PHY524 Cryogenics-1

Cryogenic system; thermal insulation; thermal conduction

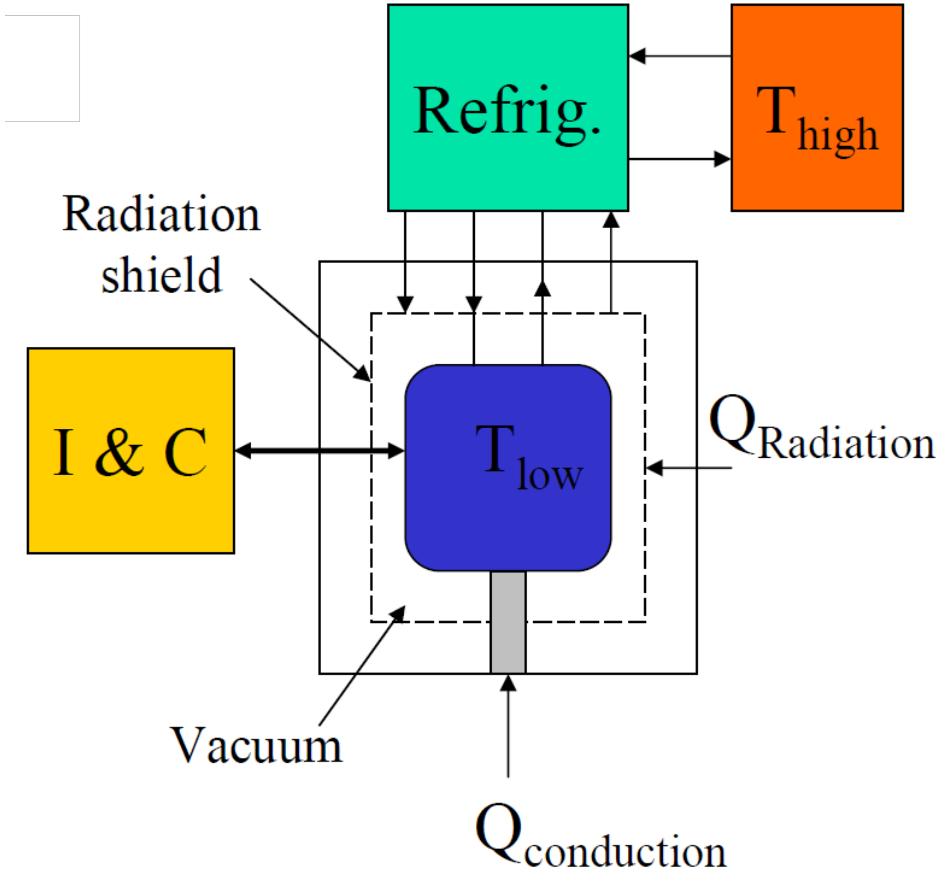
11/6/2025

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

A cryogenic system has the following components:

- Low temperature environment
- Source of refrigeration
- Heat exchange medium
- Thermal insulation
- Structural support
- Instrumentation and Control

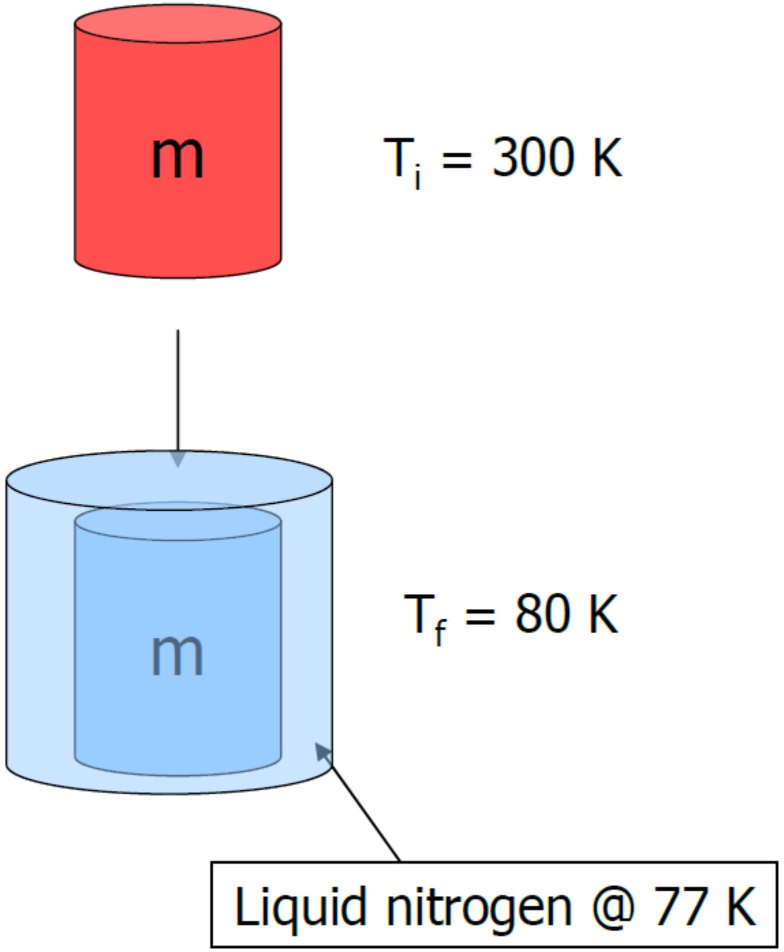


All these components need to operate in convert, reliably and safely

Purpose of a cryogenic system: to cool things!

Cryogenics involves cooling things to low temperature. Therefore one needs to understand the process.

Ex: use liquid nitrogen to cool blocks of metal, plastic, etc...



- If the mass and type of the object and its material are known, then the heat content at the designated temperatures can be calculated by integrating 1st Law.

$$dQ = Tds = dE + \cancel{pdv} \quad \sim 0$$

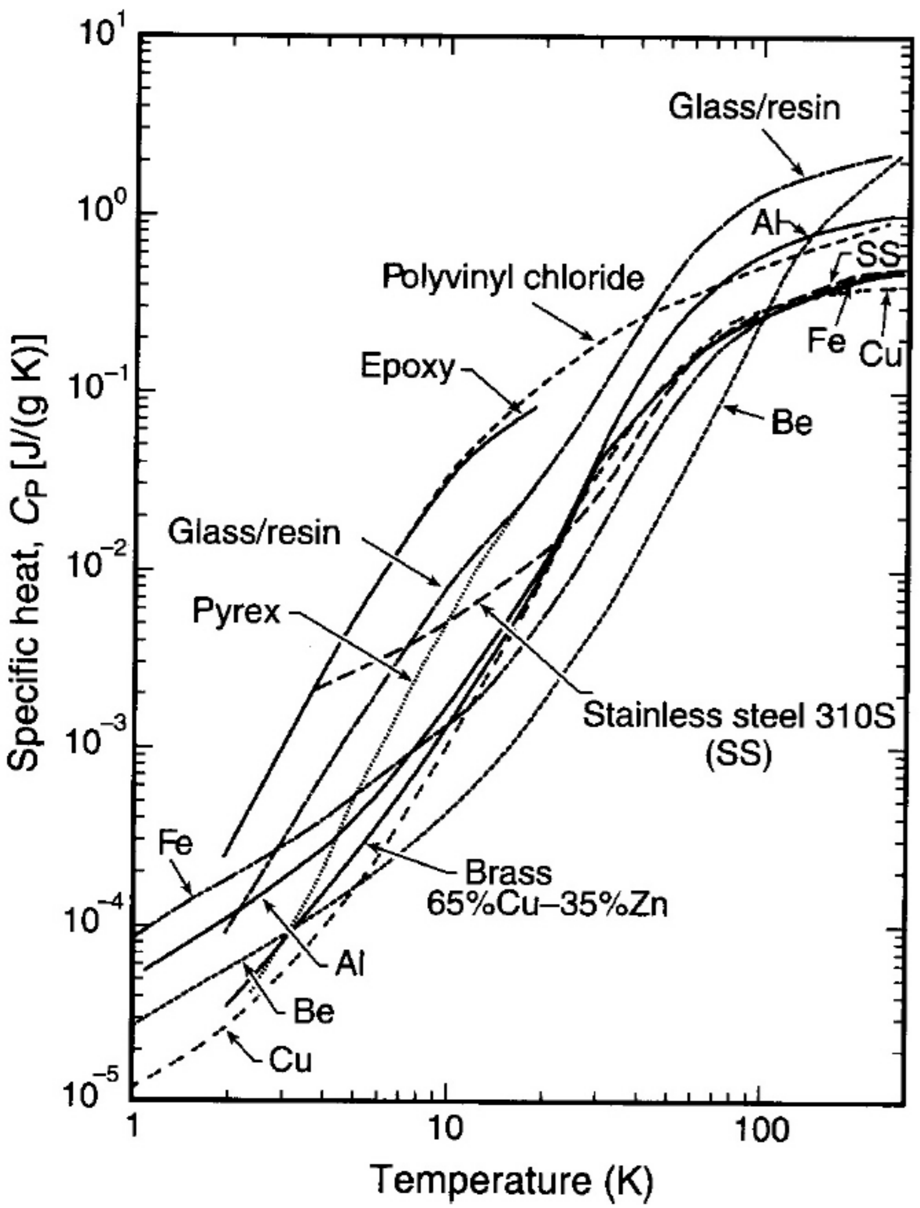
- The heat removed from the component is equal to its change of internal energy,

