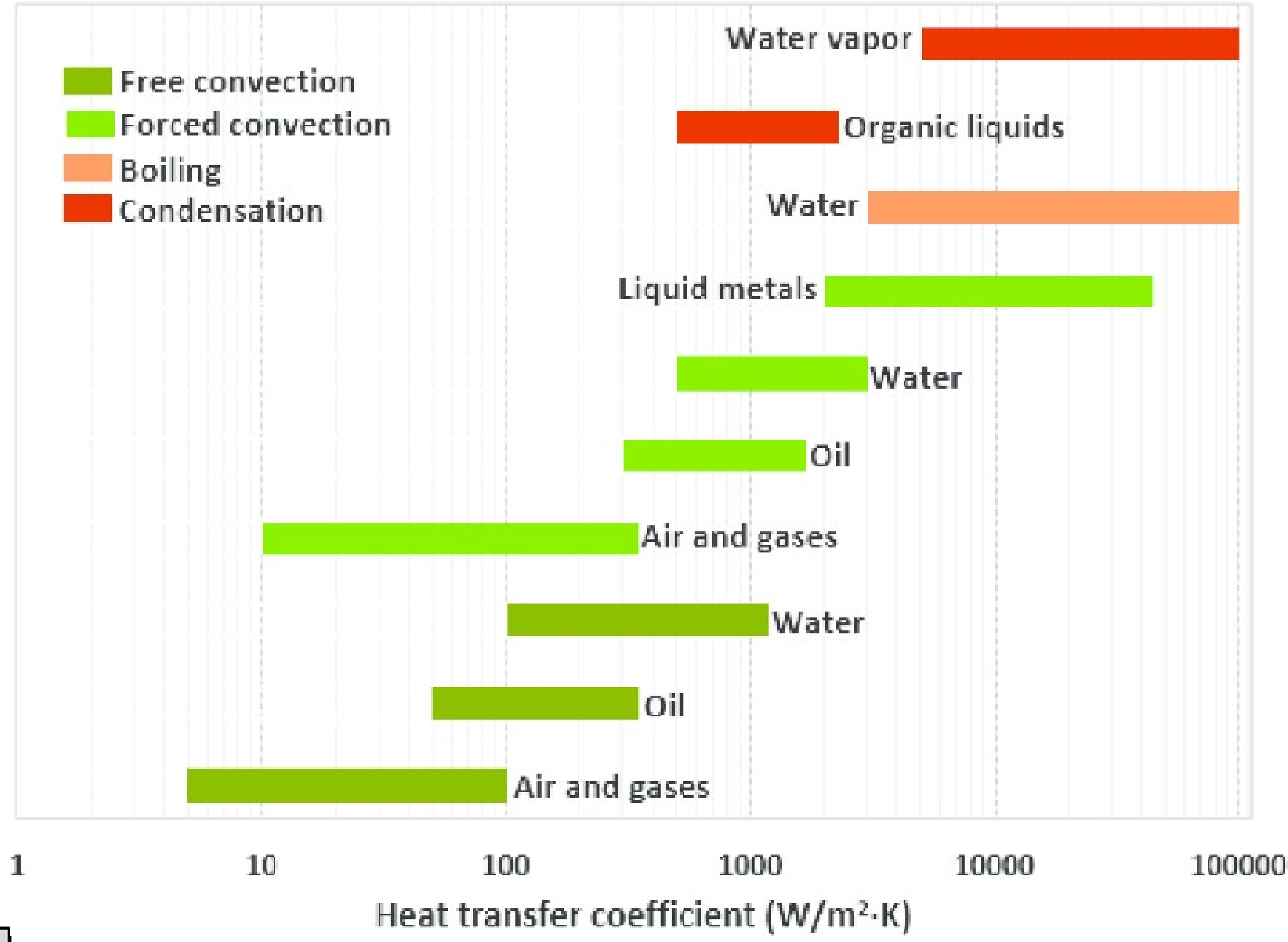
$$q = h(T_s - T_\infty)$$

where $h$ is the heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$], $T_s$ the temperature of the solid and $T_\infty$ is the temperature far from the solid.

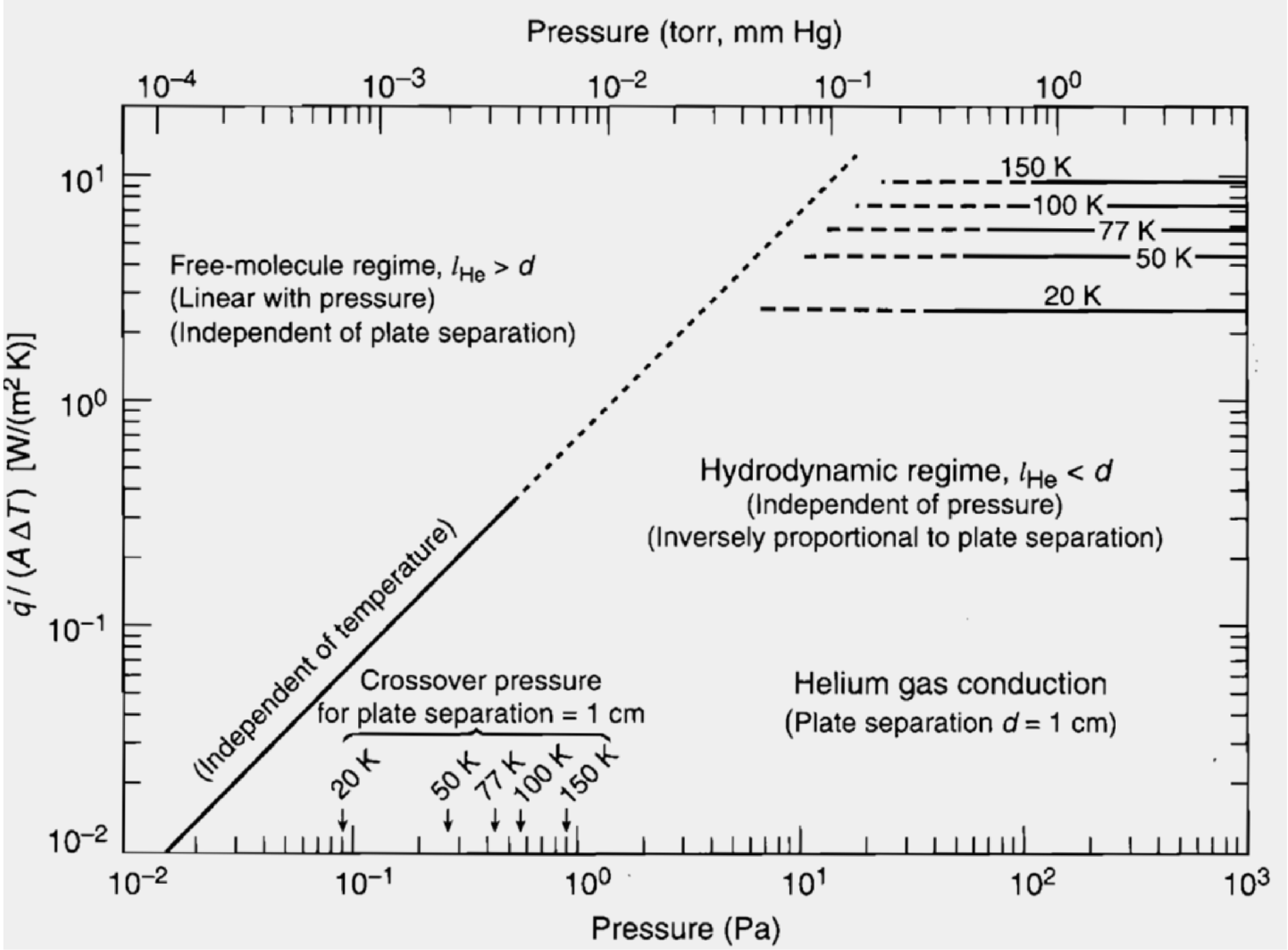
At the boundary, the local heat flux through the conductive layer of the fluid is

$$q_n = k.\nabla T_n$$



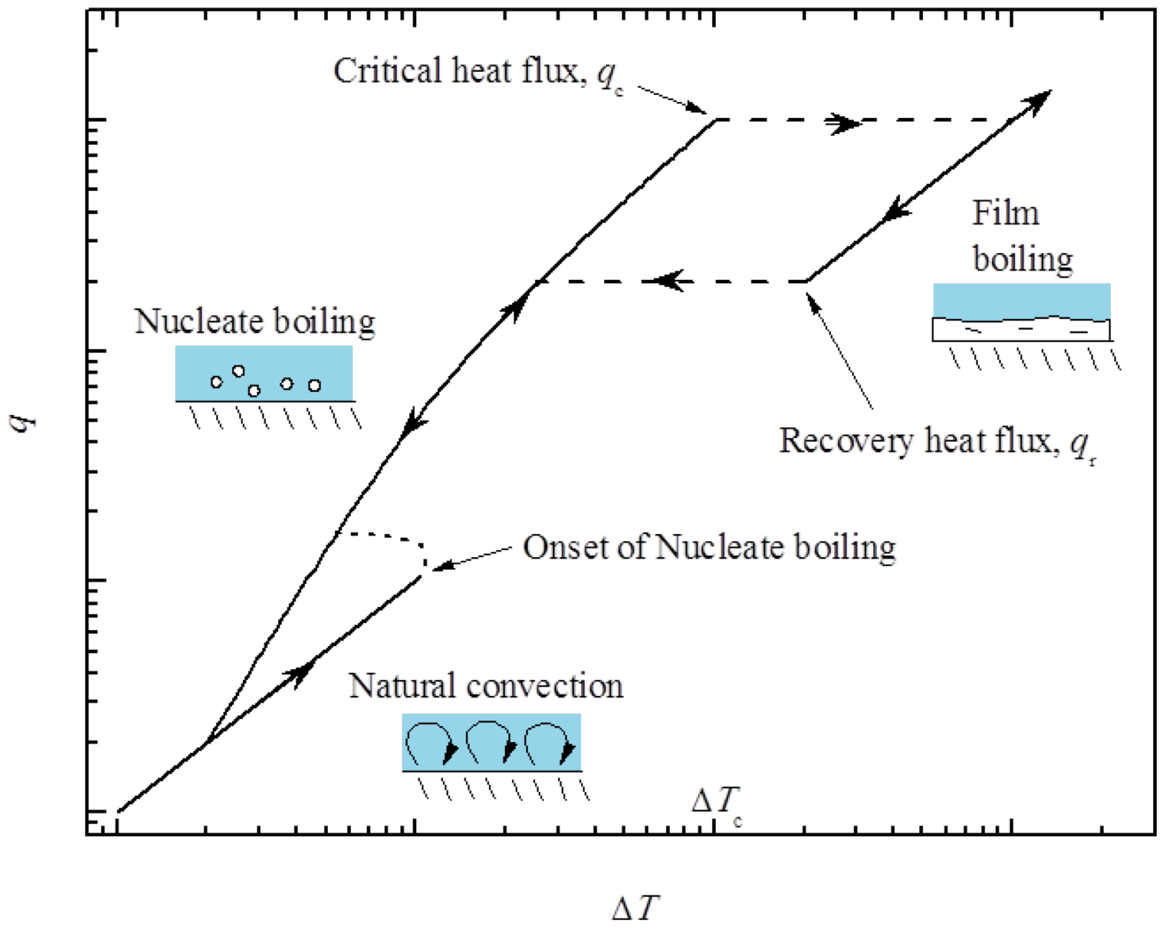



# He Gas



Pressure (torr, mm Hg)
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
150 K
100 K
77 K
50 K
20 K
10¹
10⁰
10⁻¹
10⁻²
q̇ / (A ΔT) [W/(m² K)]
Free-molecule regime, $l_{He} > d$
(Linear with pressure)
(Independent of plate separation)
(Independent of temperature)
Hydrodynamic regime, $l_{He} < d$
(Independent of pressure)
(Inversely proportional to plate separation)
Crossover pressure
for plate separation = 1 cm
20 K
50 K
77 K
100 K
150 K
Helium gas conduction
(Plate separation $d$ = 1 cm)
10⁻²
10⁻¹
10⁰
10¹
10²
10³
Pressure (Pa)

# Types of convection in liquids




- Natural convection
  - When the fluid movement is created internally, by a decrease or increase of the fluid density or by the buoyancy effect.
- Forced convection
  - Mostly turbulent flows. A laminar flow in pipes is very rare, except in porous media
- Boiling convection
  - Heat transfer combines
    - natural convection in the liquid,
    - latent heat to be absorbed for the bubble formation, and
    - the bubble hydrodynamics.
  - The heat transfer process depends on the bubble growth rate, the detachment frequency, the number of nucleation sites, and the surface conditions.

