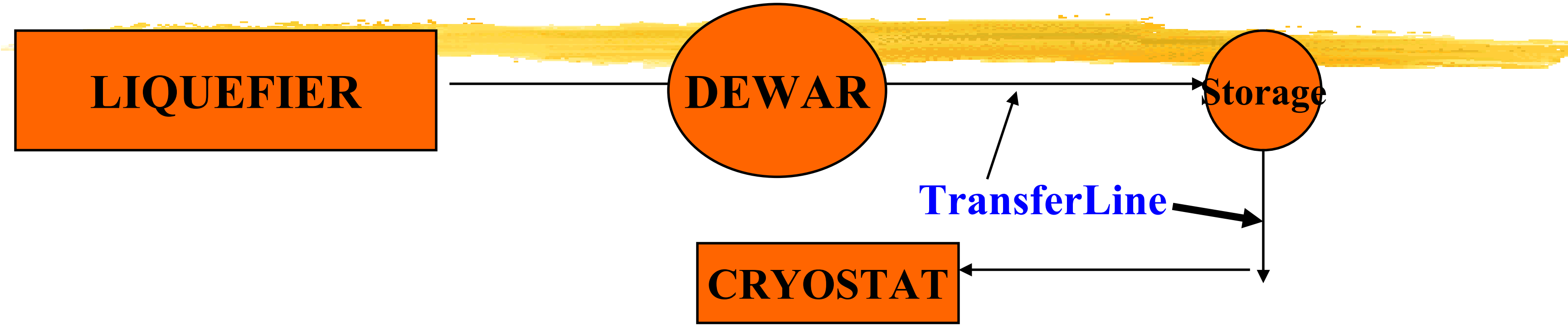
Cryogenics Course Material : 3-4

- Introduction : What is Cryogenics and Why Cryogenics for accelerator , Present Scenario
- How to Generate low Temperature / Production of Cryogen : Thermodynamics / Refrigeration Cycle
- **How to Store & Transfer Cryogen : Heat transfer, Cryomodule Design, Properties of Material :**
- **Measurement at Low temperature :**

CRYOGEN STORAGE VESSEL, CRYOSTAT & Transfer Line

- **INTRODUCTION**
- **DIFFERENT MODES OF HEAT TRANSFER**
- **TECHNIQUE TO REDUCE IT (Cryogenic Insulation)**
- **PROPERTIES OF MATERIAL AT LOW TEMPERATURE (DESIGN FACTOR)**

CRYOGEN CYCLE



STORAGE VESSEL : To Store liquid Nitrogen, liquid Helium, Liquefied Natural Gas (LNG) at their Boiling Point (Fixed T)
Capacity : 5 litres to 500,000 litres

Transfer line : To Transfer Cryogen from one point to another

Cryostat : To Carry out Expt at low temperature (Variable T)

Both need good Insulation (Tr - Tb) Higher

WHY STORAGE IS SO CRITICAL

A. LOW LATENT HEAT

B. LARGE TEMPERATURE DIFFERENCE

Property	He	H_2	N_2	Water
Boiling Point	**4.2K**	**20K**	**78K**	**373K**
Density	**0.12kg/liter**	**0.07kg/ litre**	**0.81kg/litre**	**1kg/litre**
Heat of Vaporisation	***20KJ/ kg***	***428***	***198***	***2250***
Liquid evaporated on 100 W Heat input	**140 l/ hr**	**12 l/hr**	**2.2 l/hr**	**0.16 l/hr**

1 W HEAT LOAD EVAPORATES 34 LITRES Lhe in ONE DAY

THANKS TO MLI (MULTILAYER INSULATION TECHNOGY)

EVAPORATION RATE ONLY 1 LITRES/ DAY

HEAT TRANFER TO CRYO VESSEL/ CRYOSTAT

Simple Configuration

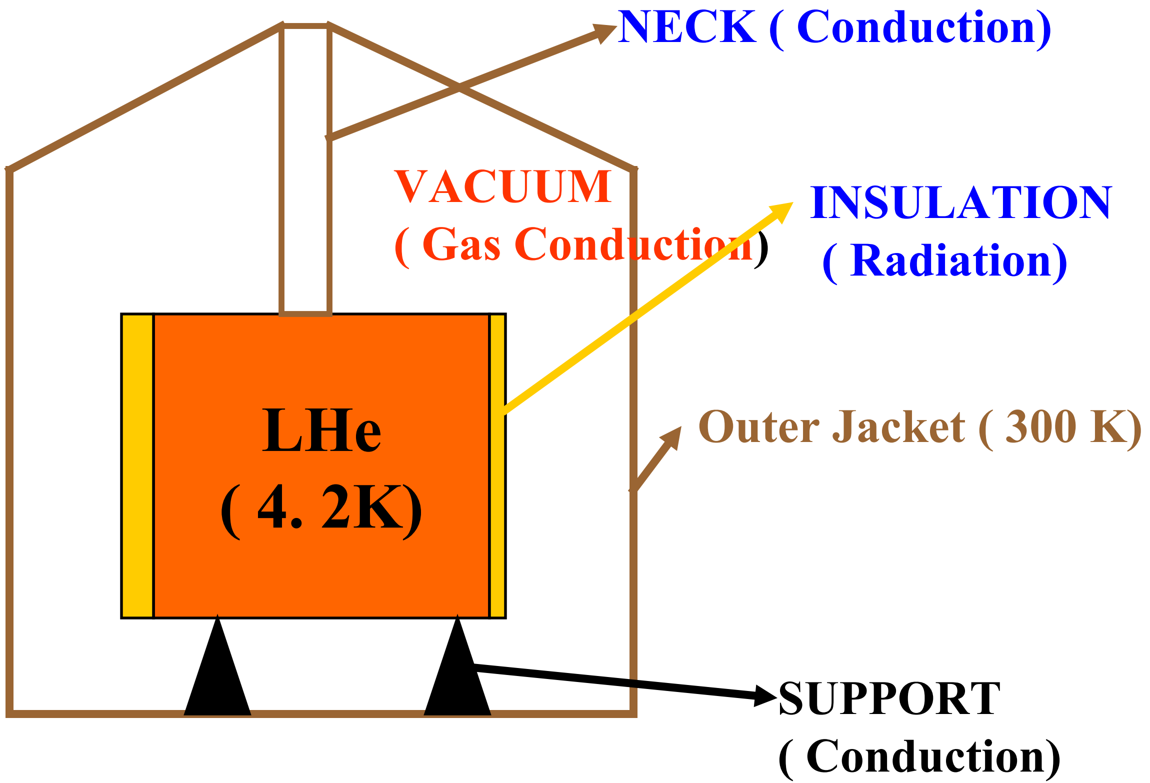
Design Goal :