$$\Delta E = m\left(\int_{T_f}^{T_i} C\,dT\right)$$

Specific Heat of Material

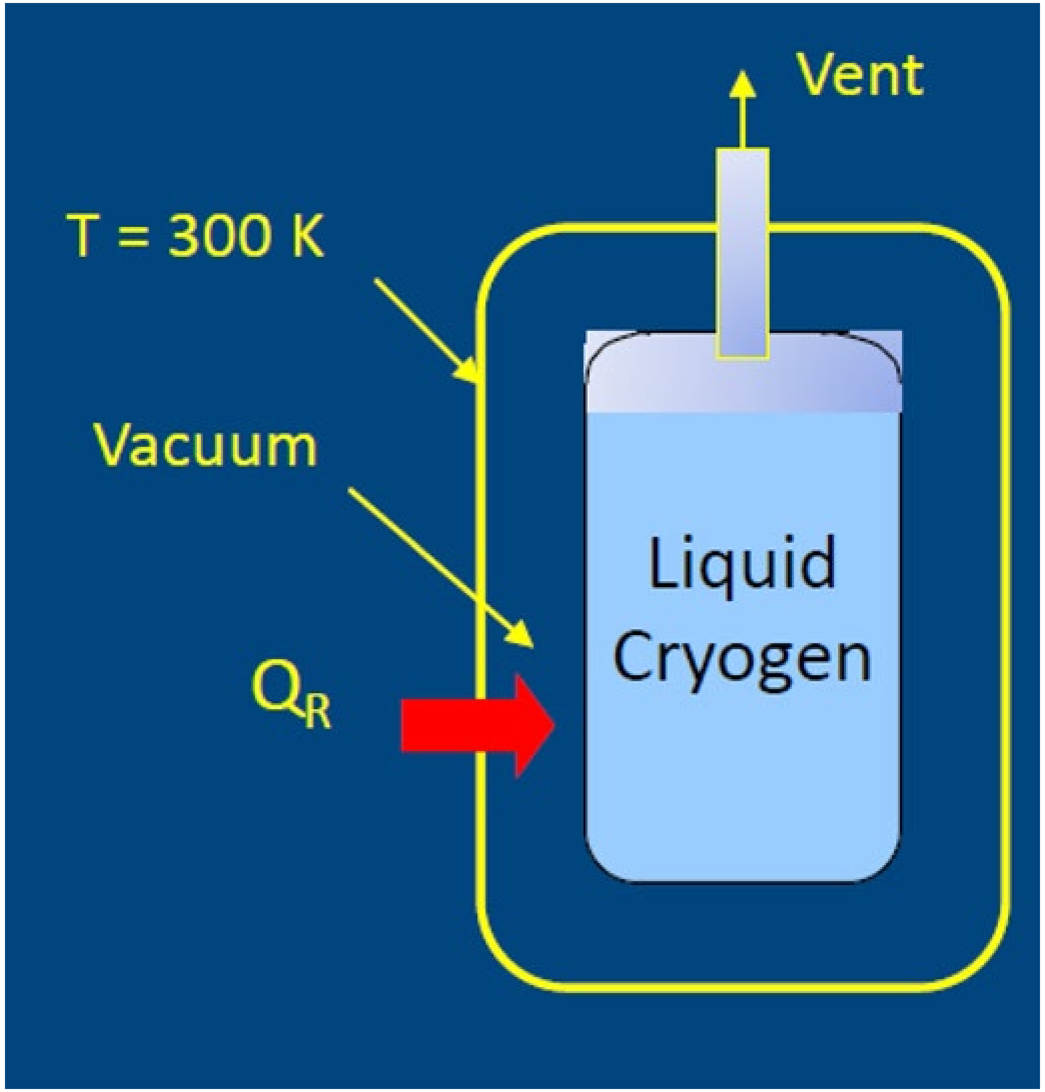
General characteristics:

- Specific heat decreases by ~ 10x between 300 K and LN_2 temperature (77 K)
- Decreases by factor of ~ 1000x between RT and 4 K
- Temperature dependence
  - C ~ constant near RT
  - $C \sim T^n$, n ~ 3 for T < 100 K
  - C ~ T for metals at T < 1 K



Insulation for the low-temperature environment

EX: A liquid cryogen storage tank



- High performance insulation system all involve some level of vacuum.
  - How low vacuum is needed?
- Even for perfect vacuum, thermal radiation can still contribute significantly to total heat leak.
  - Q ~ T^4 so process is dominated by high temperature surfaces (usually 300 K)
- Materials used for insulation:
  - To reduce radiant heat, one can put materials between two surfaces at different temperatures
  - However, adding materials affects conduction heat transfer
  - Insulating material may significantly contribute to total cost of system

Cryogen Safety: volume change for cryogenic fluids

Recall Volume Changes for Cryogenic Fluids
from Normal Boiling Point to 300 K & 1 Bar

EUROPEAN SPALLATION SOURCE

Fluid	(Volume of gas at 1 Bar, 300 K) / (Volume of liquid at normal boiling point)
Propane	323
Ethane	446
Xenon	556
Krypton	711
Methane	660
Argon	861
Oxygen	879
Nitrogen	720
Neon	1488
Hydrogen (Para)	875
Helium	783

Dewar Explosion

State Fire Marshal's Alert

February 22, 2006

University Campus Liquid Nitrogen Cylinder Explosion

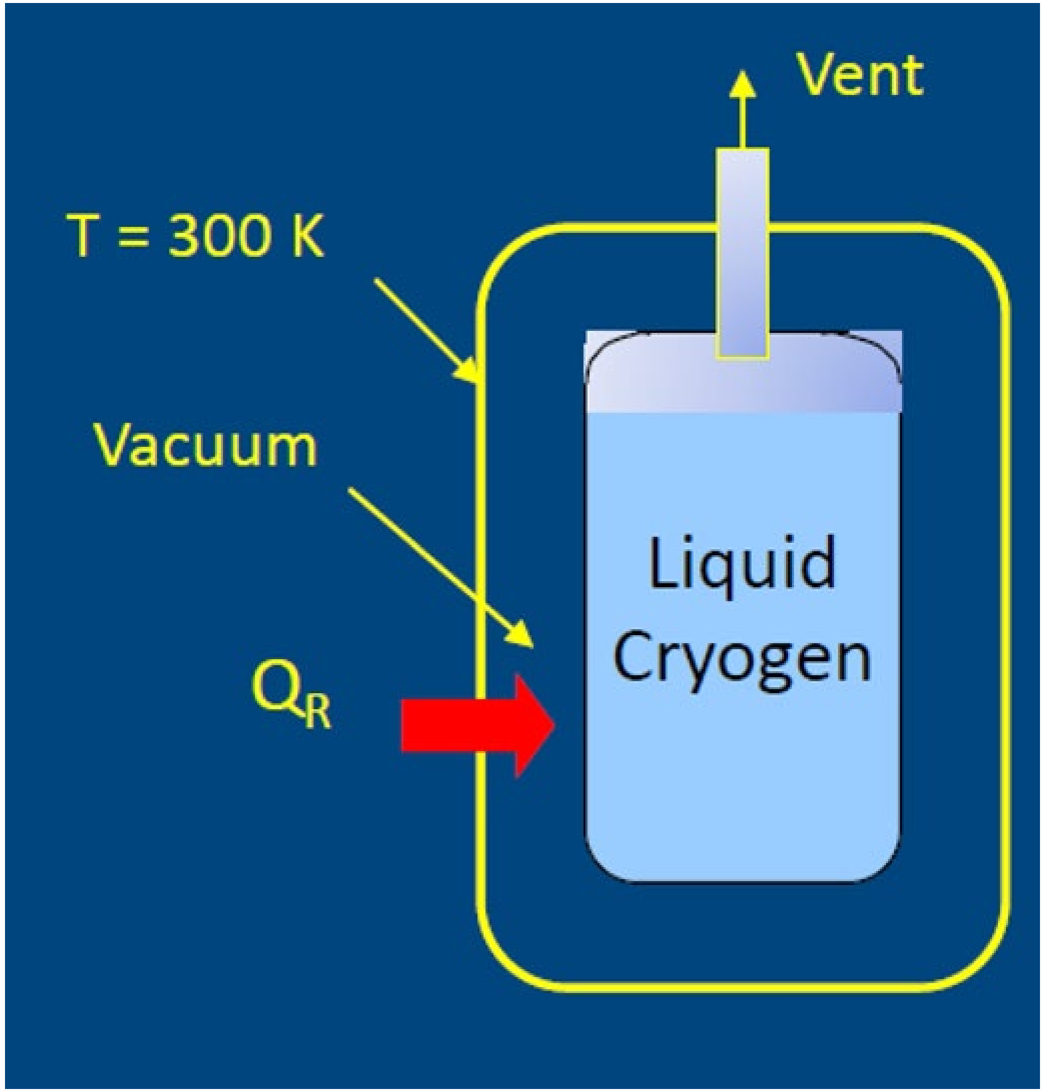
Figure 1 -Effect of Explosion on Dewar Cylinder Compared to unaffected cylinder

Incident Specifics

Figure 2 - Hallway Outside Laboratory Showing Explosion Damage

Figure 3 - Inside the Laboratory after Explosion

Thermal Isolation: Vacuum



- Vacuum Vessel: The outermost cryostat component that interfaces with the surrounding systems
- Insulating vacuum is generally in the 10^{-4} to 10^{-6} torr range; the lower the better.
- The design for internal and external pressure are addressed by the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2 and specific workplace codes

Vacuum Vessel

Needs to:

1. Contains the insulating vacuum to withstand the inward force from atmospheric pressure.
   Failure → implosion
2. Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.
   Failure → explosion

	Carbon steel	Stainless steel	Aluminum
Pros	Inexpensive Readily available Weldable	Mostly non-magnetic Weldable Good fracture toughness	Inexpensive Readily available Non-magnetic Weldable Good fracture toughness Light weight
Cons	Magnetic Low fracture toughness Rust preventative required	Expensive	Difficult to implement metal seals Difficult to use threated holes
Alloys	SA 516	304, 304L	6061, 5083

Thermal Insulation: Solid Foam

- Solid foam insulations not used very often in cryogenics because they have relatively poor performance.
- Since these materials are gas filled, their thermal conductivity is typically > k_{gas} ~ 20 mW/m*K.