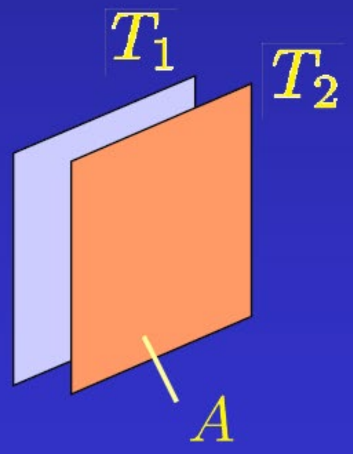
# Radiative Heat Transfer

radiative heat flow from a body with surface A

$$\dot{Q}_{\mathrm{rad}} = \sigma \, \varepsilon \, A \, T^4$$ Stefan-Boltzmann Law

$\varepsilon$: emissivity 0.01 … 1

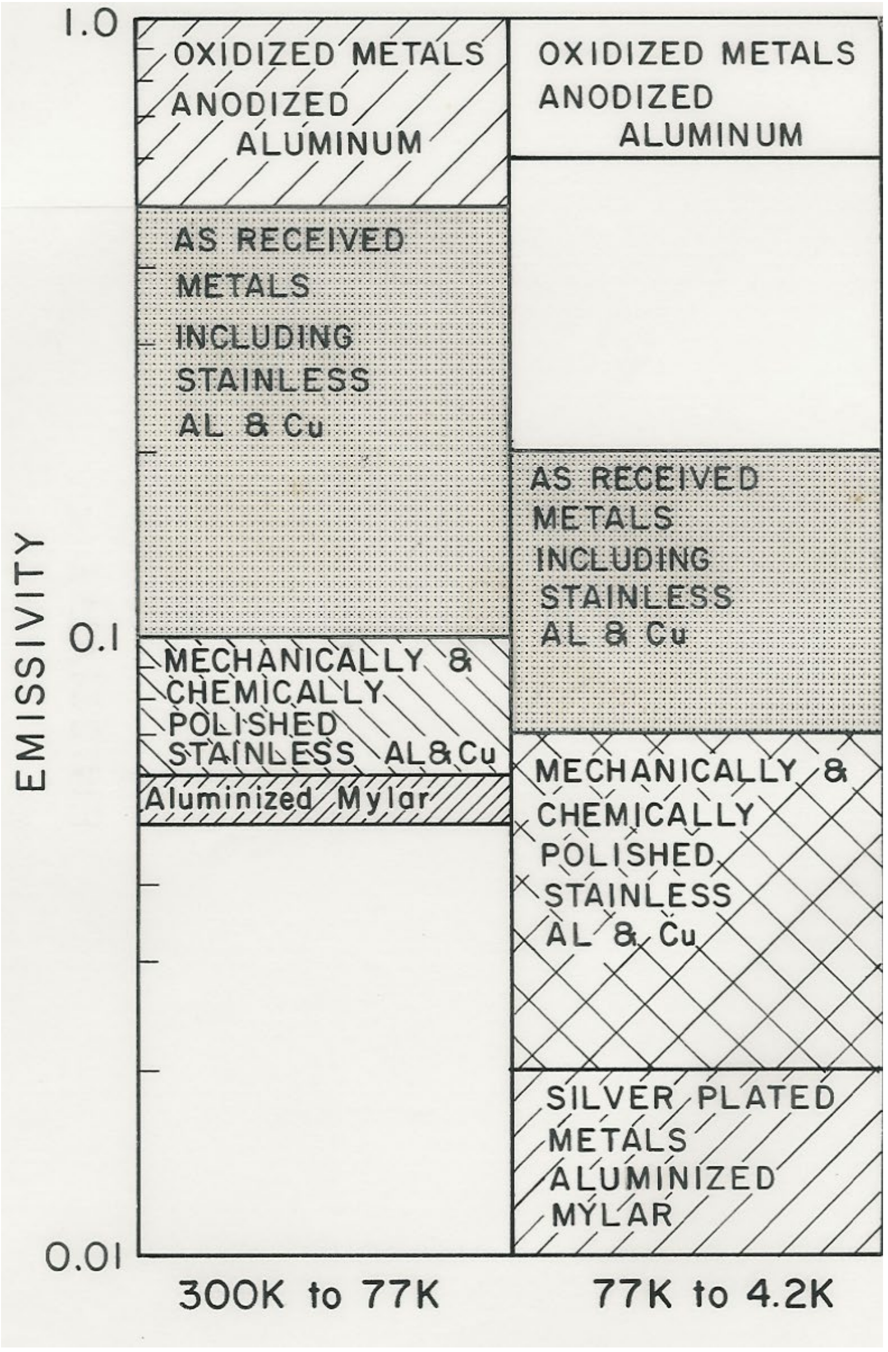
$$\sigma = 5.67 \times 10^{-8} \, [\mathrm{W/(m^2K^4)}]$$




$$\dot{Q}_{\mathrm{rad}} = \sigma \, \mathcal{E} \, A \, \left(T_2^4 - T_1^4\right)$$

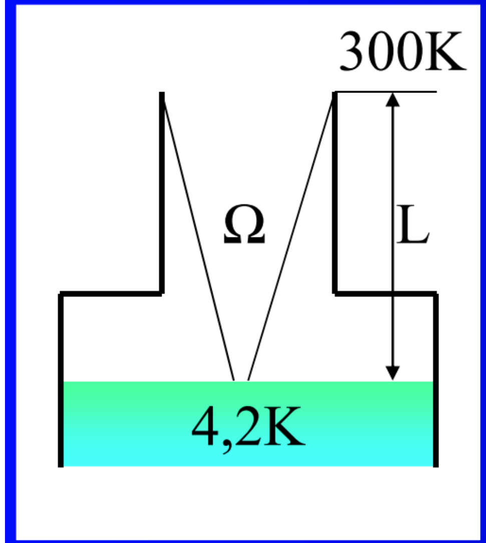
Wien's law $\lambda T = 2900$ [µm K]

wave lenght 300 K 0.01 mm
3 K 1 mm



# Radiation heat load

## Radiation of neck : $Q_{Rcol}$




- We have :

$$Q_{Rneck} = S\varepsilon_e \sigma T^4 \cdot \Omega$$

$$with\ T^4 = 300^4$$

$$\Omega = solid\ angle = \frac{R^2}{R^2 + L^2}$$

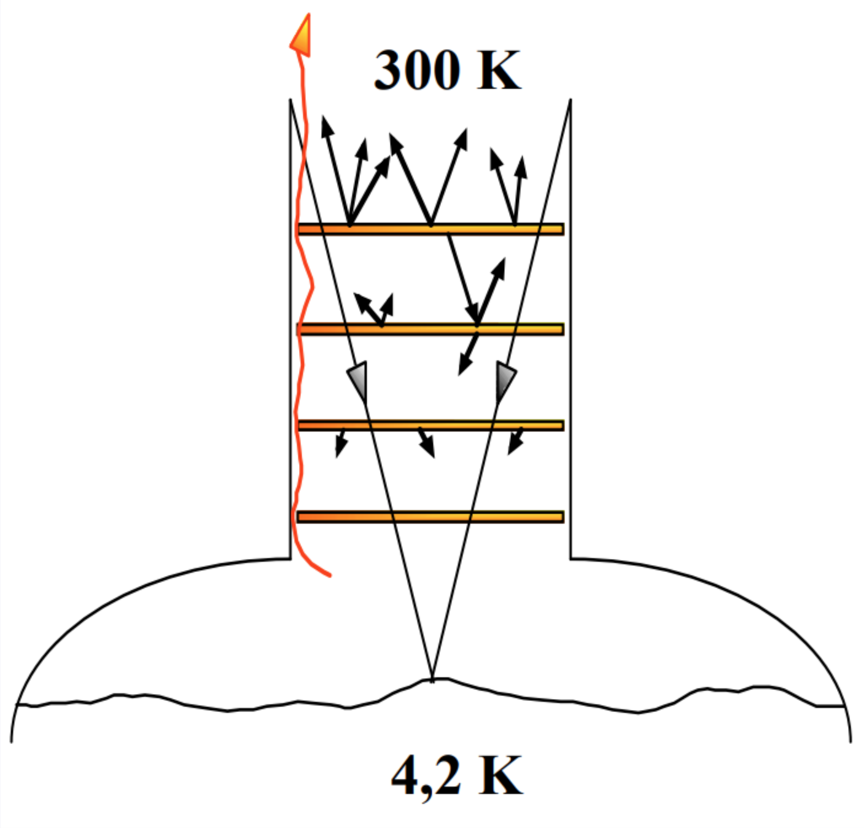
- Example
  - Ø = 150 mm then, S = 180 cm$^2$
  - L = 300 mm
  - εΩ ~ 0.05 (typical value)
- $Qr_{neck}$ = 0.38 watt ←A large value!

Homework:

1. Estimate the heat load due to thermal radiation from the top assembly

# Baffles

- The cover plate radiates directly on the bath
  - Important losses!
- Solutions
  - *Thermal shields distributed along the neck*
  - *Low emissivity ($\varepsilon < 0.1$)*
  - *The heat recovered by the shields is evacuated by the vapors*



# Heat Load Calculation

## A few Numbers

| | |
|---|---|
| twisted pair of copper wire: | diameter 125 µm, 1,5 m long |
| | heat transfer between 300 K to 4 K: 0.14 mW |
| stainless steel tube: | diameter 2 cm, wall thickness 0.4 mm, 1,5 m long |
| | heat transfer between 300 K to 4 K: 51 mW |
| radiation: | two plates with 30 $cm^2$ surface area |
| | heat transfer between 300 K to 4 K: 26 W |
| exchange gas: | two plates with 30 $cm^2$ surface area, 1 mBar, 1 cm |
| | heat transfer between 300 K to 4 K: 45 W |

Homework:

1. Estimate the heat load due to thermal radiation from the top assembly

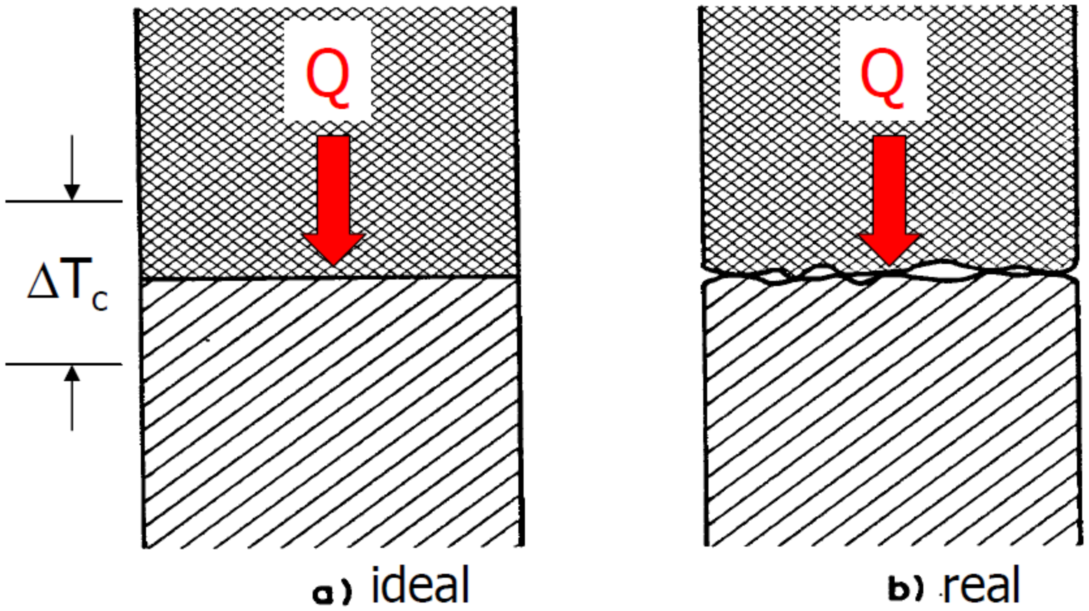
# Thermal anchoring

Samples, Sample Holders, Wires and Cables

- Welding
- Soldering
- Varnish and glue joints
- Press contacts
- Exchange gas

# Contact Resistance

- Joints or contacts can lead to considerable resistance in a thermal (electrical) circuit.
- Contact resistance can vary considerably depending on a number of factors
  - Bulk material properties (insulators, metals)
  - Surface condition (pressure, bonding agents)