Reduce Heat Flux from Outside

Structural Stability

Avoid Collapsing

Safety Features



The 3 modes of heat transfer

- **Conduction: heat transported in solids or fluids at rest**

$$Q = -k(T)A\,grad\,T$$

FOURIER's law:

- **Convection: heat transport produced by flow of fluid**

$$Q = hA(T_w - T_f)$$

Convection exchange:

- **Radiation: heat carried by electromagnetic radiation**

Stefan-Boltzmann's law: $$Q = \sigma\varepsilon A(T_h^4 - T_c^4)$$

HEAT TRANSFER MECHANISM

A. Solid conduction heat transfer : *Necktube, Support structure .*

B. Radiation heat transfer : *Through vacuum*

C. Gas conduction : *Residual gas in the vacuum space.*

Solid Conduction :

$$\mathbf{Q_c = K_m (A_c / L) (T_h - T_c)}$$

A_c = Cross sectional area (example for a rod of dia (d), $A_c = \pi d^2/4$,
Similarly for a pipe of outer diameter d and thickness 't', $A_c = \pi dt$)

L = Length of rod/ pipe,

Conductivity $k_m = F(T)$ $$k_m = [\oint k\, dT / (Th - T_c)]$$

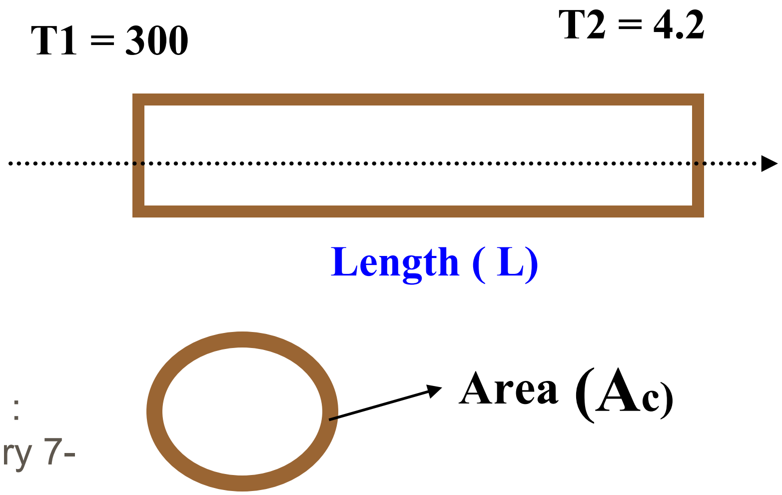
$$Q_c = (A_c /L) \int k\, dT.$$

Cnductivity integral value of stainless steel between 300K and 80 K is evaluated by

$$\int_{80}^{4.2} k\, dt = \int_{300}^{4.2} k dT - \int_{80}^{4.2} k dT = (30.6 - 3.49) = 26.1 \text{ W/ cm}$$

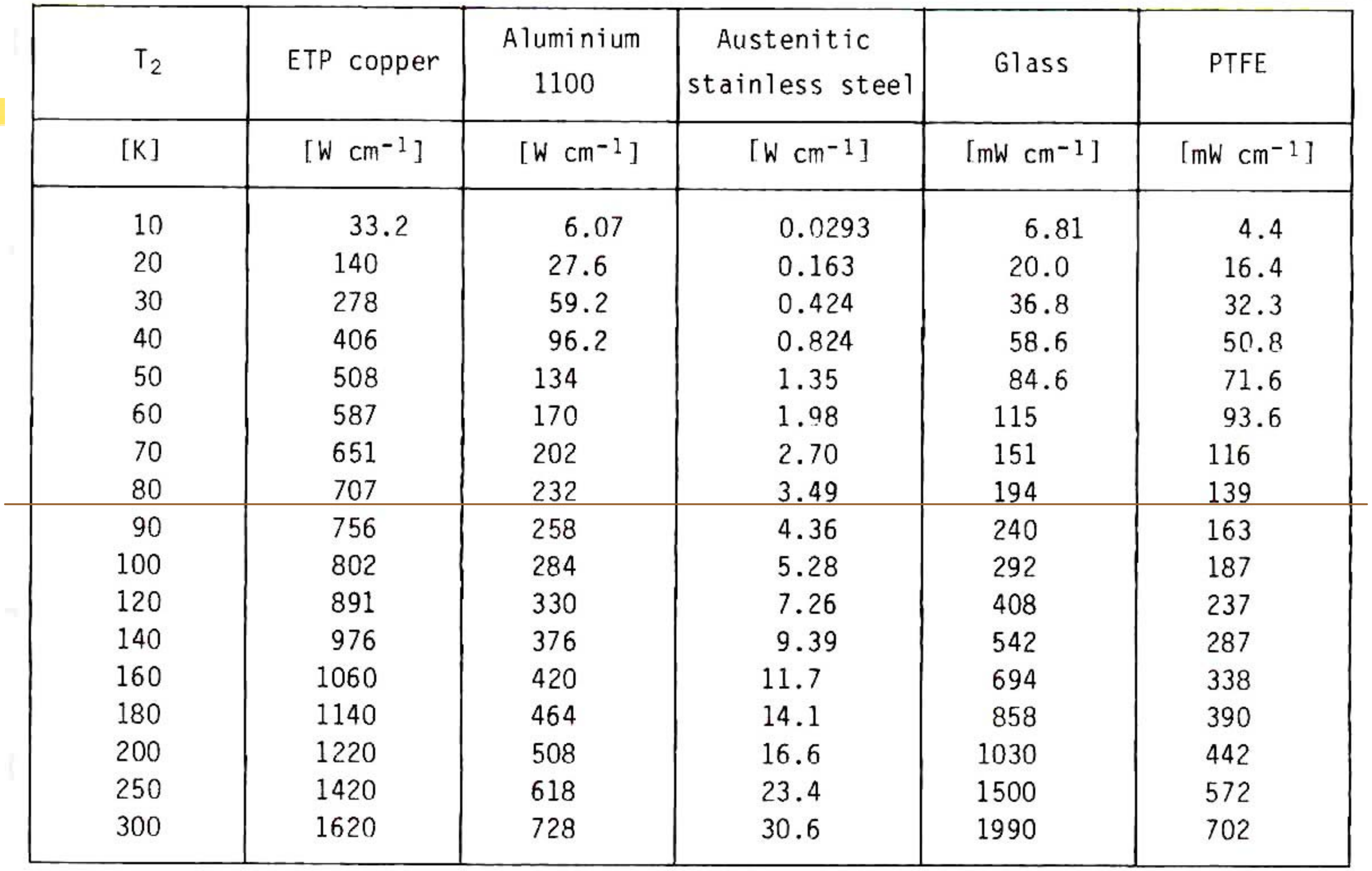
CONDUCTION REDUCED BY;