Example: Consider a Polystyrene LN_2 vessel with 20 mm wall and 1 m^2 surface area.

$$Q = k \cdot A \cdot \frac{\Delta T}{L} = 33 \cdot 1 \cdot \frac{(300-77)}{0.02} = 368\ W$$

$$h_{fg}(LN_2) = 200\ {}^{kJ}/_{kg} \qquad \rho(LN_2) = 800\ {}^{kg}/_{m^3}$$

$$\frac{dm}{dt} = \frac{Q}{h_{fg}} = 1.84\ {}^{gr}/_{s} = 8.3\ l/hr$$

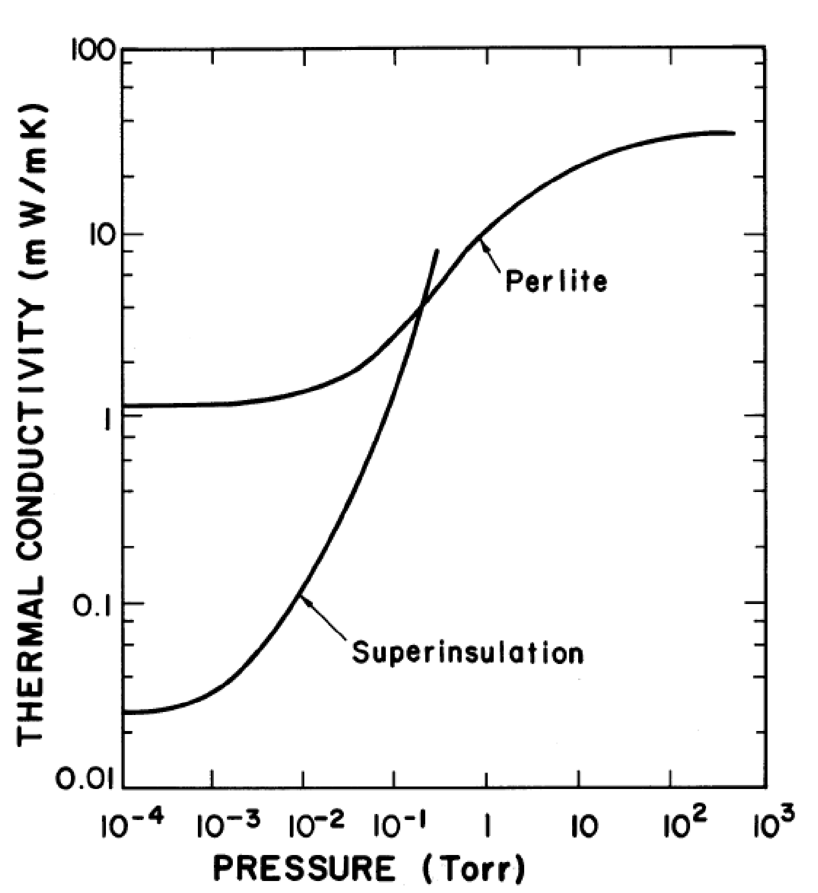
Table 7.12. Apparent thermal conductivity of foam insulations for boundary temperatures of 300 K (80°F) and 77 K (−139°F)

	Density		Thermal Conductivity	
Foam	kg/m³	lb_m/ft^3	mW/m-K	Btu/hr-ft-°F
Polyurethane	11	0.70	33	0.019
Polystyrene	39	2.4	33	0.019
	46	2.9	26	0.015
Rubber	80	5.0	36	0.021
Silica	160	10.0	55	0.032
Glass	140	8.7	35	0.020

Thermal Insulation: Powder

Powder Insulations

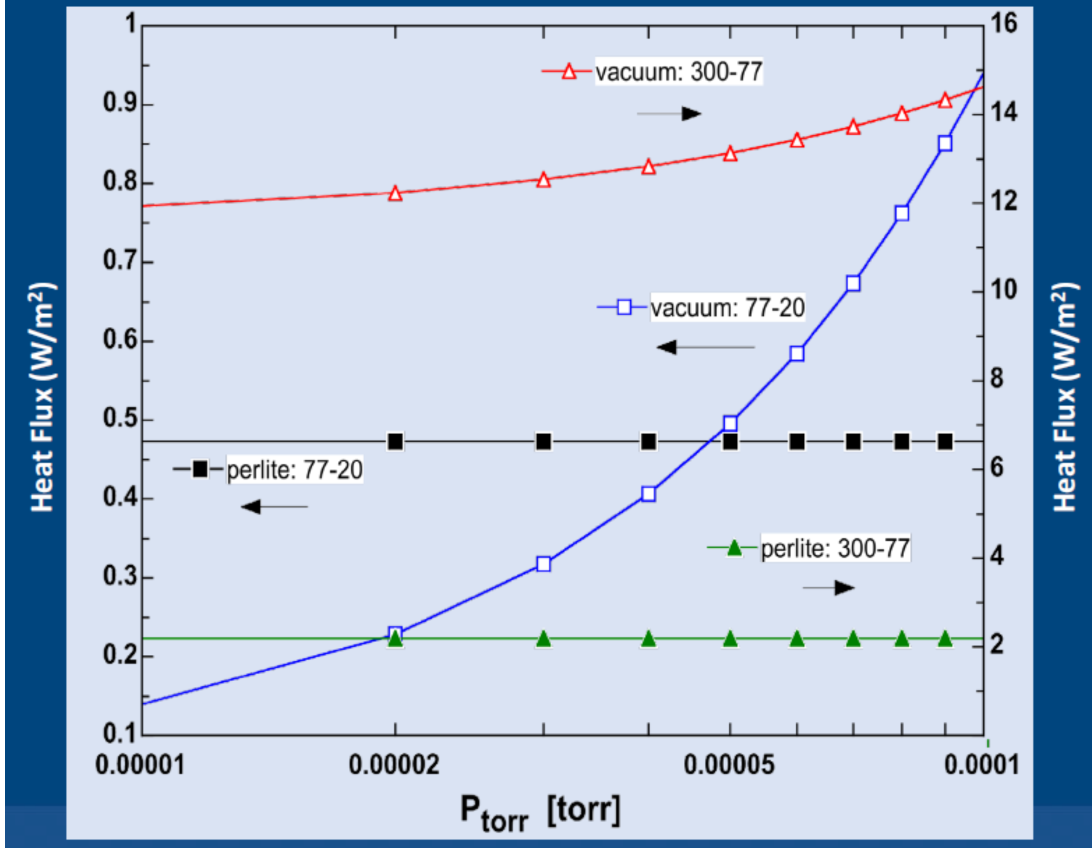
- Powder insulations were developed for ease of installation in less stringent operating conditions.
- Perlite is a natural product that is cheap and easily installed.
- Glass micro-spheres 100 to 1000 μm in diameter are also good candidates for this application.
- Vacuum requirements for these materials are less critical. Good performance at p ~ 0.1 Torr compared to 10^{-4} Torr for Super Insulation (discussed next).
- Powder insulations is mostly used for less stringent cryogenic vessels such as LN_2 or LNG containers.



Mean value between 77 K and 300 K

Which is the better insulation?

Note: Left ordinate is for 77 to 20 K; right is for 300 to 77 K



Below T = 77 K and P = 5×10^{-5} Torr, vacuum provides superior insulation to perlite

Radiation Shields - Superinsulation

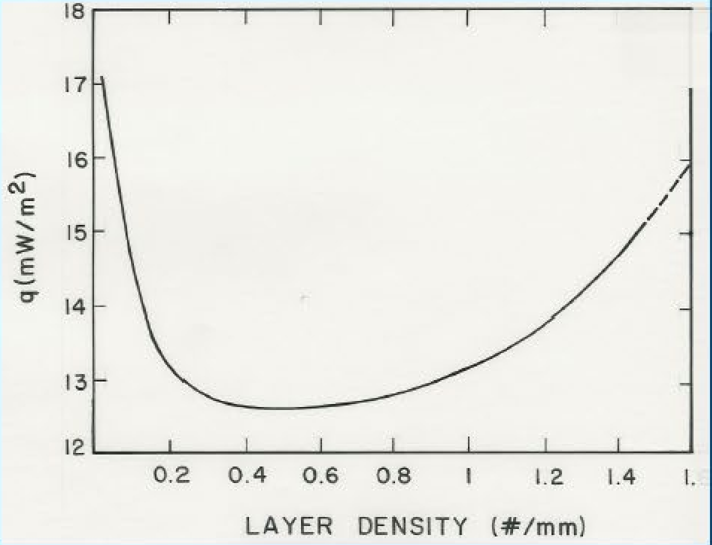
multiple radiation shields → smaller steps → reduction of heat flow

30 to 80 layers of low conductivity high reflection material → aluminized Mylar

apparent thermal conductivity
~ 10^{-4} to 10^{-5} W/(m K)

Multilayer Insulation (MLI)

- MLI (also referred to as super insulation) is a material developed to approximate a large number of thermally insulated shields.
- MLI consists of aluminum (5 to 10 nm thick) on mylar film with low density fibrous material between layers.
- To be effective MLI must operate in **vacuum**
- Heat transfer is by a combination of conduction and radiation.
- MLI must be carefully installed covering all surfaces with parallel layers, not wrapped since conduction along layer will produce a thermal short.
- Engineering applications must include factor of safety compared to ideal data.