Heat transfer coefficient

$$Q = h_c A \Delta T$$

# Thermal contact conductance (conductive)

Contact point between two materials can produce significant thermal resistance

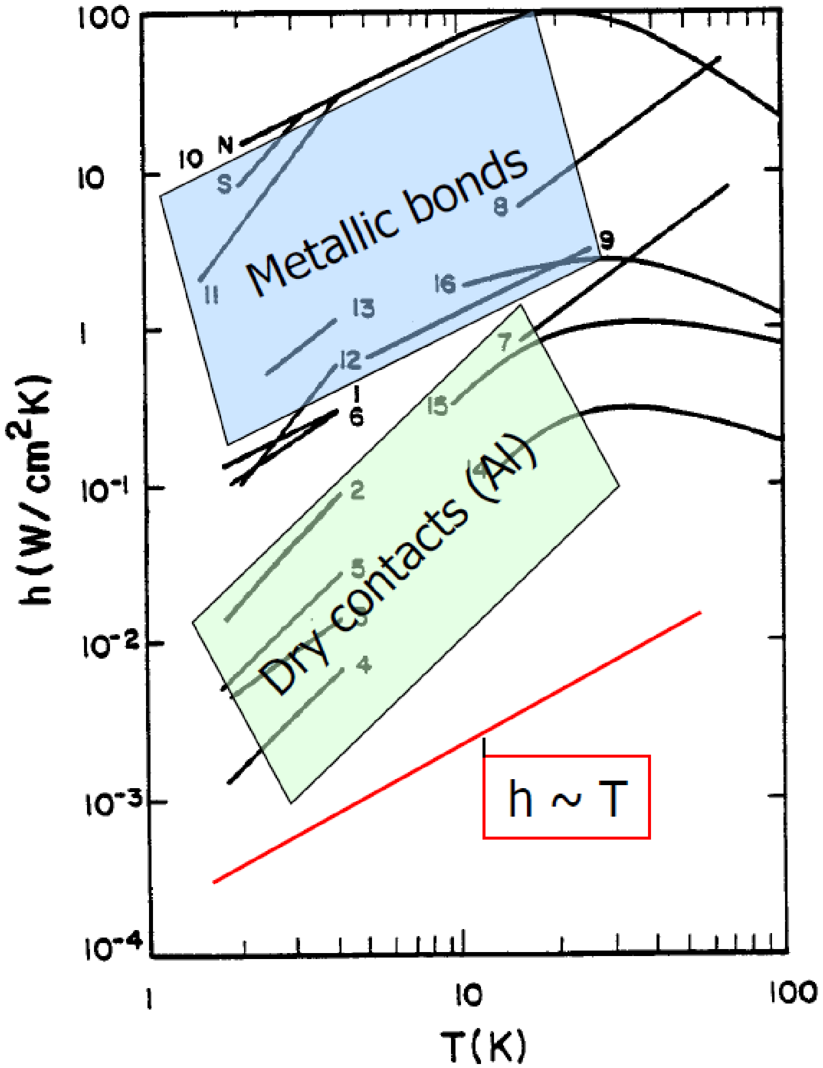
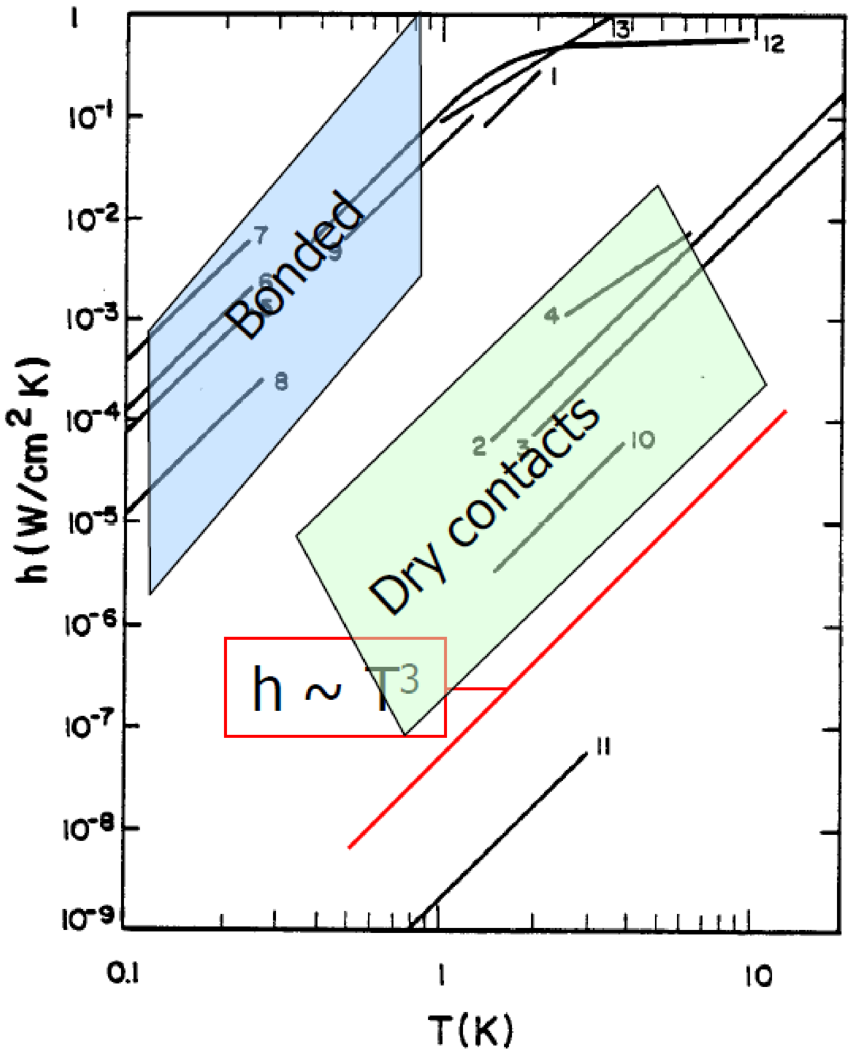



Table II. Thermal Conductance of Metallic Contacts

| | Material | Contact | Pressure (MPa) | $h(W/cm^2\ K)$ | Temp. Range (K) | Ref |
|---|---|---|---|---|---|---|
| 1. | Al-Al (alloy) | machined | torque=20 Nm | $0.075\ T$ | 1.8-4.2 | Wanner /13/ |
| 2. | Al-Al alloy | electropolished | torque=20 Nm | $3.6x10^{-3}\ T^{2.3}$ | 1.8-4.2 | |
| 3. | Al-Al alloy | Au plated | torque-20 Nm | $1.9x10^{-3}\ T^{1.4}$ | 1.8-4.2 | |
| 4. | Cu-Cu | machined | 2.8 | $4x10^{-4}\ T^2$ | 1.8-4.2 | Berman /8/ |
| 5. | Cu-Cu | machined | 14 | $1.67x10^{-3}\ T^2$ | 1.8-4.2 | |
| 6. | Au-Au | -- | 5.6 | $0.05\ T^{1.3}$ | 2-4 | Berman & Mate /7/ |
| 7. | SS-SS (302) | polished | 21 | $0.014\ T^{1.5*}$ | 15-300 | Lyon & Parrish /14/ |
| 8. | SS-SS (302) | polished | 390 | $0.10\ T^{1.5*}$ | 15-300 | |
| 9. | Cu-Cu | machined | 7 | $0.13\ T$ | 5-25 | Nilles & Van Sciver /15/ |
| 10. | Cu-Cu | in solder | -- | $7.5\ T^*$ | 2-150 | Radebaugh /16/ |
| 11. | Cu-Cu | Pb solder | -- | $0.64\ T^{2.8}$ | 1.5-4 | Challis & Cheeke /17/ |
| 12. | Cu-Cu | woods metal | -- | $0.018\ T^{2.5}$ | 2-4 | |
| 13. | Cu-Cu | PbSn solder | -- | $0.13\ T^{1.6}$ | 2.5-4 | Foster /18/ |
| 14. | Al-Al | SnPb foil | 26 | $0.02\ T^{0.8*}$ | 10-300 | Friedman & Gasser /19/ |
| 15. | Cu-Al | SnPb foil | 9 | $0.04\ T^*$ | 10-300 | |
| 16. | Cu-Cu | SnPb Foil | 7 | $0.17\ T^*$ | 10-300 | |

# Contact conductance (Insulating)




| | Material | Contact | Pressure (MPA) | h(W/cm$^2$ K) | Temp range (K) | Ref. |
|---|---|---|---|---|---|---|
| 1. | In-sapphire | bonded | -- | 0.03 $T^3$ | 1.4-2.1 | Neeper & Dillinger /6/ |
| 2. | sapphire-sapphire | dry | 4 | 9 x $10^{-6}$ $T^3$ | 2-20 | Berman & Mate /7/ |
| 3. | Cu-diamond | dry | 4 | 2 x $10^{-5}$ $T^3$ | 1.5-20 | |
| 4. | Cu-Teflon-Cu | 12 mil foil | 4 | 1.8 x $10^{-4}$ $T^2$ | 2-5 | Berman /8/ |
| 5. | Cu-epoxy-Cu | bonded | -- | 0.09 $T^3$ | 0.05-0.25 | Peterson & Anderson /2/ |
| 6. | Al-epoxy-Al | bonded | -- | 0.13 $T^3$ | 0.05-0.25 | |
| 7. | Pb-epoxy-Pb | bonded | -- | 0.40 $T^3$ | 0.05-0.25 | |
| 8. | Be-epoxy-Be | bonded | -- | 0.013 $T^3$ | 0.05-0.25 | |
| 9. | Cu-LiF | Ge-7031 | -- | 0.05 $T^3$ | 0.4-1.3 | Ackerman & Anderson /9/ |
| 10. | Cu-sapphire-Cu | dry | 0.1 | 1 x $10^{-6}$ $T^3$ | 1.5-4 | Yoo & Anderson /10/ |
| 11. | Cu-sapphire-Cu | $Al_2O_3$ | 0.1 | 2 x $10^{-9}$ $T^3$ | 0.8-3 | |
| 12. | Cu-epoxy-Cu | bonded | -- | 0.16 $T^{0.5}$ | 2-8 | Matsumoto et al. /11/ |
| 13. | Cu-epoxy-Cu | bonded | -- | 0.089 $T^{1.9}$ | 1-4 | Schmidt /12/ |

# Welding: metal to metal contact

| | |
|---|---|
| Oxygen-acetylene welding | very hot flame, porous joint, surface oxidation<br>Large surface area for trapping gas |
| Electric-arc welding | conducts electric current to heat, same problems as oxygen-acetylene welding → inert gas welding |
| Laser-beam welding | similar to electric are welding, heat sourse laser beam |
| Electric resistance welding | Joule heating melts the metal locally<br>usually restricted to small areas: spot welding |
| Pressure welding | soft metals, very cleans surfaces,<br>very high pressures, cold welding |
| Friction welding | used for joining dissimilar metals: Steel and Al, ... |