1. **Low Croosectional Area**
2. **Long Length**
3. **Low conductivity pipe (SS/ FRP)**
4. **Thermal interception**



Thermal conductivity integrals

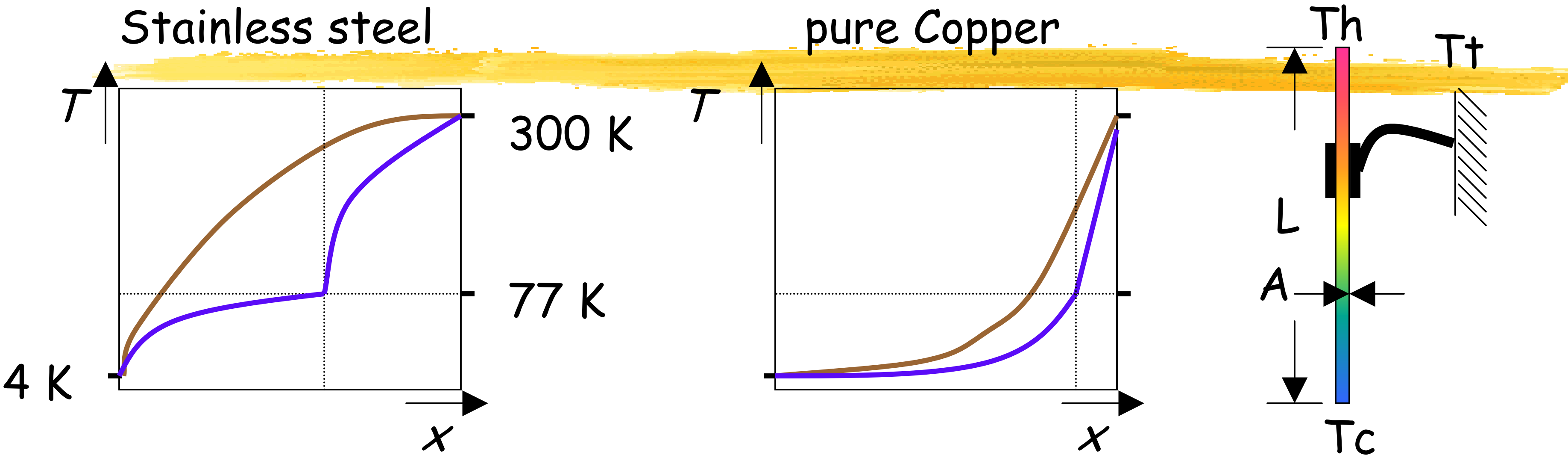
Tc=4 K



T_2 [K]	ETP copper [W cm^{-1}]	Aluminium 1100 [W cm^{-1}]	Austenitic stainless steel [W cm^{-1}]	Glass [mW cm^{-1}]	PTFE [mW cm^{-1}]
10	33.2	6.07	0.0293	6.81	4.4
20	140	27.6	0.163	20.0	16.4
30	278	59.2	0.424	36.8	32.3
40	406	96.2	0.824	58.6	50.8
50	508	134	1.35	84.6	71.6
60	587	170	1.98	115	93.6
70	651	202	2.70	151	116
80	707	232	3.49	194	139
90	756	258	4.36	240	163
100	802	284	5.28	292	187
120	891	330	7.26	408	237
140	976	376	9.39	542	287
160	1060	420	11.7	694	338
180	1140	464	14.1	858	390
200	1220	508	16.6	1030	442
250	1420	618	23.4	1500	572
300	1620	728	30.6	1990	702

- Reduction of heat flow to the cold boundary temperature by thermal interception at intermediate temperature

Intermediate heat interception



Example : SS tube Structure (2.54 Cm x 1mm x 1 m length) (300- 4.2 K)

No Thermal interception Q = 0.24 W (3.14 x 2.54 x.1 x 30.6/100)

80 K Thermal Interception at 70 Cm, Q = 0.04W (3.14 x 2.54x .1 x 3.49/ 70)

80 K Thermal Interception at 10 Cm , Q = 0.27W (3.14 x 2.54x .1 x 3.49/ 10)

Refrigeration properties of cryogens

Working domain close to critical point:

properties of liquid and vapor phase are similar

low vaporization heat

Low viscosity hence excellent leaktightness required for He

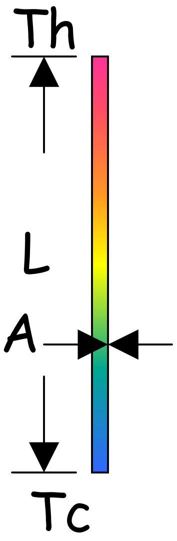
		He	N_2	H_2O
Normal boiling Pt		4.2	77	373
Critical temperature		5.2	126	647
Critical pressure		2.3	34	221
Liquid density/ Vapor density*		7.4	175	1600
Heat of vaporization	$[Jg^{-1}]$	20.4	199	2260
*Liquid viscosity *	[µpoise]	3.2	152	283
Enthalpy increase between T_1 and T_2	$T_1 = 4.2$ K $T_2 = 77$ K	384	-	-
	$T_1 = 4.2$ K $T_2 = 300$ K	**1157**	**228**	-

*at normal boiling point

highly effective for self-sustained vapor cooling!