Radiation heat load for different densities between 4.2 K and 77 K

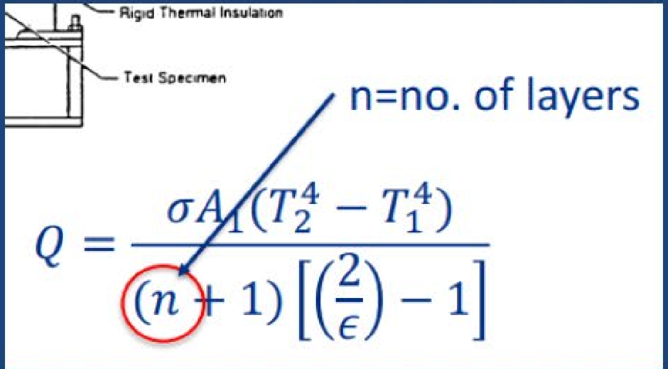
Recommended values:

q_r (77 K, 4 K) ~ 50 to 100 mW/m^2

q_r (300 K, 77 K) ~ 1 to 1.5 W/m^2

Superinsulation

- Multi-layer insulation (MLI)
  - Material: Alternate layers of aluminized mylar foil + polymer spacer
  - No. of layers: usually 30-60 layers on a thermal shield at ~80 K and 10-15 layers on a lower temperature shield or cold mass; layer density is usually 50-60/inch
  - Vacuum: 1e10-4 torr or lower.
  - Realistic heat load: ~1.5 W/m^2 at 80 K and ~0.15 W/m^2 at 4.5 K
- Floating radiation shields



$$Q = \frac{\sigma A_1 (T_2^4 - T_1^4)}{(n+1)\left[\left(\frac{2}{\epsilon}\right) - 1\right]}$$

MLI: calculations

Multi-layers

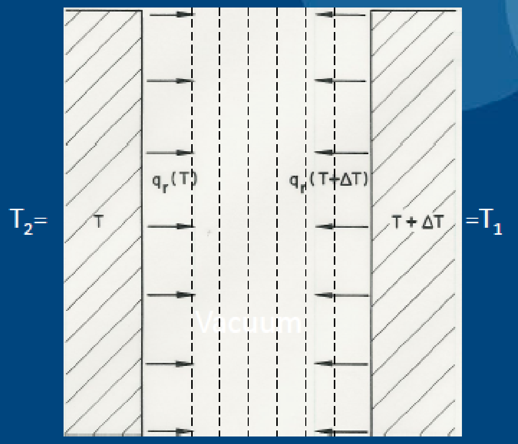
- Adding shielding between the radiant surfaces can significantly reduce the heat transfer. For n shields with emissivity ε, the heat exchange is: $q_r = \left(\frac{\varepsilon}{(n+1)(2-\varepsilon)}\right)\sigma\left(T_1^4 - T_2^4\right)$

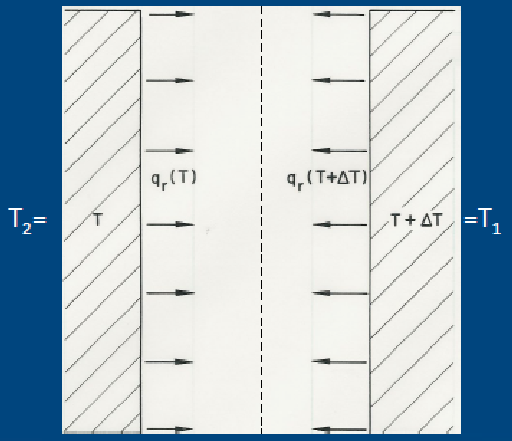
  which for ε << 1, reduces the q_r by a factor of 1/n+1

- Note that the shield temperatures are not equally distributed because the heat exchange is not linear. Consider one shield and all emissivities = ε in steady state:

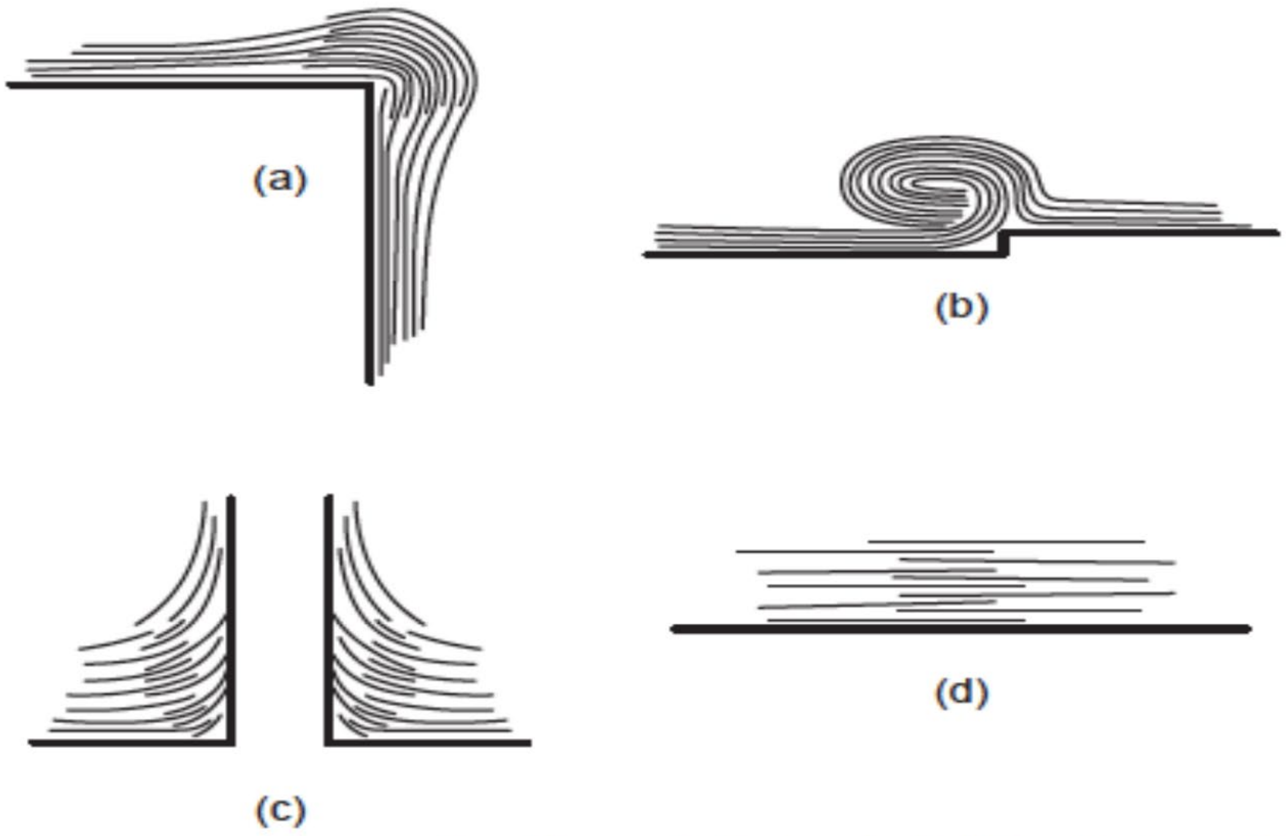
$$q_r(1,s) = \frac{\varepsilon}{2}\sigma\left(T_1^4 - T_s^4\right) = q_r(s,2) = \frac{\varepsilon}{2}\sigma\left(T_s^4 - T_2^4\right)$$

or $T_s = \left(\frac{T_1^4 + T_2^4}{2}\right)^{1/4}$ ~ 252 K for T_1 = 300 K and T_2 = 77 K