# Solder Joints

Hard solders: silver solder ~ 700 °C

Soft solders: lead and tin based solders 200 to 400 °C

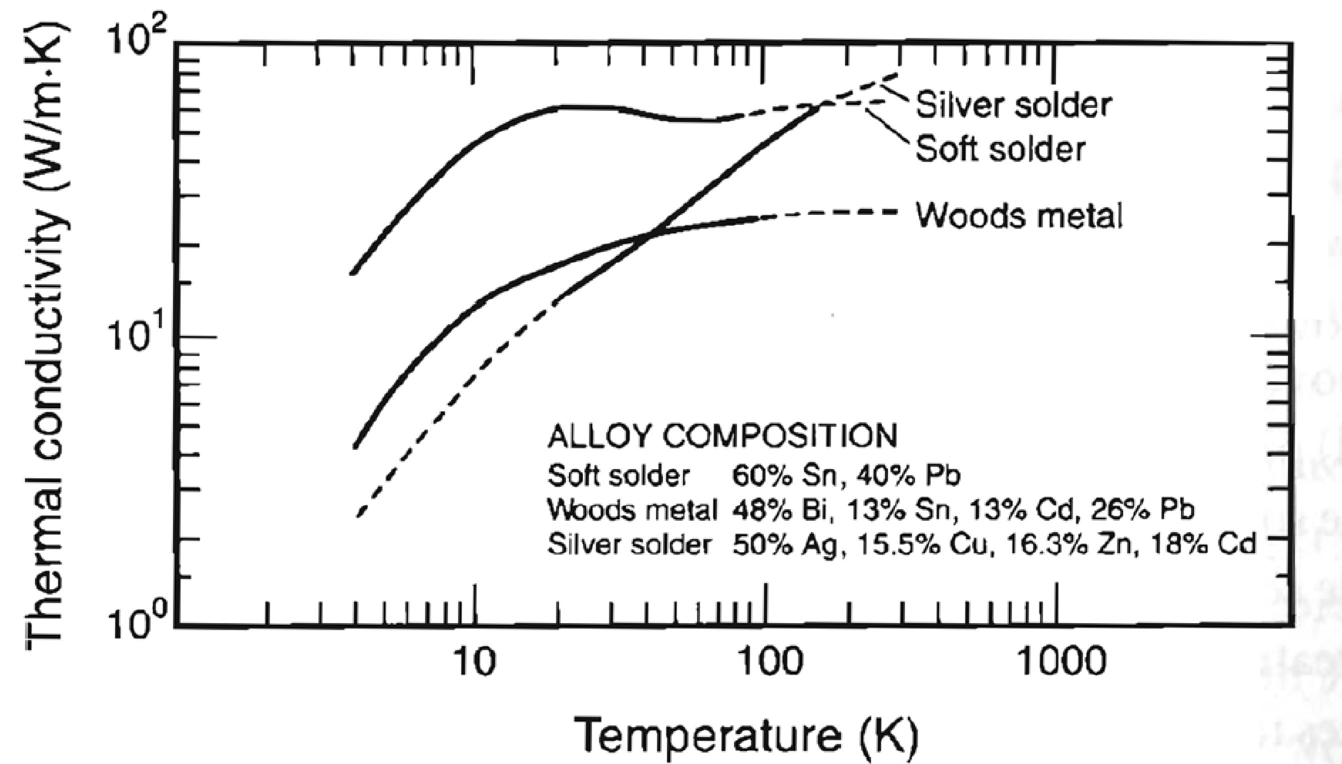
Very low temperature solders: Bismuth based below 100 °C

general problem at very low temperatures:

solder Joints become Superconductive

use the right flux

acid flux can be dangerous by creating pin holes

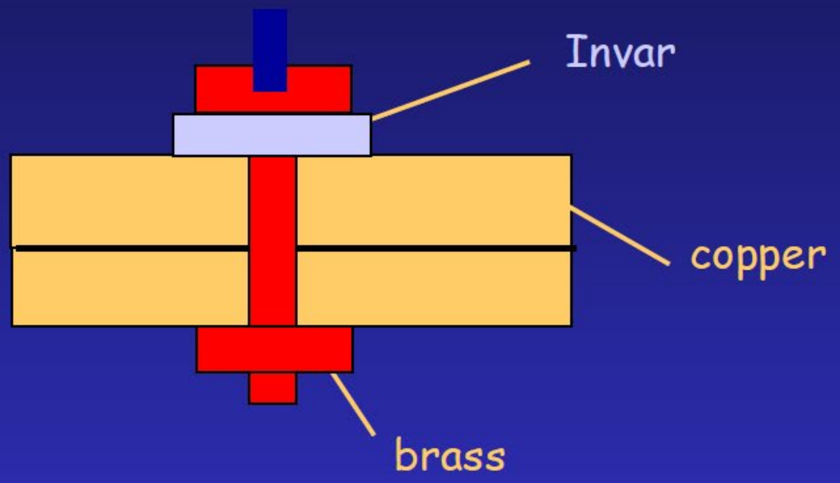


# Press Contact

Thermal conductance increase roughly linearly with pressure

Gold plating before bolting together

Look at thermal expansion



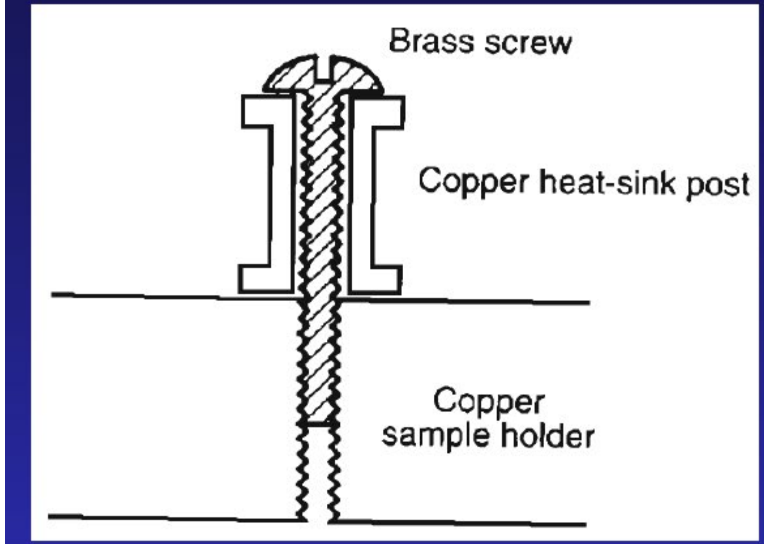

Empirical formula

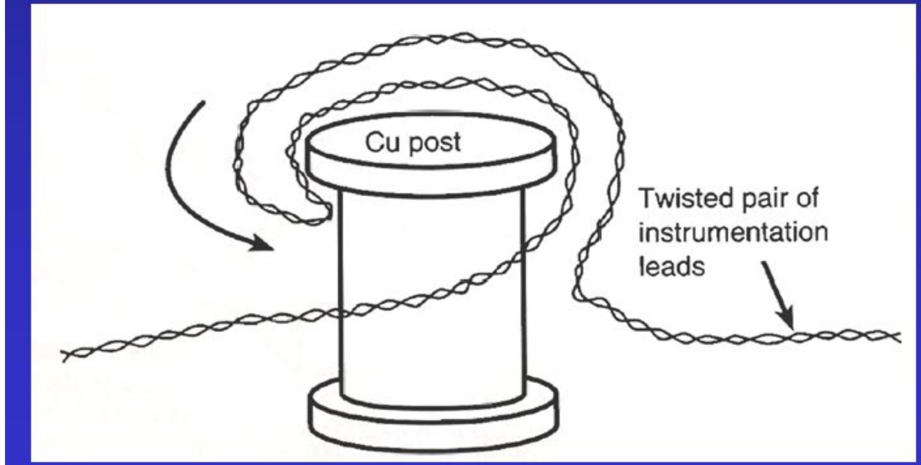
$$\dot{Q}(T) = \dot{Q}(445\,\mathrm{N}, 4\,\mathrm{K}) \left(\frac{F}{445N}\right) \left(\frac{T}{4.2\mathrm{K}}\right)^{\gamma}$$

To grease or not to grease?

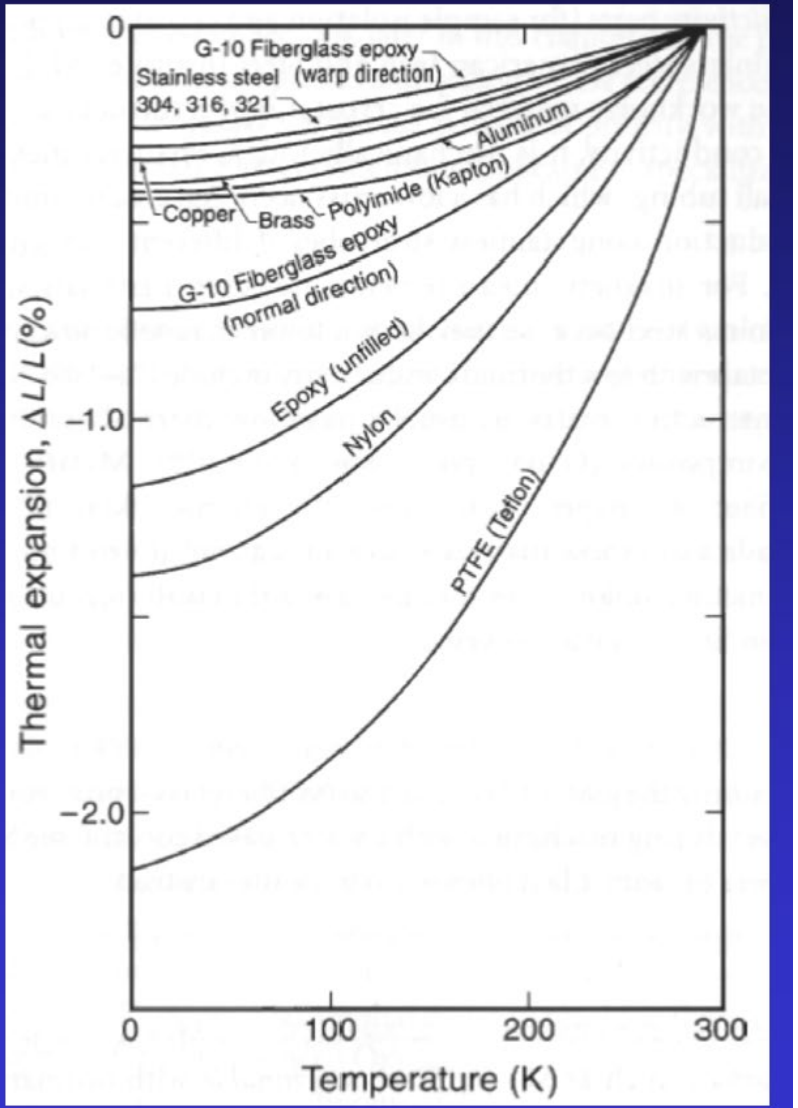
Large area and low pressure → grease (Apiezon N)