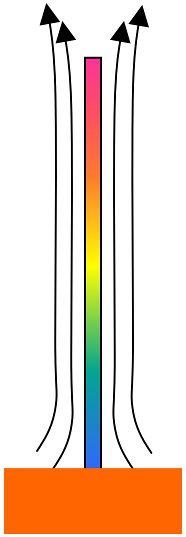
Shielding potential of cold vapours

Pure conduction heat losses evacuated at the coldest temperature



$$\dot{Q} = \frac{A}{L}\int_{T_1}^{T_2} k(T)\,dT$$

Self sustained vapour cooling: vapour flow generated only by heat leak is used to cool the device

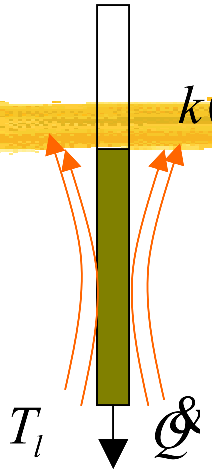


Heat evacuation across a small ΔT thermodynamically much more efficient

Shielding potential of cold vapours

heat balance, perfect exchange

$$\dot{Q} = k(T)A\frac{dT}{dx} - \dot{m}C_p(T - T_l)$$



$$k(T)A\frac{dT}{dx} - \dot{m}C_p(T - T_l)$$

self-sustained evaporation of fluid

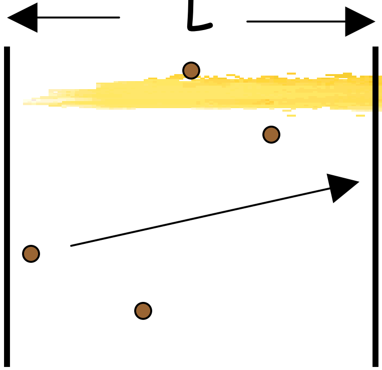
$$\dot{Q} = \dot{m}L_v$$

$$\dot{Q} = \frac{A}{L}\int_{T_l}^{T_2}\frac{k(T)dT}{1 + (T - T_l)C_p / L_v}$$

$$\dot{Q} = \frac{A}{L}\int_{l}^{T_2} k(T)dT$$

Th.conductivity integral	**[W cm^{-1}]**	**[W cm^{-1}]**
ETP copper	128	1620
OFHC copper	110	1520
Aluminium 1100	39.9	728
AISI 300 st.steel	**0.92**	**30.6**

Conductivity of gases:



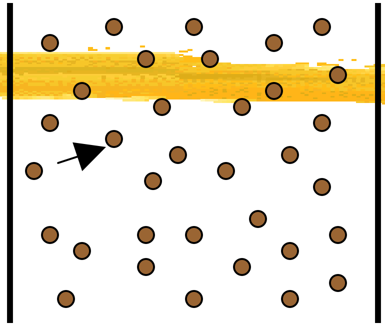
mean free path

vs

wall distance L

$$\lambda = 115 \cdot \frac{\mu}{p}\sqrt{\frac{T}{M}}$$

[Pa.s],[Pa],[cm]



molecular:

q proportional to p

q independent from L

P [Pa]	10^{-2}	100
Ar	0.63 cm	6.3 10^{-5}
N_2	1.8	1.8 10^{-4}
He	0.60	6.0 10^{-5}

viscous:

q independent from p

$q=kS\Delta T/L$

k predicted by kinetic theory of gases

$$k = \frac{1}{3}\rho\left(\frac{8RT}{\pi M}\right)^{\frac{1}{2}}\lambda C_v$$

$k \sim T^{0.7}$

Molecular regime: Kennard's law

$$\dot{Q} = A_1 \alpha \left(\frac{\gamma+1}{\gamma-1}\right)\left(\frac{R}{8\pi}\right)^{1/2} \frac{p}{\sqrt{MT}}\left(T_2 - T_1\right)$$

$\gamma = C_p / C_v$

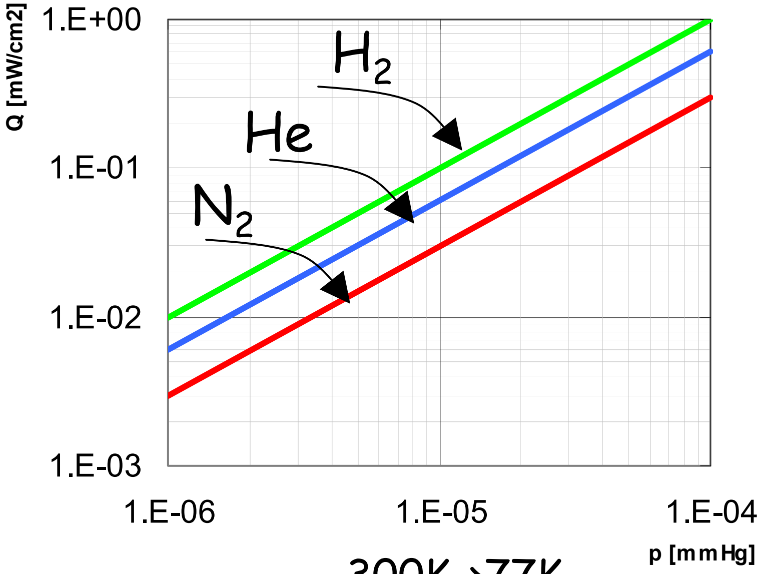
R ideal gas constant

α accomodation coefficient

$0<\alpha<1$, degree of thermal equilibrium between molecules and wall, α~0.7-1 for heavy gases.

$$\alpha = \frac{\alpha_1 \alpha_2}{\alpha_2 + \alpha_1 (1-\alpha_2) \dfrac{A_1}{A_2}}$$

for simple geometries, (parallel plates, coaxial cylinders, spheres)



300K->77K

Residual gas conduction :

At lower pressure : Mean Free Path of the molecules >> ANNULAR GAP

$$Q_{gc} = C\,\alpha\,P\,(T_h - T_c)$$

C = constant, α = accommodation coefficient, P = Gas pressure

Residual gas conduction can be reduced

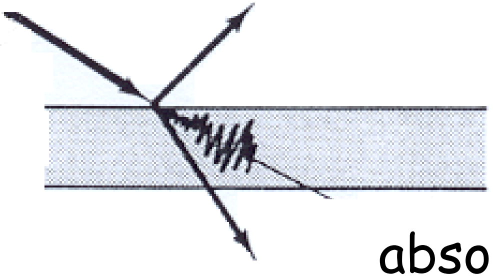
1. Clean surface (low α) 2. by high vacuum.