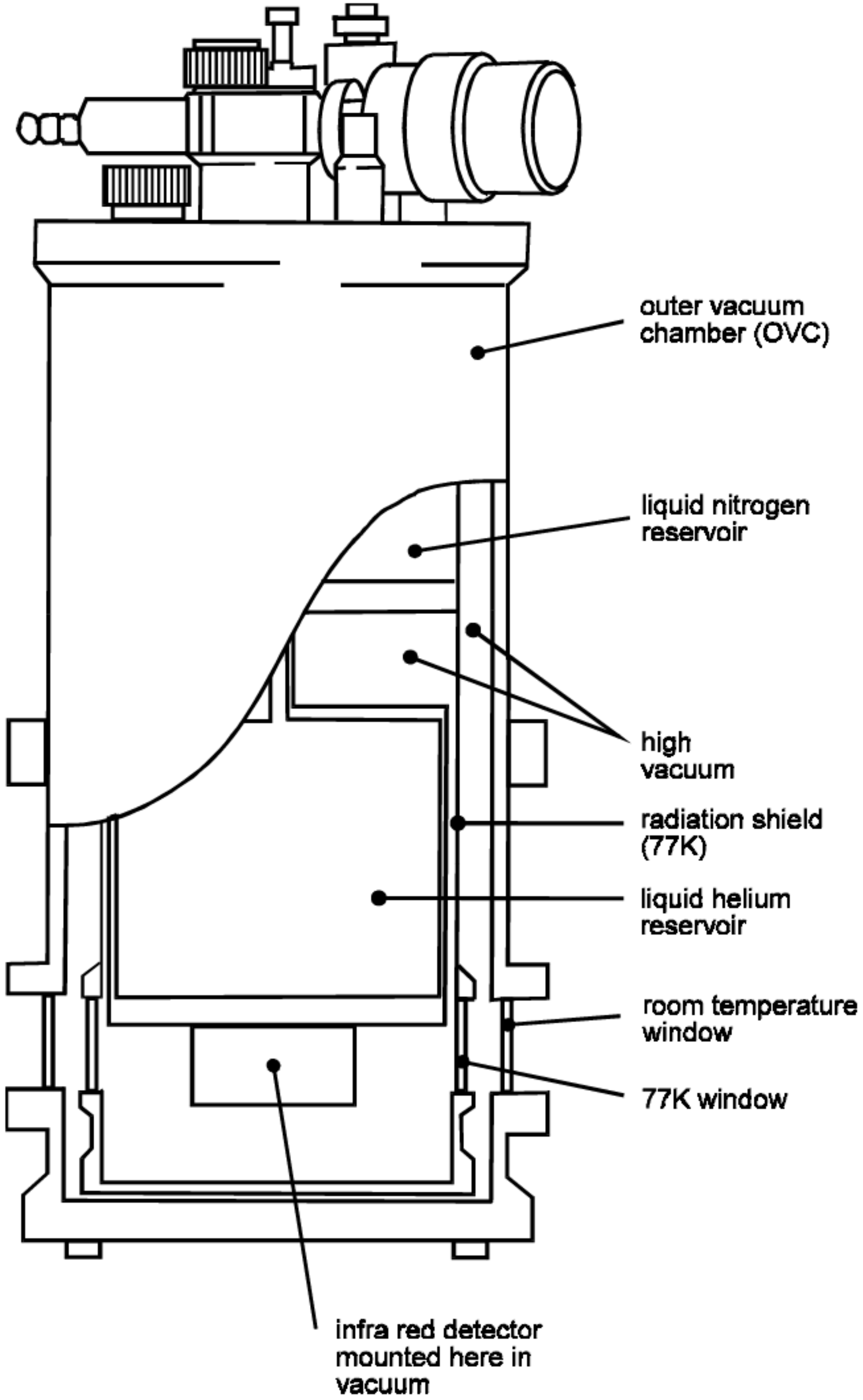




Proper MLI installation



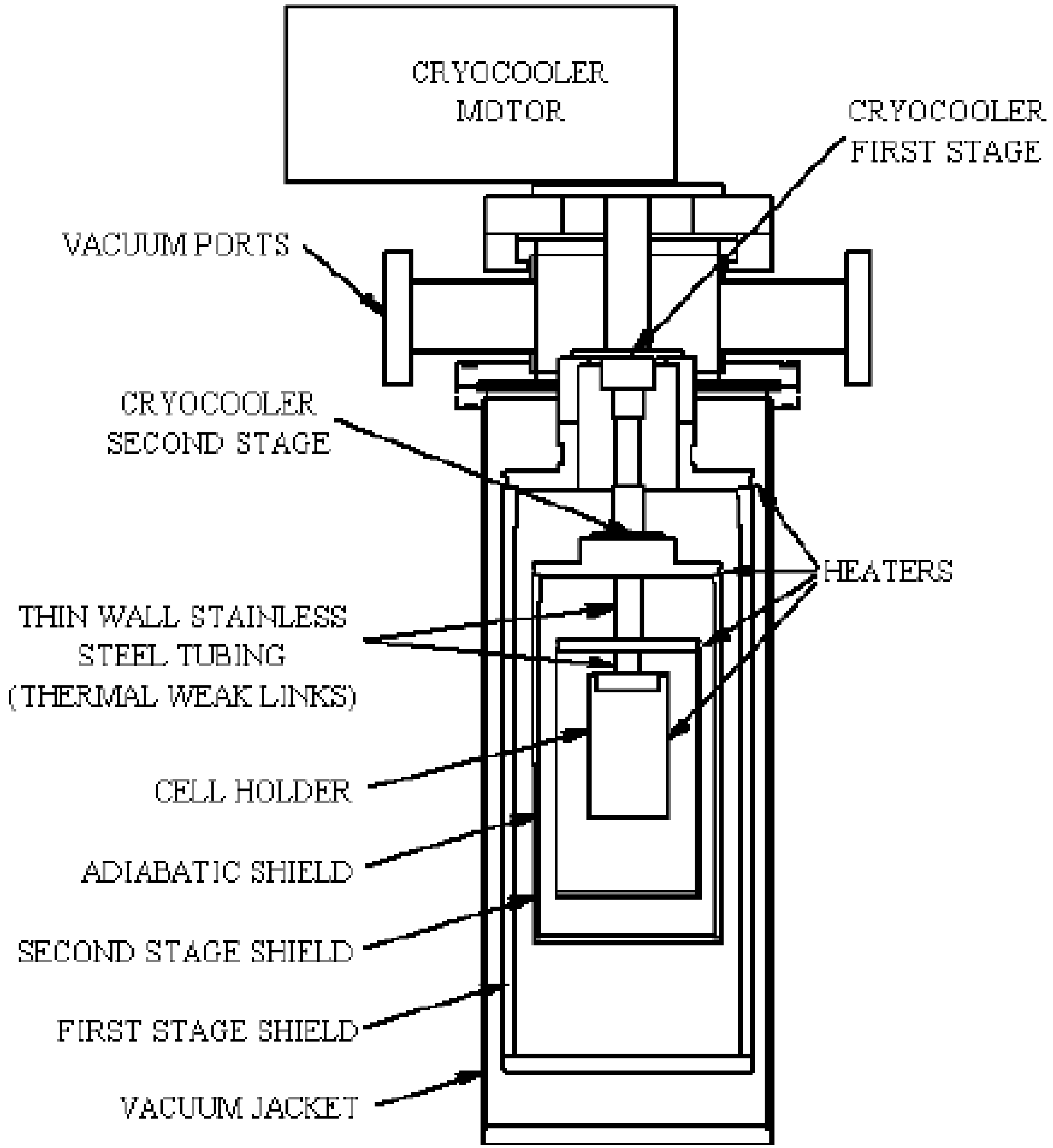
From "Cryogenic Engineering" in *Wiley Mechanical Engineer's Handbook*



Thermal Shield

The purpose is to intercept radiative heat transfer between the room temperature vacuum vessel and the cold working load:

- High temperature shield: 50-80 K, low temperature shield: 5K, 20K
- Normally cooled by LN2, GHe, or cryocooler
- Serves as the heat sink for structural supports, current leads, power couplers, warm-to-cold transitions, etc.
- Surface is usually covered with multi-layer insulation (MLI) or aluminum foil



Thermal shield

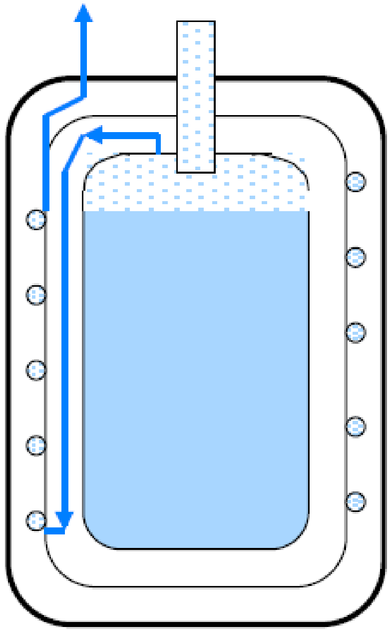
A "passive" component in the system, so the cooldown time should be kept small

- Use material with high thermal conductivity and low volumetric heat capacity

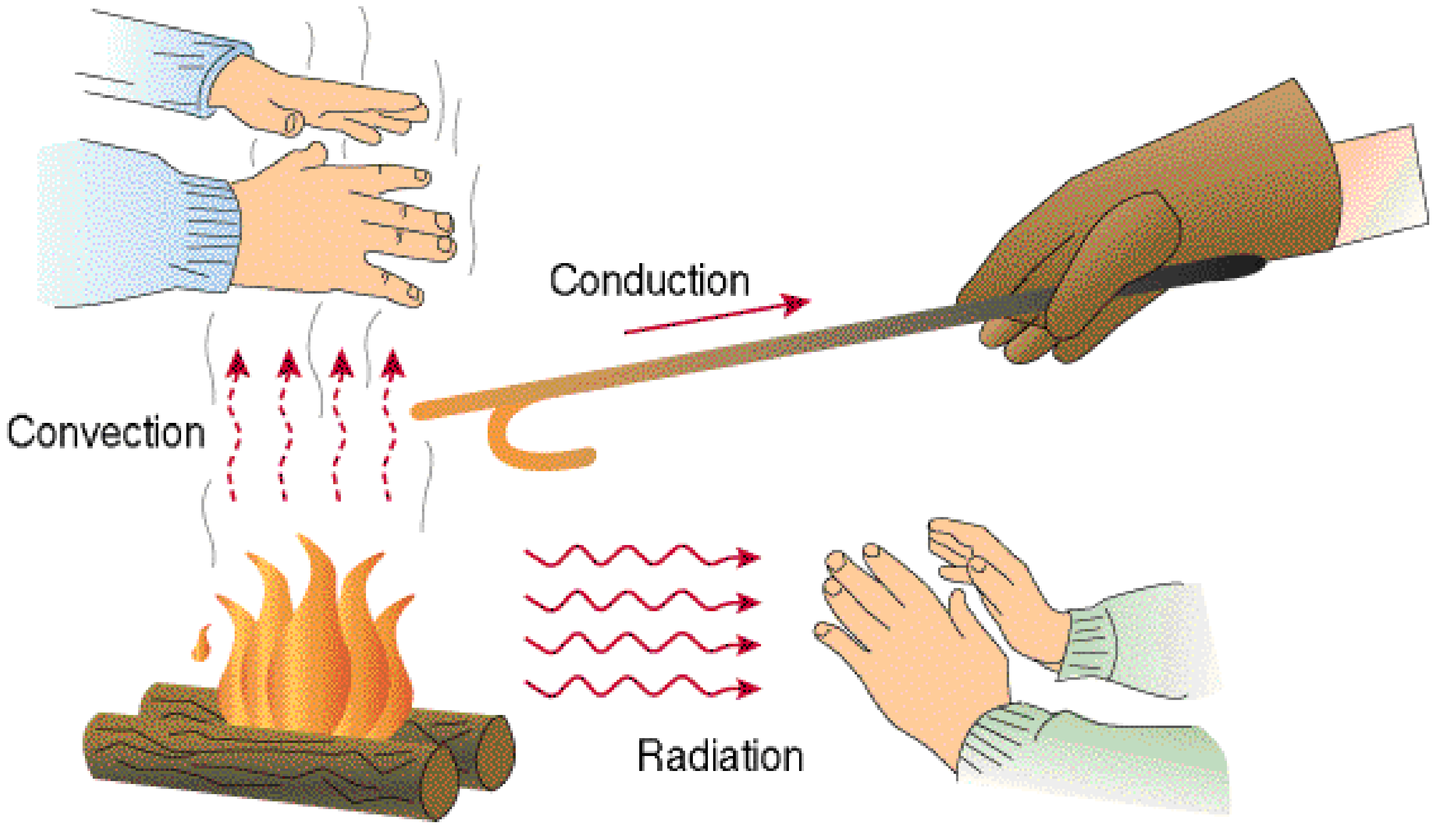
	Copper	Aluminum
Pros	Readily available Good thermal conductivity Readily soldered or brazed	Inexpensive Readily available Good thermal conductivity(*) Weldable Light weight
Cons	Expensive Heavy	(*)Thermal conductivity good, but not as good as copper Difficult to join to stainless steel
Alloys	OFHC, ETP, C101	1100, 6061