# Thermal Anchoring of Wires and Cables

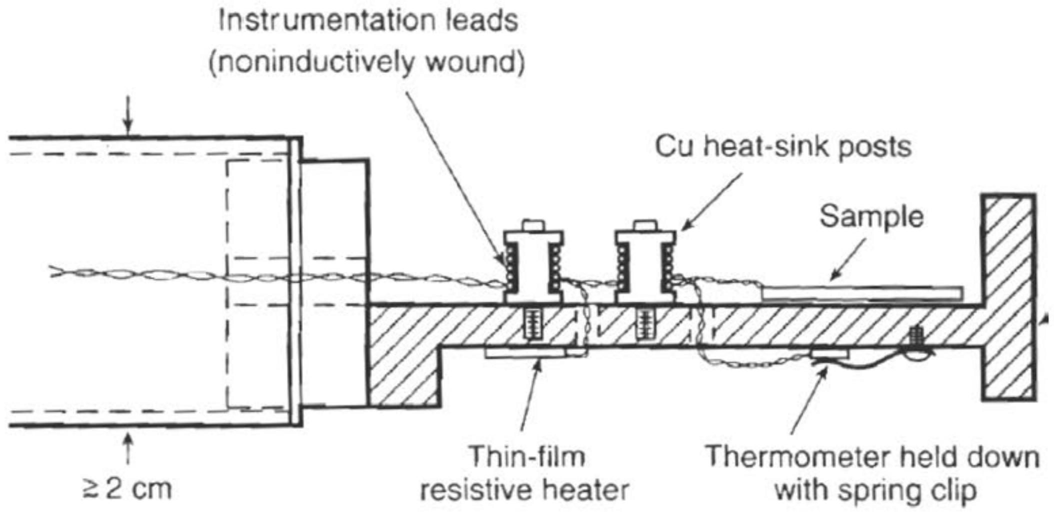


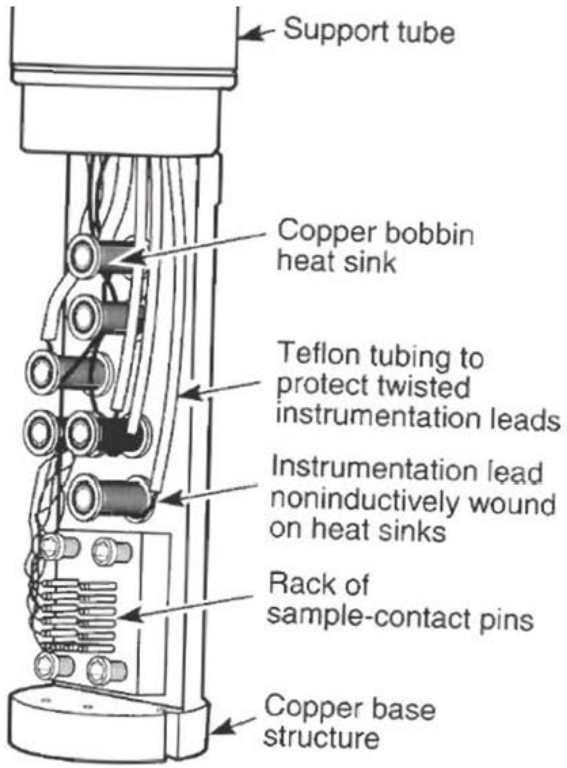



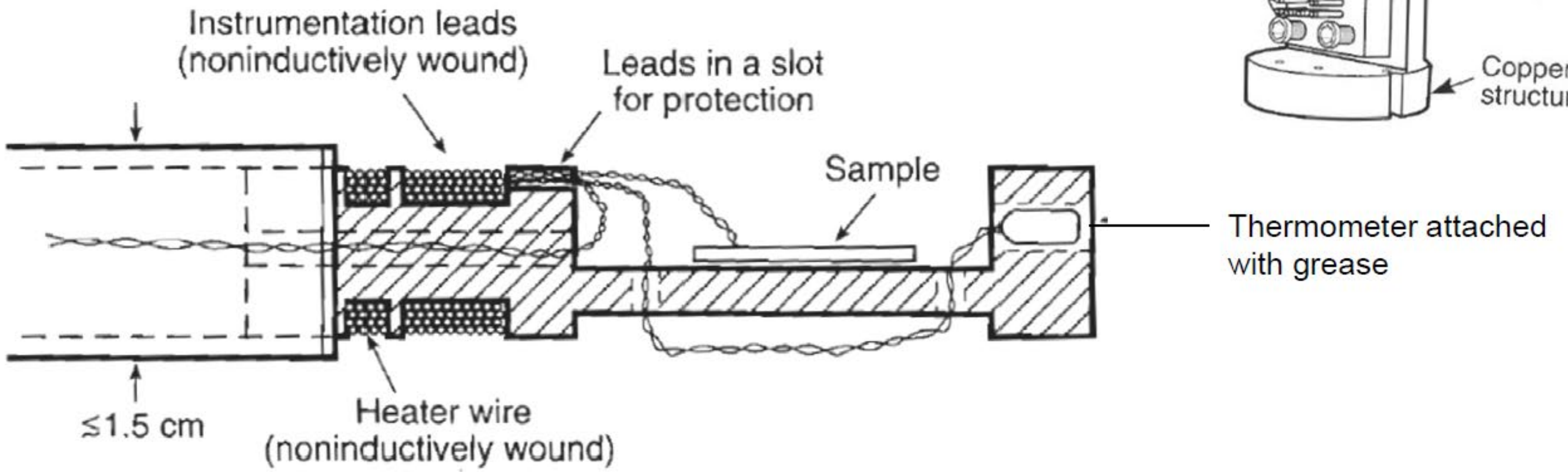

Non-inductactive wire anchoring



# Thermal Anchoring of Wires and Cables

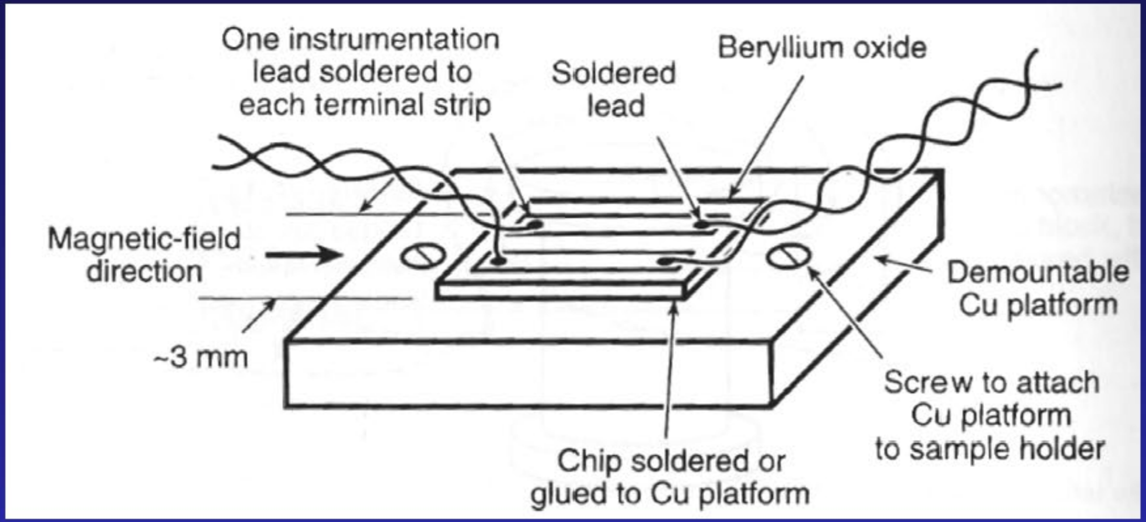


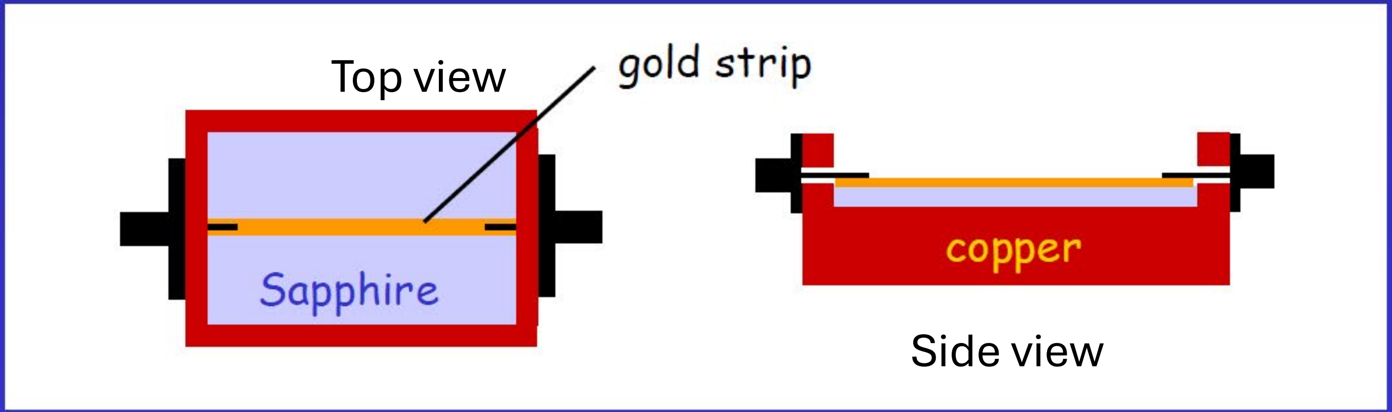



# Thermal Anchoring of Wires and Cables

Heat sink of wires

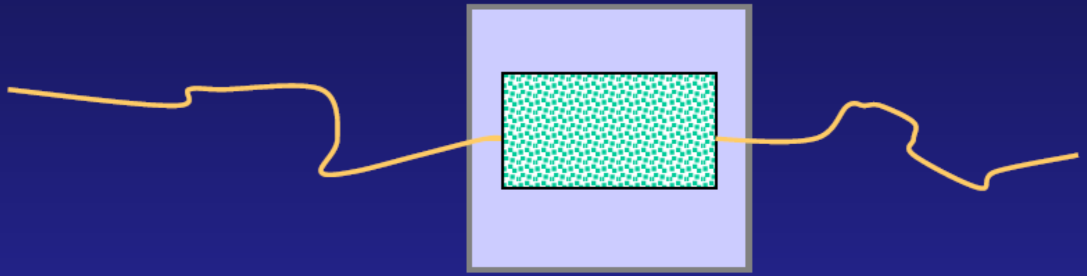



Heat sinking coaxial cables for high frequencies: Mircostripline

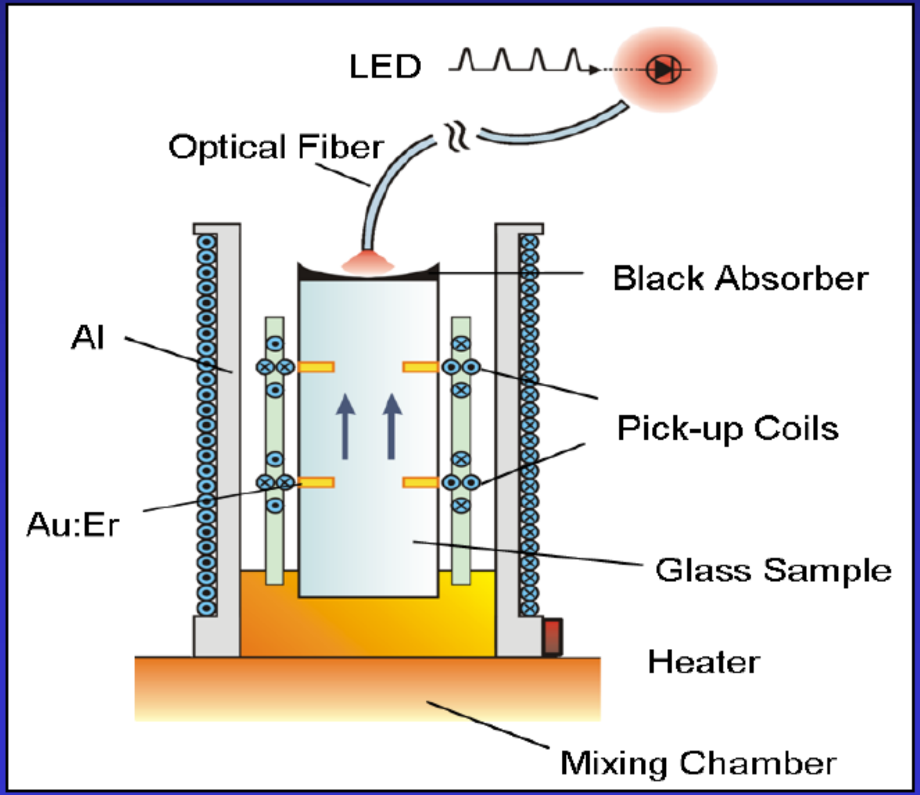


# Ultra low temperature (T < 10 mK)

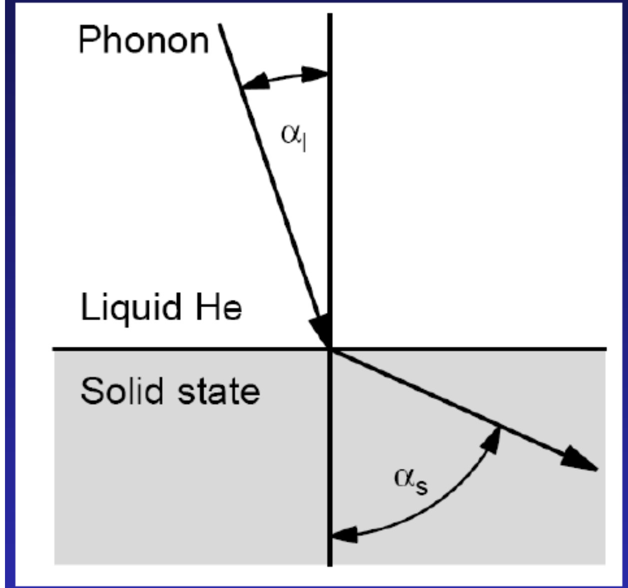
Heat sink of wires by using silver sinter and $^3He$ cells