Gas	*C*	*α*	*P (Torr)*	*T2/T1*	*Qgc (W/m^2*
Air	**0.02**	**0.8**	**10^{-5}**	**300/78**	**0.35**
Air	0.02	0.8	10^{-5}	78/4.2	0.11
Air	**0.02**	**0.8**	**10^{-3}**	**300/78**	**35**
Helium	0.03	0.35	10^{-5}	300/4.2	0.31
Helium	0.03	0.35	10^{-5}	78/4.2	0.07

RADIATION

Any surface T>0K absorbs (α) and emits (ε) energy as electromagnetic radiation:

depending on direction and wavelength



incident P

reflected ρP

absorbed αP

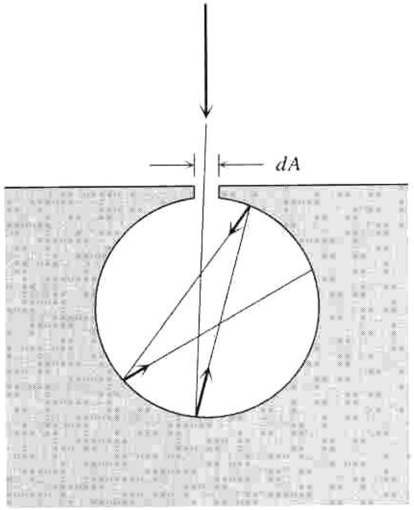
transmitted τP

Energy conservation $\rho+\alpha+\tau=1$

Opaque medium $\rho+\alpha=1$

BLACK-BODY:

The whole incident radiation is absorbed: α=1



Heat transfer between 2 real surfaces

$$\dot{q} = \sigma A_1 \varepsilon_{12} (T_2^4 - T_1^4)$$

ε_{12} effective emissivity
(emissivities + view factor)

Parallel plates	$\dfrac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + (1 - \varepsilon_2)\varepsilon_1}$
Spheres and long cylinders **self-contained, not concentrical/coaxial (A1<A2)**	$\dfrac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + \dfrac{A_1}{A_2}(1 - \varepsilon_2)\varepsilon_1}$

$A_2 >> A_1$ equivalent to A_2 black: black-body radiation fills the cavity between the two surfaces and is collected by A_1 proportionally to ε_1

Radiation :

For vacuum insulation, the dominant contribution to heat inleak into a storage vessel or cryostat is Radiation

Radiant heat transfer rate between two parallal surfaces

$$Q_r = Fe\, F_{1-2}\, \sigma A_1 \,(T_2^{\,4} - T_1^{\,4})$$

Fe = Effective emmissivity, F_{1-2} = Geometry factor = 1, σ = Stefen Boltzman constant = 5.6×10^{-8} w/ m^2 K. A_1 = Surface area of inner vessel.

$1/F_e = 1/e_1 + A_1/A_2\,(1/e_2 - 1)$, **e : emmissivity for inner and outer surface.**

Radiation Heat transfer is reduced by :

1. *Intermediate thermal shield*

Liquid helium/ hydrogen vessel : liquid nitrogen cooled shield

heat transfer reduction : by a factor of 200 ~ $(300/80)^4$

2. *Material of low emmisivity : by electropolishing or aluminum tape.*

SS : 0. 34, SS (Mech. Polished) : 0.12, SS (Elec. Polish : 0.1

SS + Al Foil : 0.056 , Copper : 0.12 : Careful on Oxide formation

3. *Optimizing the surface area for a fixed volume.*

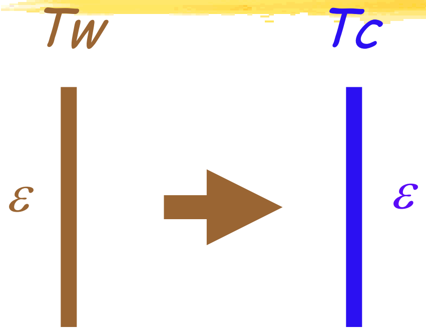
Heat Transfer for Vacuum Insulation on bare Polished SS surface (Radiation)

T_2 (K)	T_1 (K)	Heat flux (W/ m^2)	Evaporation rate (l/hr)
300	78	45	1 litre/hr liquid Nitrogen
200	78	9	0.2 litre/hr
300	20	45	5 litres/ hr liquid Hydrogen
80	20	0.23	0.026 litre/hr
300	4.2	45	65 litres/hr liquid Helium
80	4.2	0.23	0.33 litres/hr

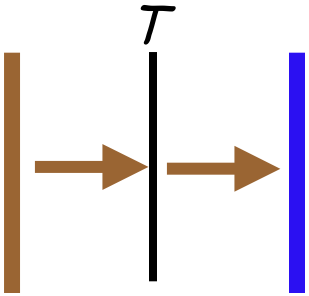
Standard Helium Dewar of 100 litres : Evaporation < 1 litres/ day

Floating radiation screens

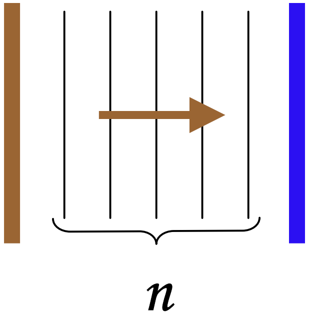
Floating = not actively cooled, they operate at a temperature determined by heat balance



$$\dot{q} = \left(\frac{\sigma\varepsilon}{2-\varepsilon}\right)(T_w^4 - T_c^4)$$



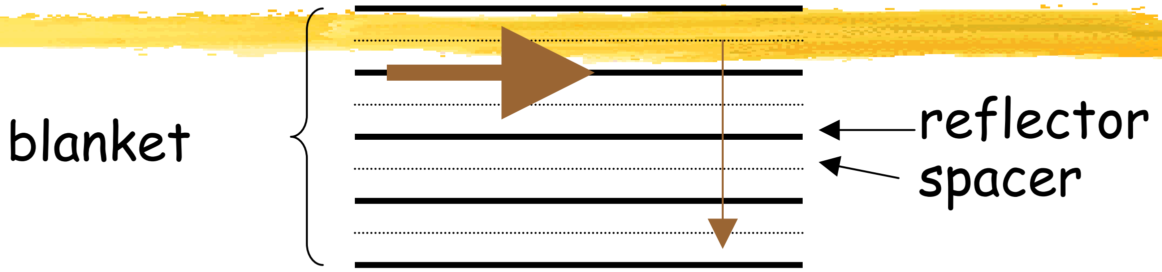
$$\dot{q} = \frac{1}{2}\left(\frac{\sigma\varepsilon}{2-\varepsilon}\right)(T_w^4 - T_c^4) \qquad T^4 = \frac{1}{2}(T_w^4 + T_c^4)$$



$$\dot{q} = \frac{1}{n+1}\left(\frac{\sigma\varepsilon}{2-\varepsilon}\right)(T_w^4 - T_c^4) \qquad T_i^4 = T_c^4 + \frac{T_w^4 - T_c^4}{i+1}$$

Multi-layer Insulation

Stacking of "reflectors" separated by insulating "spacers"



Reflector: low emittance radiation shield	polyester film, 300-400 A pure Al coating, usually double face
Spacer: insulating, lightweight material	paper, silk, polyester net

1. Heat transfer parallel to the layers ~1000 times greater than normal to the layers

thermal coupling between blanket edges and construction elements may dominate heat rate.