Cooling thermal shield with cold vapor

- There is significant thermodynamic advantage to actively cooling radiation shields in a cryogenic system. Examples:
  - LN_2 shield cooling in a cryostat
  - Vapor cooling in LHe storage vessels
  - Refrigerated shields
- Why would you want to do this?
  - Thermodynamic advantage of removing heat at higher temperature (COP)
  - Reduce boil-off of expensive fluid (LHe)
  - Can be done in conjunction with active cooling of other components (structural supports, current leads)



Three ways to transfer heat:



Heat Transfer

- Modes of heat transfer
  - Conduction (heat transported by solids and fluids at rest)
    - Fourier's law: $Q = -k(T) * A * (dT/dx)$
  - Convection (free and forced, pool boiling)
    - Newton's law: $Q = h_c * A * (T_{solid} - T_{fluid})$
  - Radiation (electromagnetic waves)
    - Stefan-Boltzmann law: $Q = \varepsilon\sigma_{SB}A * (T_1^4 - T_2^4)$

Heat transfer

Thermal insulations for cryogenic systems

Increasing cost & complexity

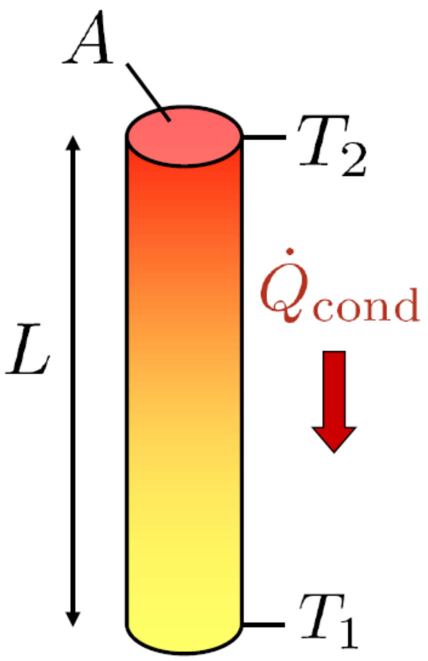
Note better performance of evacuated Perlite over high vacuum between 300 K & 77 K

	Total Heat Flux (W/m^2)	
Type of Insulation	**300 K to 77 K**	**77 K to 20 K**
Polystyrene Foam (2 lb/ft^3)	48.3	5.6
Gas Filled Perlite powder (5 – 6 lb/ft^3 filled with He)	184.3	21.8
Perlite powder in vacuum (5 – 6 lb/ft^3)	1.6	0.07
High Vacuum (10^{-6} torr $\varepsilon = 0.02$)	9	0.04
Opacified powder (Cu flakes in Santocel)	0.3	-
MLI	0.03	0.007

From Cryogenic Systems by R. Barron (for rough estimates only)

Heat Conduction Through Solids

Fourier's Law $j = -\lambda \nabla T$



$$\dot{Q}_{\mathrm{cond}} = \lambda(T) A \frac{\mathrm{d}T}{\mathrm{d}x}$$

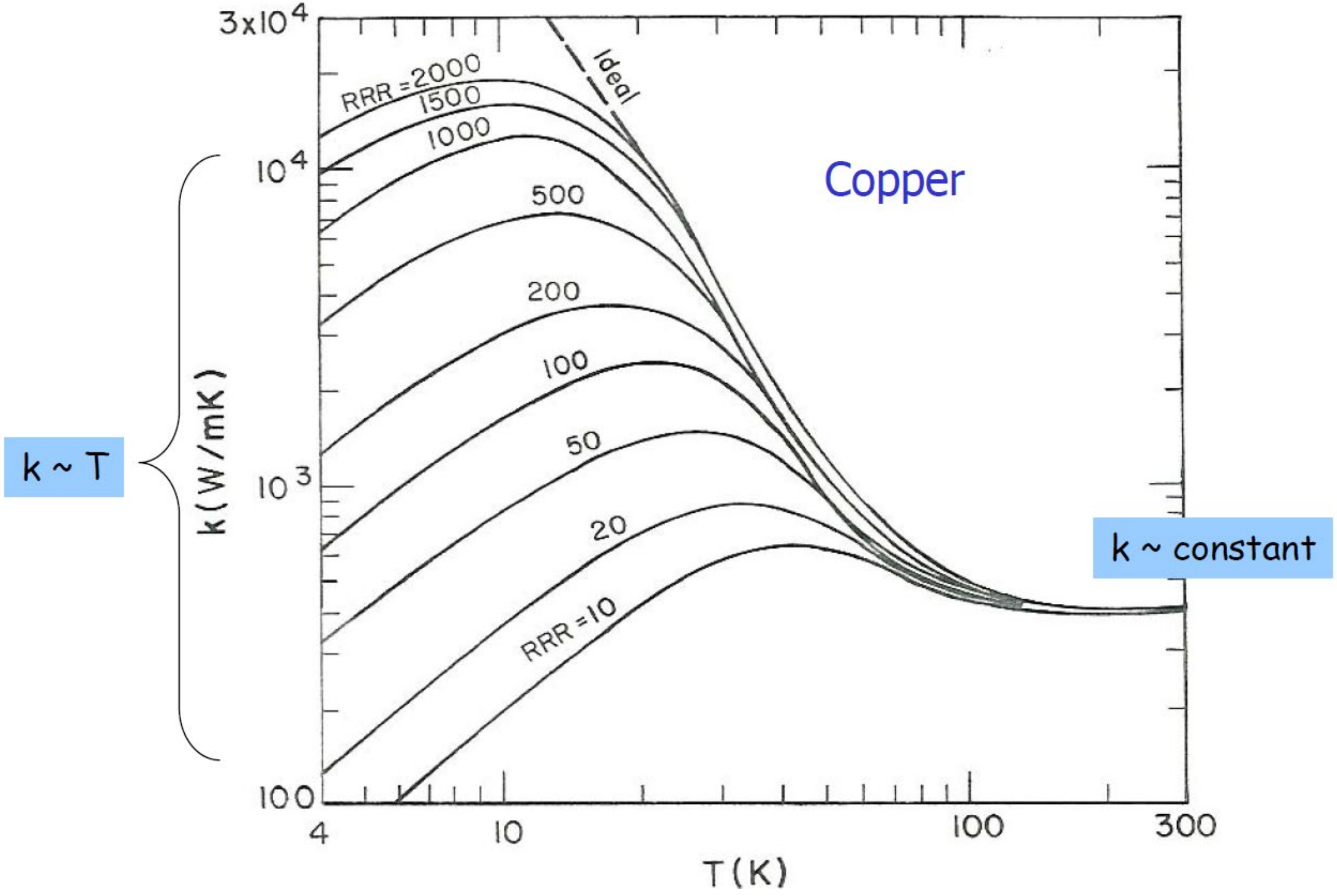
$$\dot{Q}_{\mathrm{cond}} = \frac{A}{L} \int_{T_1}^{T_2} \lambda(T)\, \mathrm{d}T = \frac{A}{L} \overline{\lambda} \Delta T$$

mean thermal conductivity

Note on this slide, the symbol for thermal conductivity

$$\lambda = k$$

Thermal Conductivity of Pure Metals



Electronic Thermal Conductivity (at low temperatures)