Go to non contact measurements if possible



# Thermal Boundary or Kapitza-Resistance




Kaptiza-Resistance occurs at any solid-solid, liquid-solid interface

Partciular problematic for liquid helium because of the low sound velocity

Snell's law of refraction

$$\frac{\sin \alpha_\ell}{\sin \alpha_s} = \frac{v_\ell}{v_s}$$

critical angle of total reflection

$$\alpha_\ell^c = \arcsin\left(\frac{v_\ell}{v_s}\right)$$

for lq. helium and copper $\alpha_\ell^c = 4°$

fraction of phonons incident within critical angle

$$f = \frac{1}{2}\sin^2 \alpha_\ell^c = \frac{1}{2}\left(\frac{v_\ell}{v_s}\right)^2 < 10^{-2}$$

# Theory on the Kapitza resistance

Transmission coefficient

$$t = \frac{4Z_\ell Z_\mathrm{s}}{(Z_\ell + Z_\mathrm{s})^2} \simeq \frac{4Z_\ell}{Z_\mathrm{s}} = \frac{4\varrho_\ell v_\ell}{\varrho_\mathrm{s} v_\mathrm{s}}$$

Acoustic impedances

$$Z_\ell = \varrho_\ell v_\ell$$

$$Z_\mathrm{s} = \varrho_\mathrm{s} v_\mathrm{s}$$

fraction of phonons crossing the interface

$$ft = \frac{2\varrho_\ell v_\ell^3}{\varrho_\mathrm{s} v_\mathrm{s}^3}$$

helium-copper

$ft < 10^{-5}$

Heat transfer (using Debye model)

$$\dot{Q} = \frac{\mathrm{d}\dot{Q}}{\mathrm{d}T}\Delta T = \frac{2\pi^2 k_\mathrm{B}^4 \varrho_\ell v_\ell}{15\hbar^3 \varrho_\mathrm{s} v_\mathrm{s}^3} A T^3 \Delta T$$

$$\dot{Q} = \frac{1}{2} f t u v_\ell A = \frac{\pi^2 k_\mathrm{B}^4 \varrho_\ell v_\ell}{30\hbar^3 \varrho_\mathrm{s} v_\mathrm{s}^3} A T^4$$

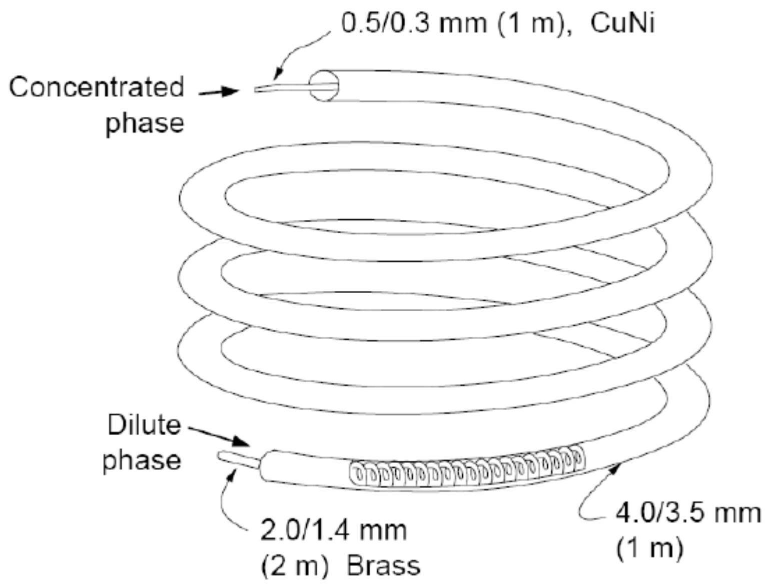
Kapitza Resistance

$$R_\mathrm{K} = \frac{A\Delta T}{\dot{Q}} = \frac{15\hbar^3 \varrho_\mathrm{s} v_\mathrm{s}^3}{2\pi^2 {k_\mathrm{B}}^4 \varrho_\ell v_\ell} \frac{1}{T^3}$$

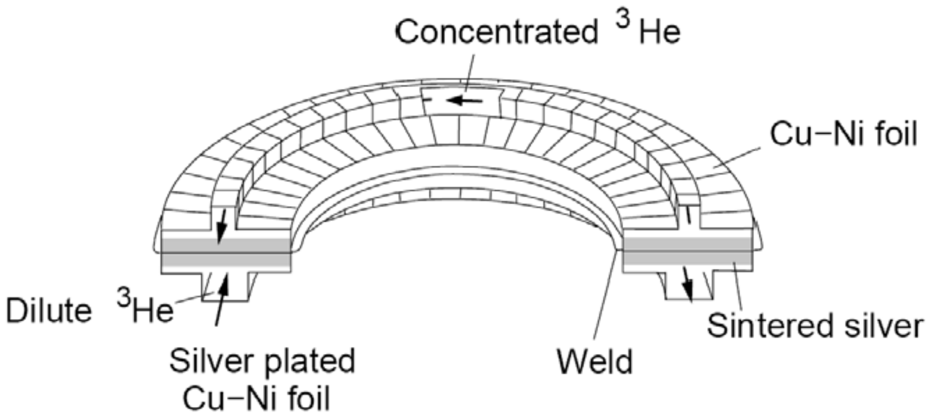
# Solutions

Used for dilution refrigerators

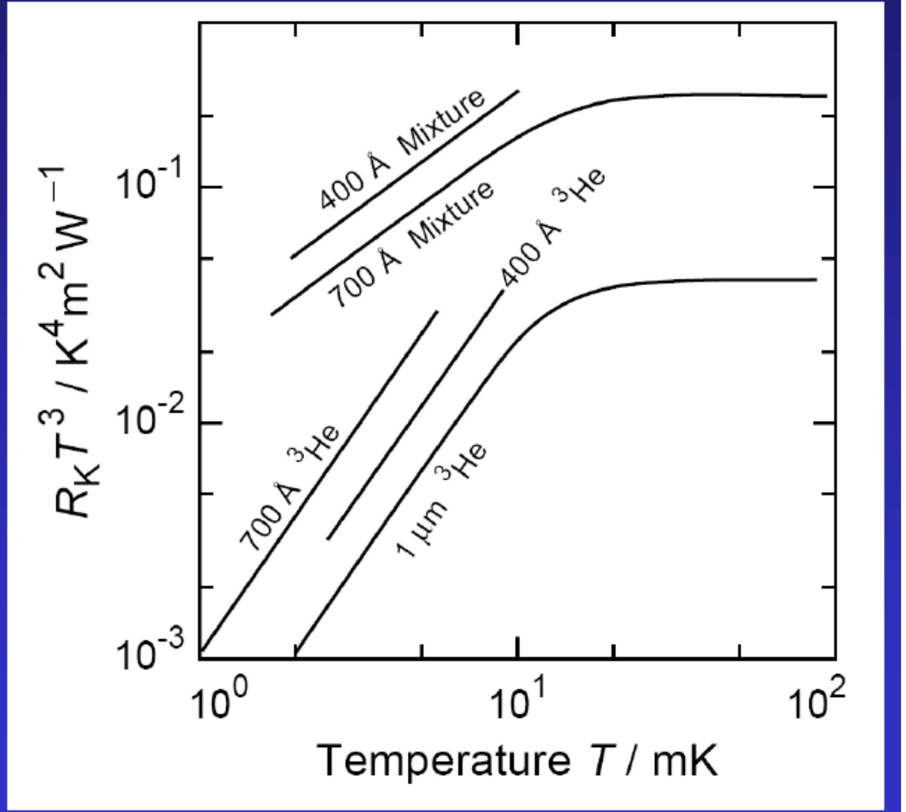
continuous heat exchanger




step heat exchanger




Data for Kapitza Resistance



# Homework

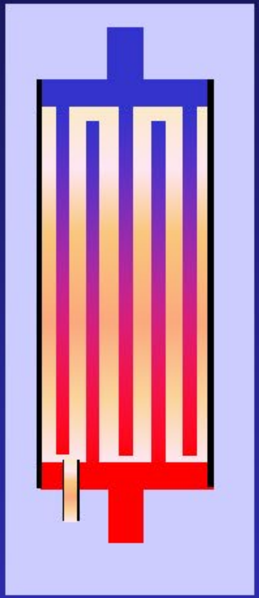
#1: Estimate the heat load due to thermal radiation from the top assembly

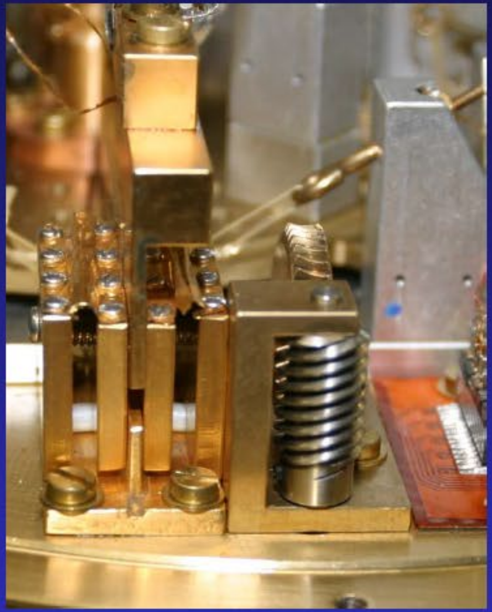
#2: Watch this video: John Allen's Movie about Superfluid Helium (https://www.youtube.com/watch?v=lEPc-rBMAuU&t=43s)