2. Heat transfer very sensitive to layer density

single local compression affects the T profile over the entire blanket, substantially degradating heat loss (factors 2-3 more !)

MLI: number of layers

30 layers,

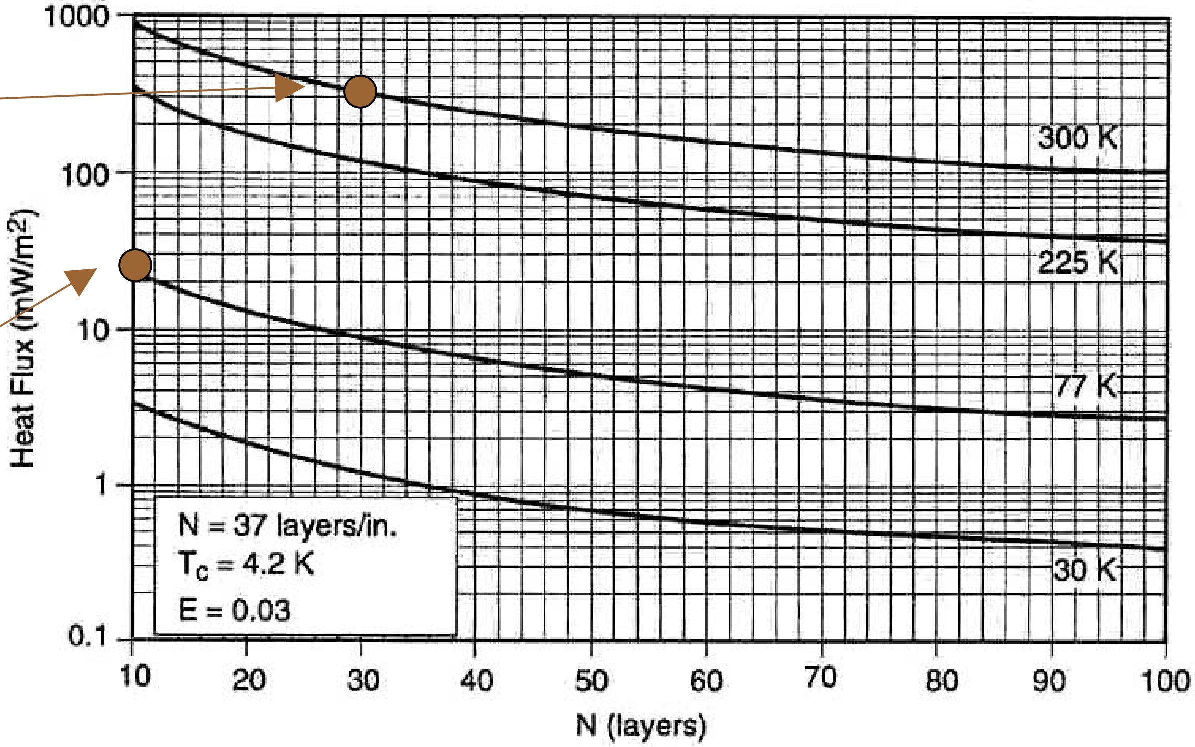
300K-> 77K,

0.5 W/m²

10 layers,

77K-> 4K,

20 mW/m²



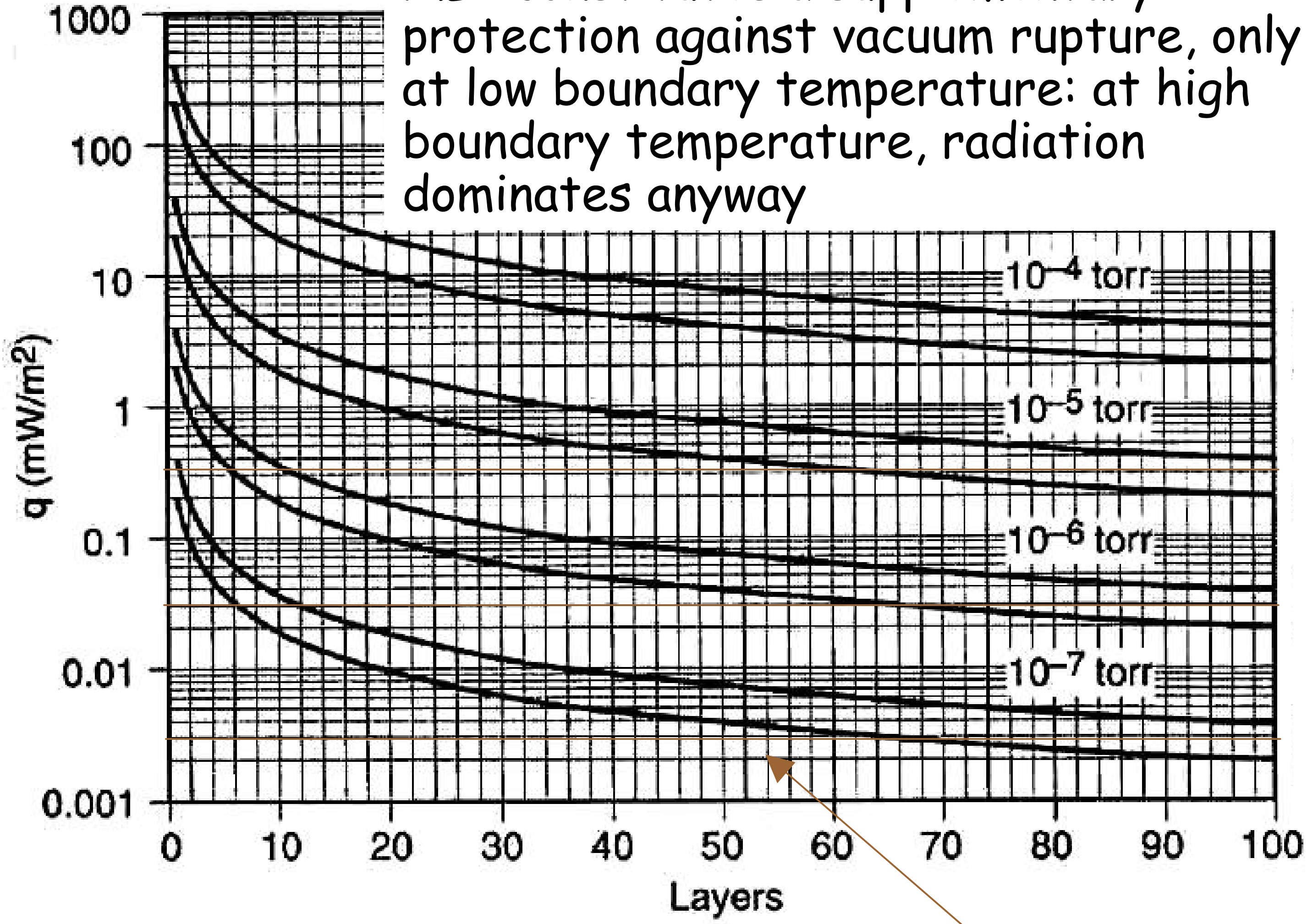
N = 15 cm^{-1}

T_c= 4.2K, ε = 0.03

MLI and residual pressure

MLI constitutes a supplementary protection against vacuum rupture, only at low boundary temperature: at high boundary temperature, radiation dominates anyway

interstitial gas: nitrogen



300 K -> 77 K
77 K -> 4.2 K

300 K -> 77 K
77 K -> 4.2 K

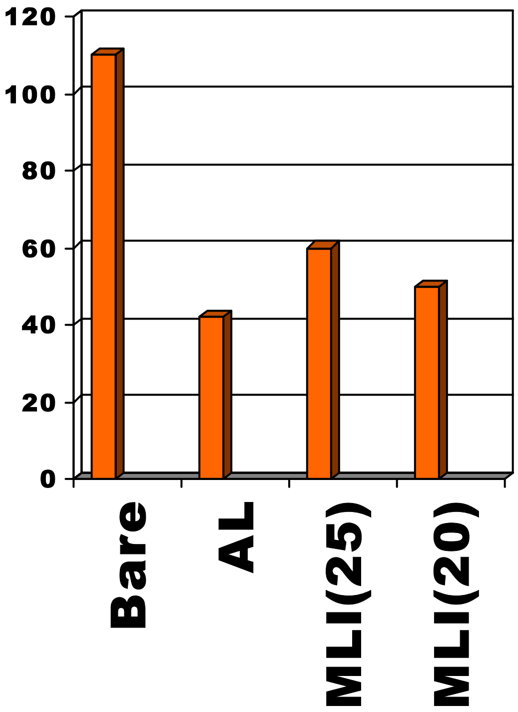