- Free electron model:

$$k = \frac{\pi^2 n k_B^2 T \tau}{3m_e}$$

Recall: τ is scattering time = ℓ/v

~ constant at high temperature
~ T at low temperature

- Weidemann-Franz law (for free electron model)

$$\frac{k}{\sigma} = f(T) = \frac{\pi^2 k_B^2}{3e^2} T \equiv L_0 T$$

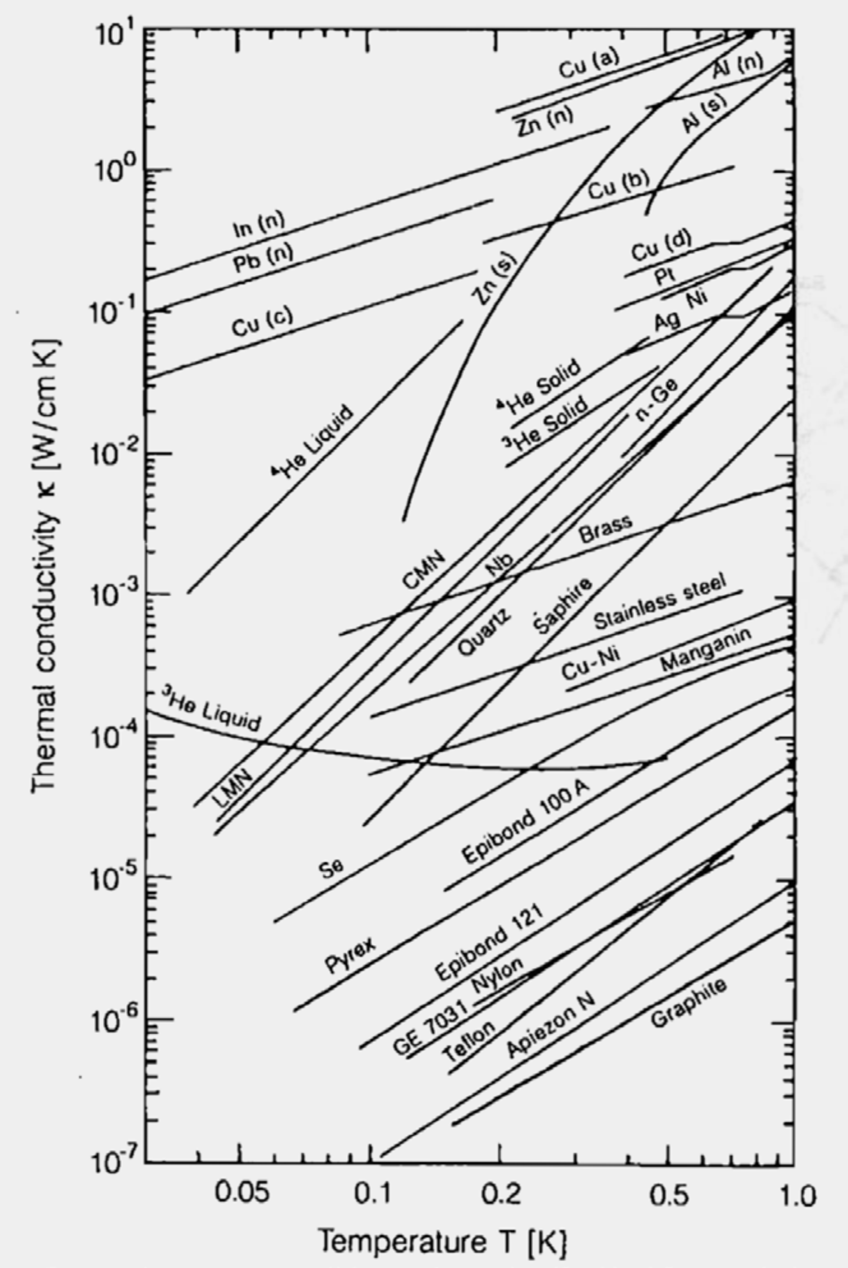
L_0 = Lorentz number = 2.443×10^{-8} WΩ/K^2

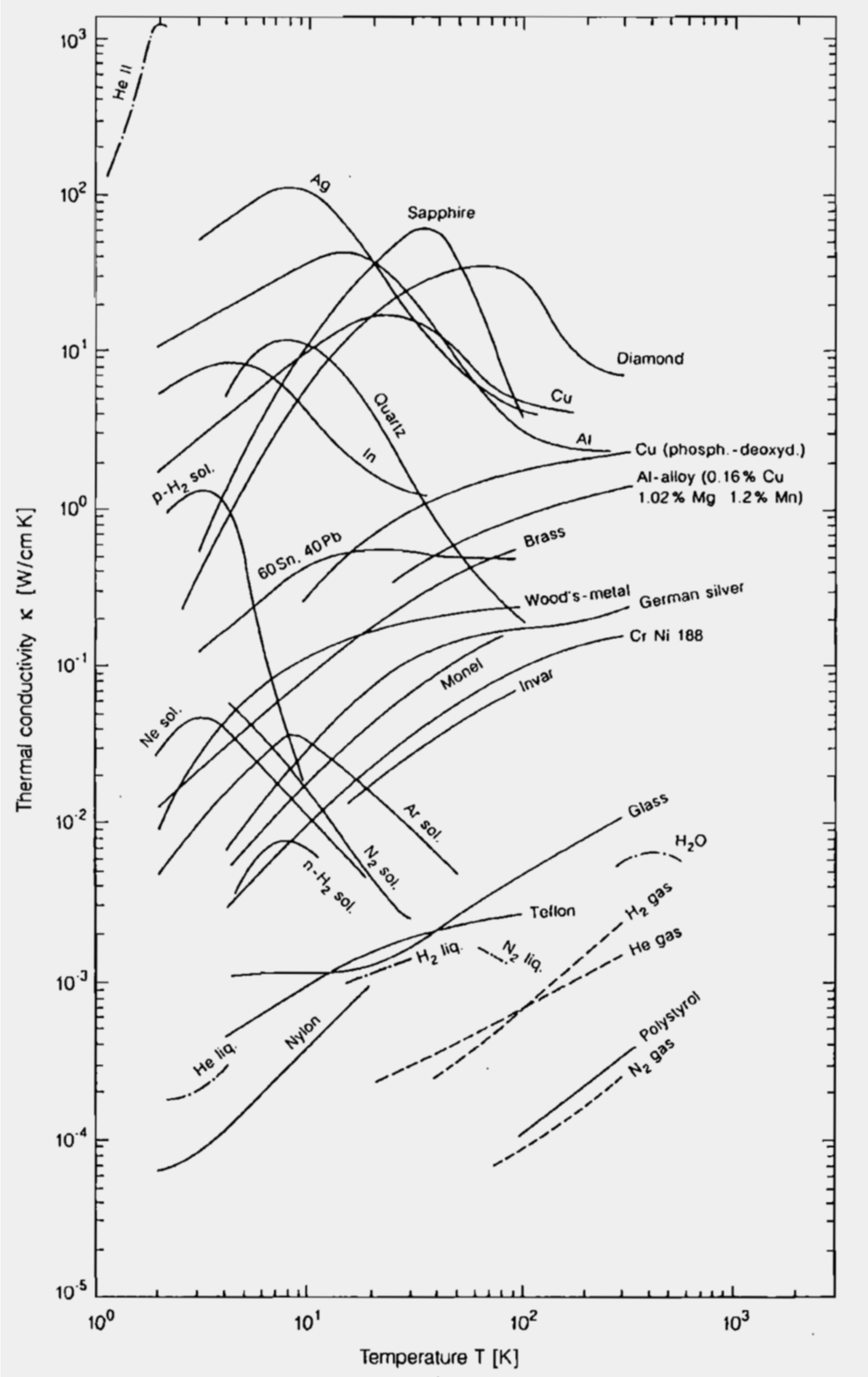
- Note that no real material obeys the W-F law, although it is a good approximation at low T and near and above RT.

Thermal conduction by lattice vibration (phonons)

- Thermal conduction by lattice vibrations (phonons) is a significant contributor to overall heat conduction particularly in non-metals and alloys.
- Metals (Alloys): $k_{total} = k_{electrons} + k_{phonons}$ (Typ. 1 to 3 orders less than that of pure metals)
- Insulating crystals only have lattice contribution, which can be large for single crystals (e.g. Al_2O_3, Sapphire)
- Insulating polymers have very low thermal conductivity (Nylon, Teflon, Mylar, Kapton)
- Insulating composites have complex behavior depending on components