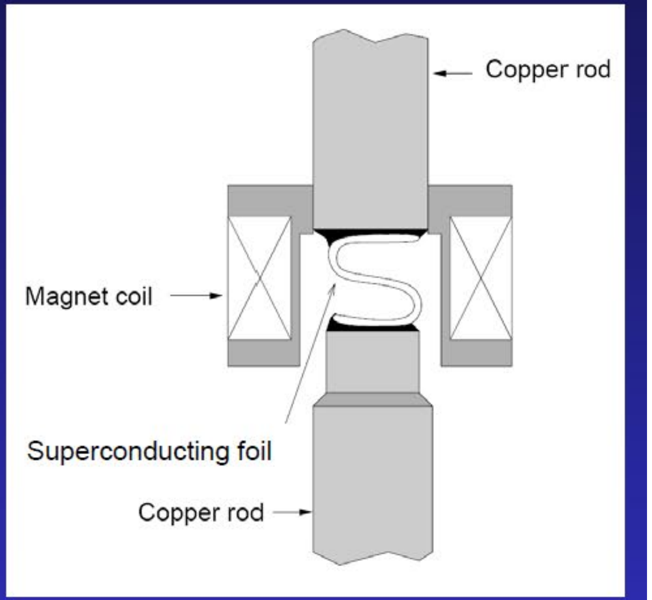
(42 mins) before Nov. 18

# Heat Switches

**Gas heat switches** | **Mechanical heat switch** | **Superconducting heat switch**








## Gas heat switches

exchange gas → pumping

$^4He$ superfluid layer
→ creep

$H_2$ ortho-para
conversion

$^3He$ no exothermic reation
no creep
high vapour pressure

## Mechanical heat switch

large force needed
typically 100 N

closed few mW/K
… 1 W/K @ 15K

heating on opening

## Superconducting heat switch

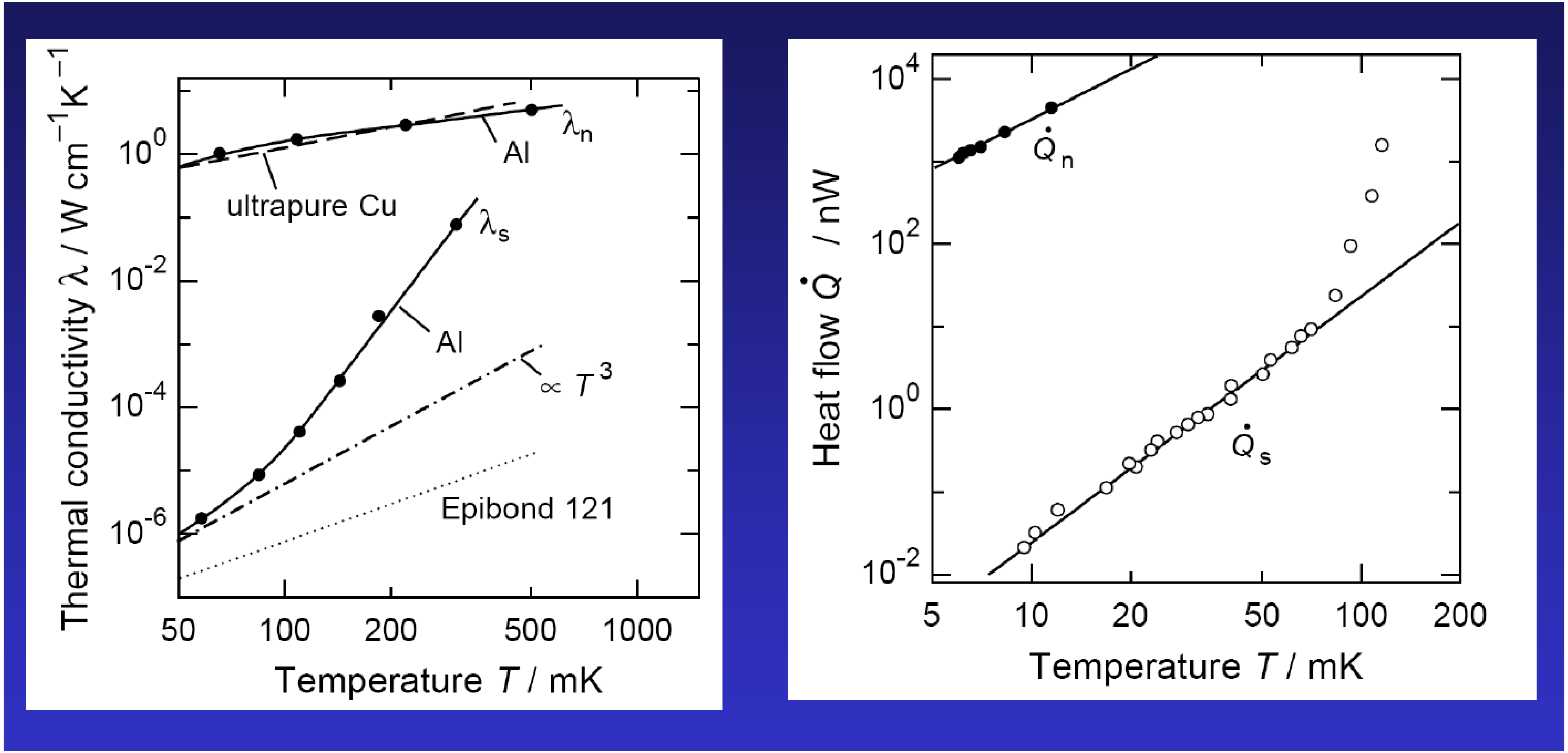
only well below $T_c$

open means low conductivity

eddy currents

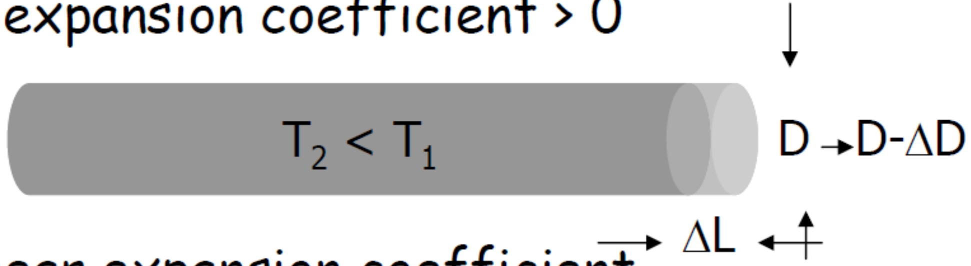
flux trapping

# Superconducting Heat Switch



# Thermal contraction

- All materials change dimension with temperature. The expansion coefficient is a measure of this effect. For most materials, the expansion coefficient > 0

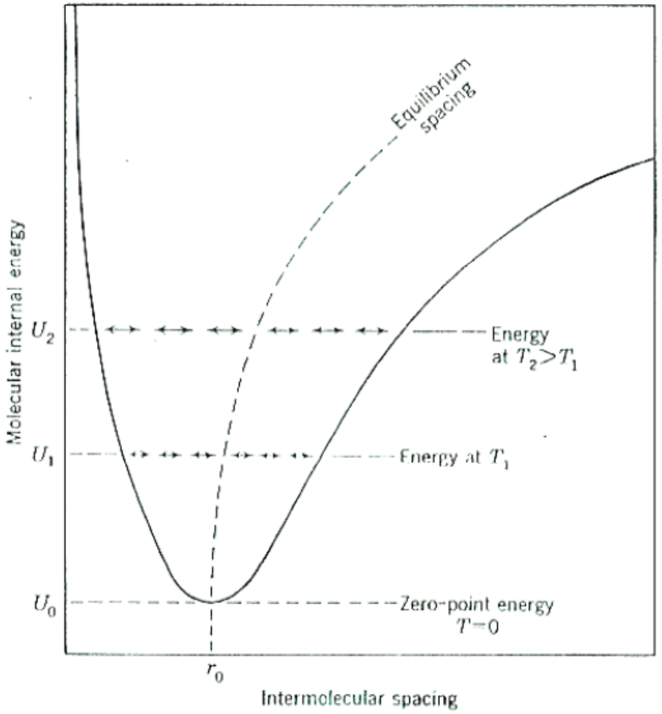



Linear expansion coefficient

$$\alpha = \frac{1}{L}\frac{\partial L}{\partial T}\bigg)_p = \frac{1}{3}\beta$$ For isotropic materials

Bulk expansivity (volume change):

$$\beta = \frac{1}{v}\frac{\partial v}{\partial T}\bigg)_p = -\frac{1}{\rho}\frac{\partial \rho}{\partial T}\bigg)_p$$




Expansivity caused by anharmonic terms in the lattice potential

# Temperature dependence of alpha and beta

- Most materials contract when cooled
  - The magnitude of the effect depends on materials:
  - Plastics > metals > glasses

- Coefficient (α) decreases with temperature
  - Thermodynamics:

$$C_p - C_v = \frac{Tv\beta^2}{\kappa} \underset{T\to 0}{\to} 0$$

$$\left.\frac{\partial v}{\partial T}\right)_p = -\left.\frac{\partial s}{\partial p}\right)_T \underset{T\to 0}{\to} 0$$

(Third law: s $\to$ 0)

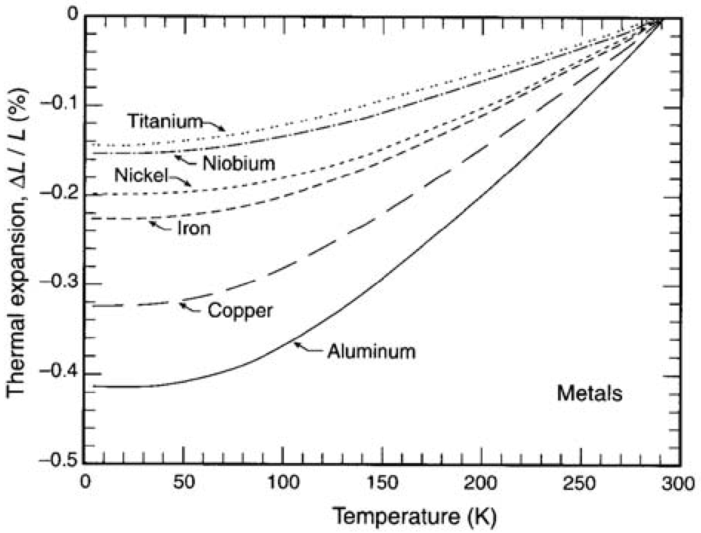



Fig. 6.6 Thermal linear expansion $\Delta L/L \equiv (L_T - L_{293})/L_{293}$ of common metals. (Compiled by Clark 1983 from data by Corruccini and Gniewek 1961, and Hahn 1970.) Tabulated values for these and other materials are given in Appendix A6.4.

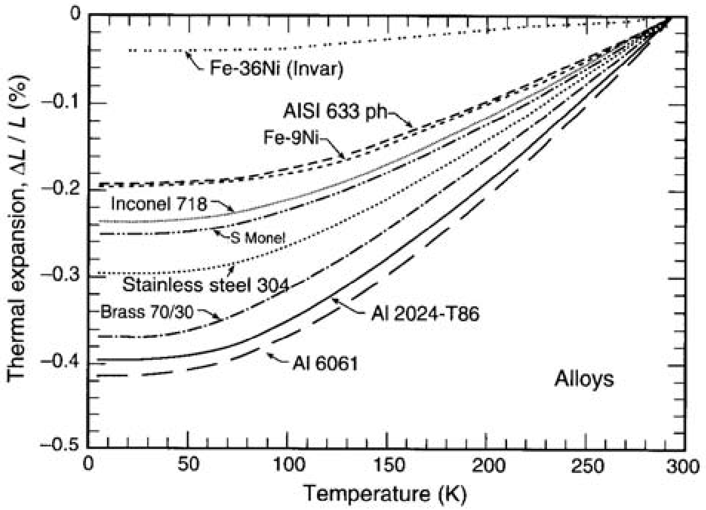



Fig. 6.7 Thermal linear expansion $\Delta L/L \equiv (L_T - L_{293})/L_{293}$ of common alloys. (Compiled by Clark 1983 from data by Clark 1968 and Arp et al. 1962.) Tabulated values for these and other materials are given in Appendix A6.4.