300 K -> 77 K
77 K -> 4.2 K

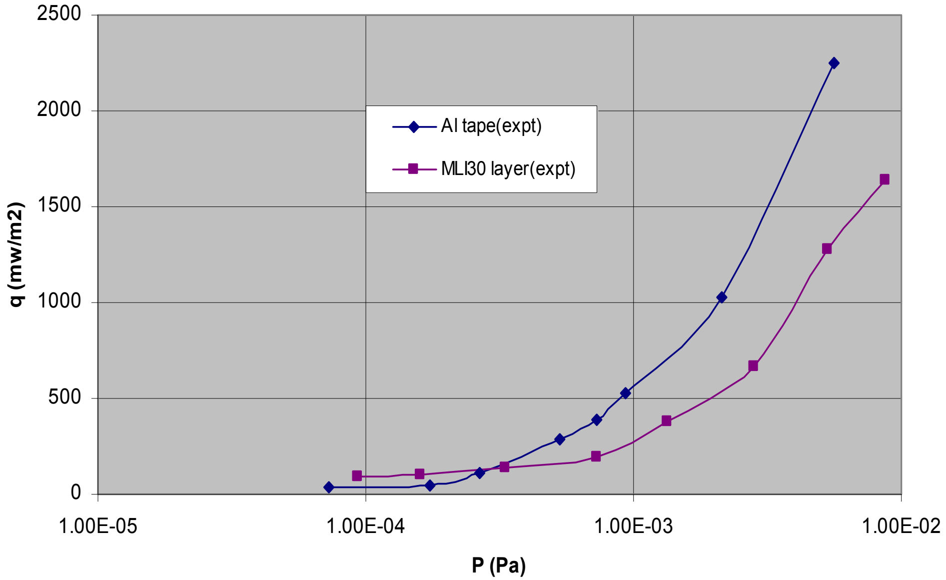
300 K -> 77 K
77 K -> 4.2 K

Kennard's law

Performance Comparison of Al tape and MLI w.r.t Vacuum (80- 4.2 K)

LOAD (mw/m2) : 80- 4.2 K





Heat load measurement repeated with different vacuum (5x 10-7 Torr to 5 x 10-4 Torr) by using a fine leak valve of Pfeiffer

Conclusion : Performance of Al tape is better than MLI if Vacuum is better than 3 x 10-6 Torr

Multilayer Insulation (MLI)

CRYOGENIC INSULATION

A. FOAM INSULATION (POLYSTYRENE, POLY URETHENE (PUF)

Aparant thermal Conductivity : 20 - 35 mw/ m.K

B. POWDER : (Evacuated Perlite Powder)

Aparant Thermal Conductivity : 1- 2 mw/ m. K

No radiation.