Thermal Conductivity





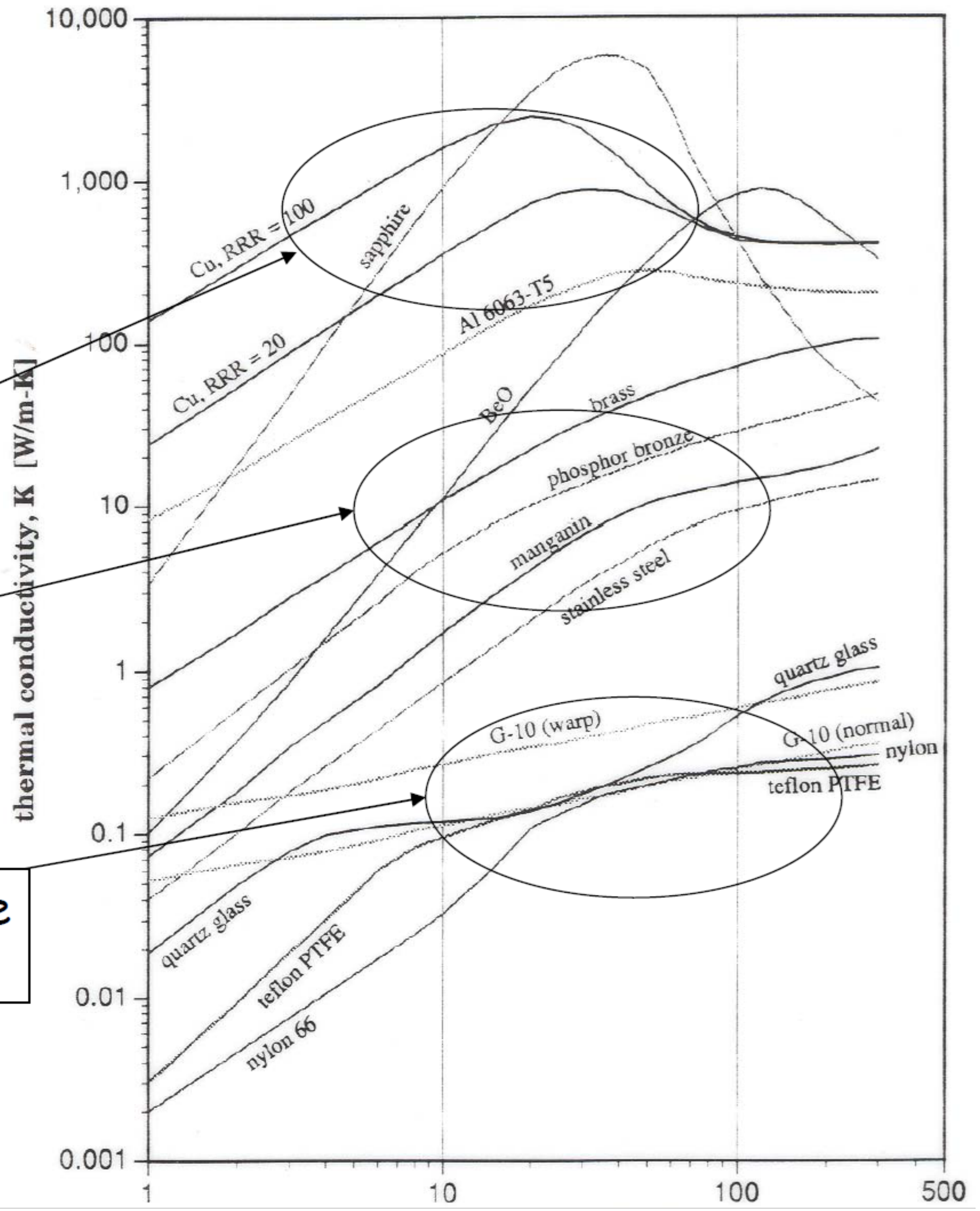
Thermal Conductivity

- Low temp. range,
  $k \sim T^n$ with $1 < n < 3$

Pure metals and crystalline insulators

Alloys

Non-crystalline Non-metallics



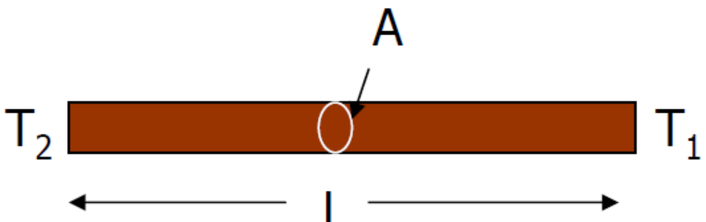
Thermal Conductivity Integrals

$$\bar{k}(T_1,T_2)=\int_{T_1}^{T_2} k(T)\,dT \quad \text{, [W/m]}$$

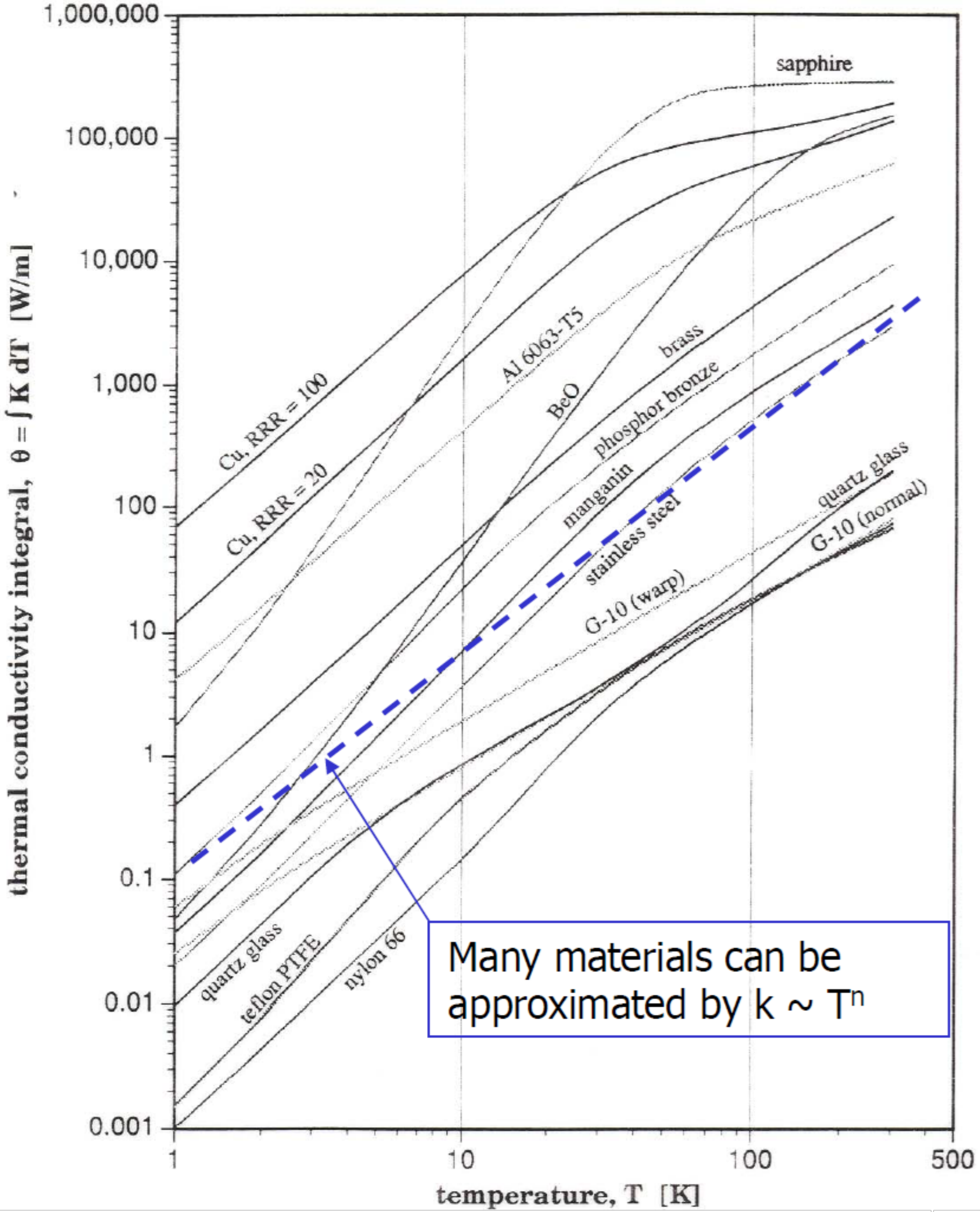
To use the graph

$$\bar{k}(T_1,T_2)=\bar{k}(0,T_2)-\bar{k}(0,T_1)$$

Heat conduction along a rod



$$Q=\bar{k}(T_1,T_2)\frac{A}{L}$$



Thermal Conductivity Integrals

$$\int_{4\,\mathrm{K}}^{T} \lambda \, \mathrm{d}T \quad [\mathrm{W/m}]$$

T(K)	Copper (wire)	Stainless Steel	Glass	Teflon
6	800	0.63	0.211	0.113
10	3 320	2.93	0.681	0.44
20	14 000	16.3	2.0	1.64
50	50 800	135	8.46	7.16
77	68 600	317	17.5	13.0
100	80 200	528	29.2	18.7
140	97 600	939	54.2	28.7
200	122 000	1 660	103	44.2
300	162 000	3 060	199	70.2

$$\dot{Q}_{\mathrm{cond}} = \frac{A}{L} \int_{T_1}^{T_2} \lambda(T) \, \mathrm{d}T = \frac{A}{L} \left\{ \int_{4\,\mathrm{K}}^{T_2} \lambda(T) \, \mathrm{d}T - \int_{4\,\mathrm{K}}^{T_1} \lambda(T) \, \mathrm{d}T \right\}$$

Homework # 1:

Estimate the heat load due to conduction down the 3 SS tubes for our small diptick cryostat.

Thermal conductivity integral from 4.2 K

T (K)	6	8	10	15	20	60	80	300
	W/cm							
Copper extra pure	166	382	636	1270	1790	2960	3090	4000
Copper cold worked	8.0	19.1	33.2	80.2	140	587	707	1620
Silver	320	670	990	1610	1980	2570	2670	3570
Alu. extra pure	73	168	280	600	907	1740	1840	2390
Alu. Commercial	1.38	3.42	6.07	15.2	27.6	170	232	728
Gold	41.0	93.0	149	274	364	612	682	1370
Brass	0.053	0.129	0.229	0.594	1.12	10.4	17.7	172
Lead normal	27.0	37.3	42.4	49.0	52.5	73.8	81.3	160
Titanium	0.115	0.277	0.488	1.21	2.20	15.5	22.6	99.6
Monel	0.0235	0.0605	0.112	0.315	0.618	5.23	8.24	52.5
Stainless steel.	0.0063	0.0159	0.0293	0.0816	0.163	1.98	3.49	30.6
Inconel							3.50	53.7
	mW/cm							
Glass	2.11	4.43	6.81	13.1	20.0	115	194	1990
Teflon	1.13	2.62	4.40	9.85	16.4	93.6	139	702
Plexiglas	1.18	2.38	3.59	6.69	10.1	68.3	110	630
Nylon	0.321	0.807	1.48	4.10	8.23	85.9	142	895
Fiber glass epoxy	1.3	2.8	4.5	10	17	95	160	1250