# Expansion coefficient for materials

**Table 2.5. Linear Thermal Contractions Relative to 293 K[a]**

| Substance T(K): | 0 | 20 | 40 | 60 | 80 | 100 | 150 | 200 | 250 |
|---|---|---|---|---|---|---|---|---|---|
| Aluminum | 41.4 | 41.4 | 41.2 | 40.5 | 39.0 | 36.9 | 29.4 | 20.1 | 9.6 |
| Copper | 32.6 | 32.6 | 32.3 | 31.6 | 30.2 | 28.3 | 22.1 | 14.9 | 7.1 |
| Germanium | 9.3 | 9.3 | 9.3 | 9.4 | 9.3 | 8.9 | 7.3 | 5.0 | 2.4 |
| Iron | 20.4 | 20.4 | 20.3 | 19.9 | 19.5 | 18.4 | 14.9 | 10.2 | 4.9 |
| Lead | 70.8 | 70.0 | 66.7 | 62.4 | 57.7 | 52.8 | 39.9 | 26.3 | 12.4 |
| Nickel | 23.1 | 23.0 | 22.9 | 22.6 | 21.8 | 20.8 | 16.5 | 11.4 | 5.4 |
| Silicon | 2.16 | 2.16 | 2.17 | 2.23 | 2.32 | 2.40 | 2.38 | 1.90 | 1.01 |
| Silver | 41.0 | 41.0 | 40.3 | 38.7 | 36.5 | 33.7 | 25.9 | 17.2 | 8.2 |
| Titanium | 15.1 | 15.1 | 15.0 | 14.8 | 14.2 | 13.4 | 10.7 | 7.3 | 3.5 |
| Tungsten | 8.6 | 8.6 | 8.5 | 8.4 | 8.1 | 7.6 | 5.9 | 4.0 | 1.9 |
| Brass (65% Cu, 35% Zn) | 38.4 | 38.3 | 38.0 | 36.8 | 35.0 | 32.6 | 25.3 | 16.9 | 8.0 |
| Cu + 2 Be | 32.4 | 32.4 | 31.9 | 31.6 | 30.0 | 28.3 | 22.0 | 16.0 | 7.0 |
| Constantan | — | — | 26.4 | 25.8 | 24.7 | 23.2 | 18.3 | 12.4 | 5.85 |
| Invar[b] | 4.5 | 4.6 | 4.8 | 4.9 | 4.8 | 4.5 | 3.0 | 2.0 | 1.0 |
| 304, 316 Stainless steel | — | 29.7 | 29.6 | 29.0 | 27.8 | 26.0 | 20.3 | 13.8 | 6.6 |
| Pyrex | 5.6 | 5.6 | 5.7 | 5.6 | 5.4 | 5.0 | 3.95 | 2.7 | 0.8 |
| Silica (1000° C)[c] | −0.1 | −0.05 | 0.05 | 0.2 | 0.3 | 0.4 | 0.5 | 0.4 | 0.2 |
| Silica (1400° C)[c] | −0.7 | −0.65 | −0.5 | −0.3 | −0.2 | −0.05 | 0.2 | 0.2 | 0.1 |
| Araldite | 106 | 105 | 102 | 98 | 94 | 88 | 71 | 50 | 25 |
| Nylon | 139 | 138 | 135 | 131 | 125 | 117 | 95 | 67 | 34 |
| Polystyrene | 155 | 152 | 147 | 139 | 131 | 121 | 93 | 63 | 30 |
| Teflon | 214 | 211 | 206 | 200 | 193 | 185 | 160 | 124 | 75 |

[a] Units are $10^4 \times (L_{293} - L_T)/L_{293}$. Sources of data include *Thermophysical Properties of Matter* (1977), Corruccini and Gniewek (1961), and *American Institute of Physics Handbook* (1972). Compiled by White.[2]

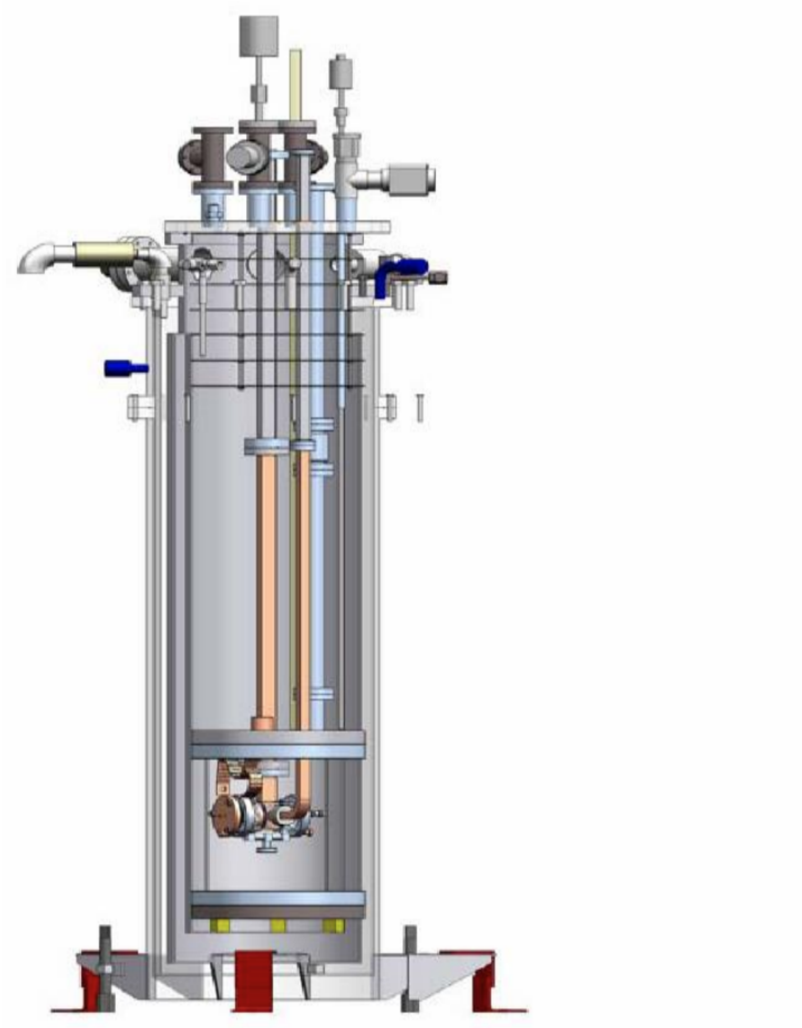
[b] The expansion of Invar NiFe alloys containing ~36% Ni is very sensitive to composition and heat treatment.

[c] These silicas were aged at 1000° C and 1400° C.

# Structural support

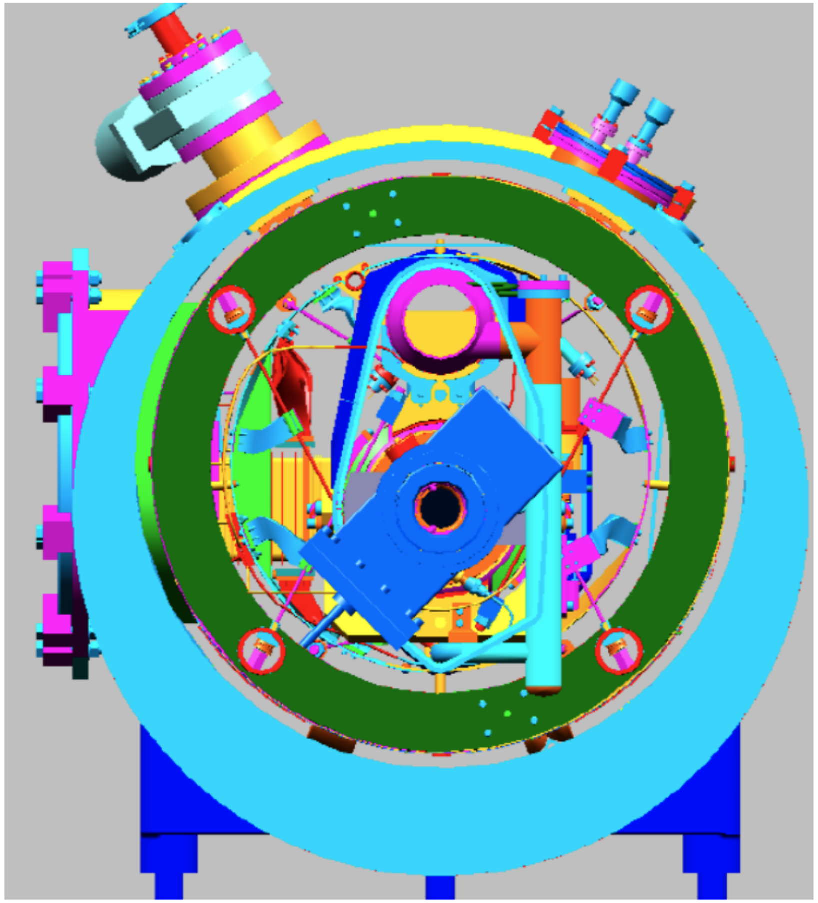
- Solution is highly dependent on cryostat requirements
- Choose materials carefully
  - Acceptable for cryogenic temperatures
  - Low heat leak
- Don’t over constrain supports: allow for thermal contraction
- Does solution meet alignment and vibration requirements?
- Must alignment be changed while cold?

# Structural support: Simple top load cryostat



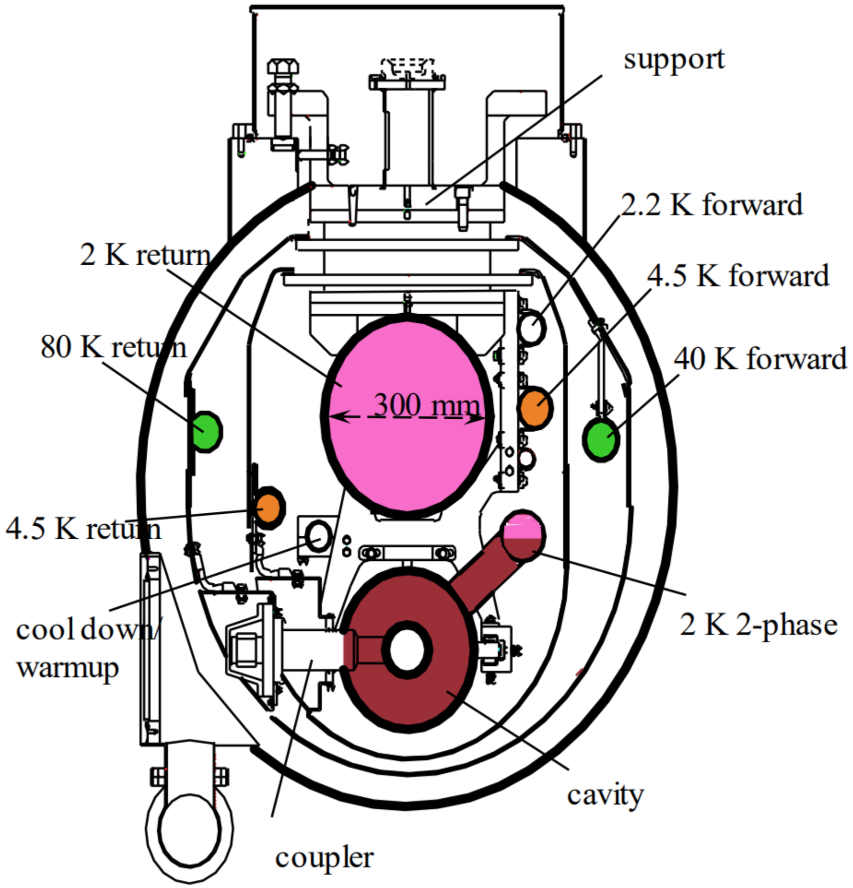
- Very common for test  cryostats
- Everything hangs from 300 K top flange
- Connections made via low conductivity piping and supports
- Everything “contracts up”
- Allows easy removal and change of cryostat components
- Useful when precise alignment not an issue

# Structural Support
# Example #2 JLab 12 GeV Upgrade Cryomodul



- All components are tied to space frame which rolls into vacuum vessel
- Connections to 300 K done via flex lines and bellows
- Same approach taken in ESS elliptical cavity cryomodules

# Structural Support Example #3 ILC Cryostat




- FRP support between 300 K and Cryo temps
- Cavity assemblies tied to 300 mm pipe backbone
- All other connections to 300 K have flex line or bellows in line
- Meets alignment specs

# Tips on designing a cryo system

1. Define and prioritize requirements first.
2. Design in safety features from the start of the project
3. Only use materials shown to be appropriate for cryogenic temperatures.
4. Review literature & learn from previous efforts. Take advantage of existing codes and standards if possible.
5. Use tested commercial solutions whenever possible.
6. Intercept heat at higher intermediate temperatures (remember the $2^{nd}$ law of thermodynamics)
7. Allow for the effect of thermal contraction on cryostat alignment and design. Do not over constrain the movement of cryostat components as they cool.
8. Avoid feed throughs & demountable seals at cryogenic temperatures.

# More tips on designing a cryo system

8. Be sure to properly heat sink temperature sensor wires to ensure reduced heat leak and an accurate reading.
9. Install sensors such a pressure transducers and flow meters at room temperature when possible.
10. Analyze the design for possible thermoacoustic oscillations
11. Conduct design reviews. These should include experts not directly involved in the design under review. Ideally, there should be at least reviews at the preliminary or conceptual level and again once the detailed design is complete.
12. Conduct prototype tests when required. Leave enough time in the design process to benefit from the results of such tests.
13. In cases where a large number of cryostats are to be produced, carry out series testing of the production cryostats in addition to any prototype testing. Allow sufficient resources (time, facilities, funding) in the project plan to accomplish these tests.