C. VACUUM ALONE (Only Radiation)

Ka : 5mw/ m. K at 10 -6 torr

C. MLI (MULTILAYER) : Highly reflective Film with low conductivity spacer)

Ka = .002 - .005 mw/ m. K

All heat transfer is Minimised $Q_r = \sigma e_1 A_1 (T_2^4 - T_1^4)/2 (N +1)$

Typical heat inleaks in a cryostat

…between flat plates, at vanishingly low temperature

	[W/m^2]
Black-body radiation from 290 K	400
Black-body radiation from 80 K	2.3
Residual gas conduction (100mPa helium) from 290 K	19
Residual gas conduction (1mPa helium) from 290 K	0.19
Multi-layer insulation (30 layers) from 290 K, pressure below 1mPa	0.5-1.5
Multi-layer insulation (10 layers) from 80 K, pressure below 1mPa	0.05
Multi-layer insulation (10 layers) from 80 K, residual pressure 100mPa	0.2

Residual Gas conduction (100mPa) from 80 K	6.8
Residual gas conduction (1mPa) from 80 K	0.07

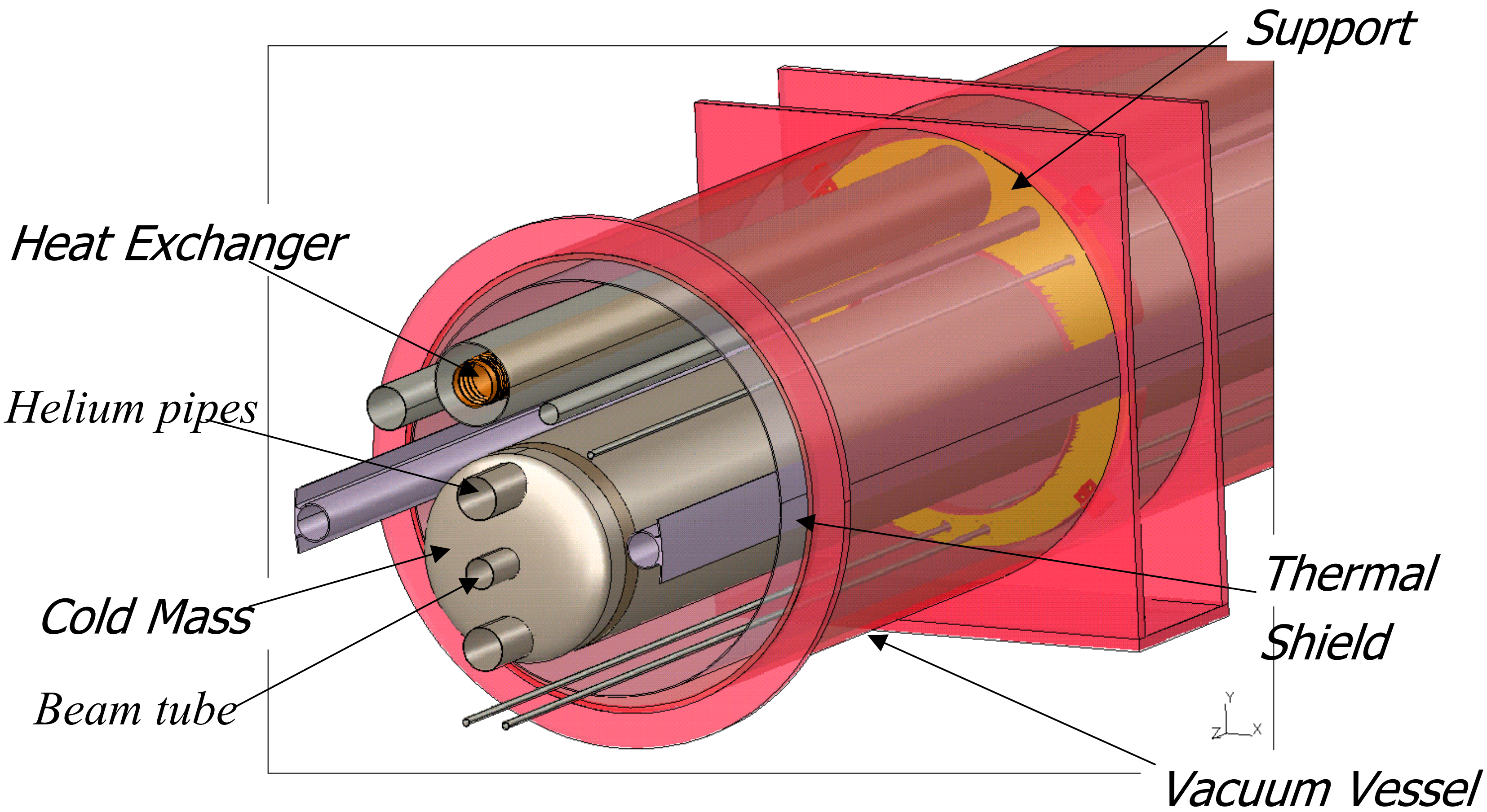
A. Thermal Conductivity Integrals of common material

4.2 K To	80 K	300K
OFHC Copper	600 w/cm	1600
AISI 304 SS	3.49	30.6
G - 10	0.18	1.53

B : Emissivity of Technical materials

	300- 77K	77- 4.2K
SS as found	0.34	0.12
SS Mech polished	0.12	0.07
SS Electropolished	0.10	0.07
SS+ Al foil	0.05	0.01
Al Mech polished	0.10	0.06
Copper, Mech polished	0.06	0.02

A superconducting accelerator magnet



A super-conducting magnet built by Fermilab for LHC at CERN in Geneva, Switzerland

Consists of layers from cold inside to warm outside -- magnet, inner pipes, thermal insulation, steel vacuum container

Summary of Heat Load Budget For Accelerator Cryomodule/ Distribution line

Input Parameters :1. **Total length of Module (Meter)**

2. **Surface area per unit length (M2/ M)**
3. **Weight of Cold Mass/ m length**
4. **Dynamic Load : Rf power, Magnet**

Whether we Need intermediate thermal shield ?

1. **Option one (No) : 30 layers of MLI , Q = 2 x 1.5 = 3W**
2. **80 K Shield (No MLI) : Q = 2 x .15 = 0.3 (one order less)**
3. **Same with one layers Al Foil q = 2 x .02 = 0.04 W**

Vacuum Level ?

10 -5 mbar Qg = 2x .07 = 0.15 W

10-3 mbar , Qg = 2 x 7 = 14 W (not acceptable)

Heat load Budget- 2

We have Seen 80 K shield+ 1 layers Al Foil and Vacuum better than 10- 5 mbar, Load from Radiation and gas conduction per m length

Qg+ Qr = .03 + 0.15 = 0.19 W

Same with vacuum 10-3 mbar, Q = 15 W

If we wrap with 10 layers of MLI

Q = 4 W (Stiil higher but better than 15 W)

Generally Vacuum is better than 10-6 mbar unless there is a leak : This further reduces the heat load

Conclusion : 80 K Shield + 10 layers MLI + vacuum better than 10-5

What About Conduction load ?

Heat load Budget- 3

Once we know the weight, we can easily calculate the Cross sectional Area Required for the load either in Compression or Tension mode

Two alternatives 1. SS 2. G 10

Thermal Interception (80 K) is required or not

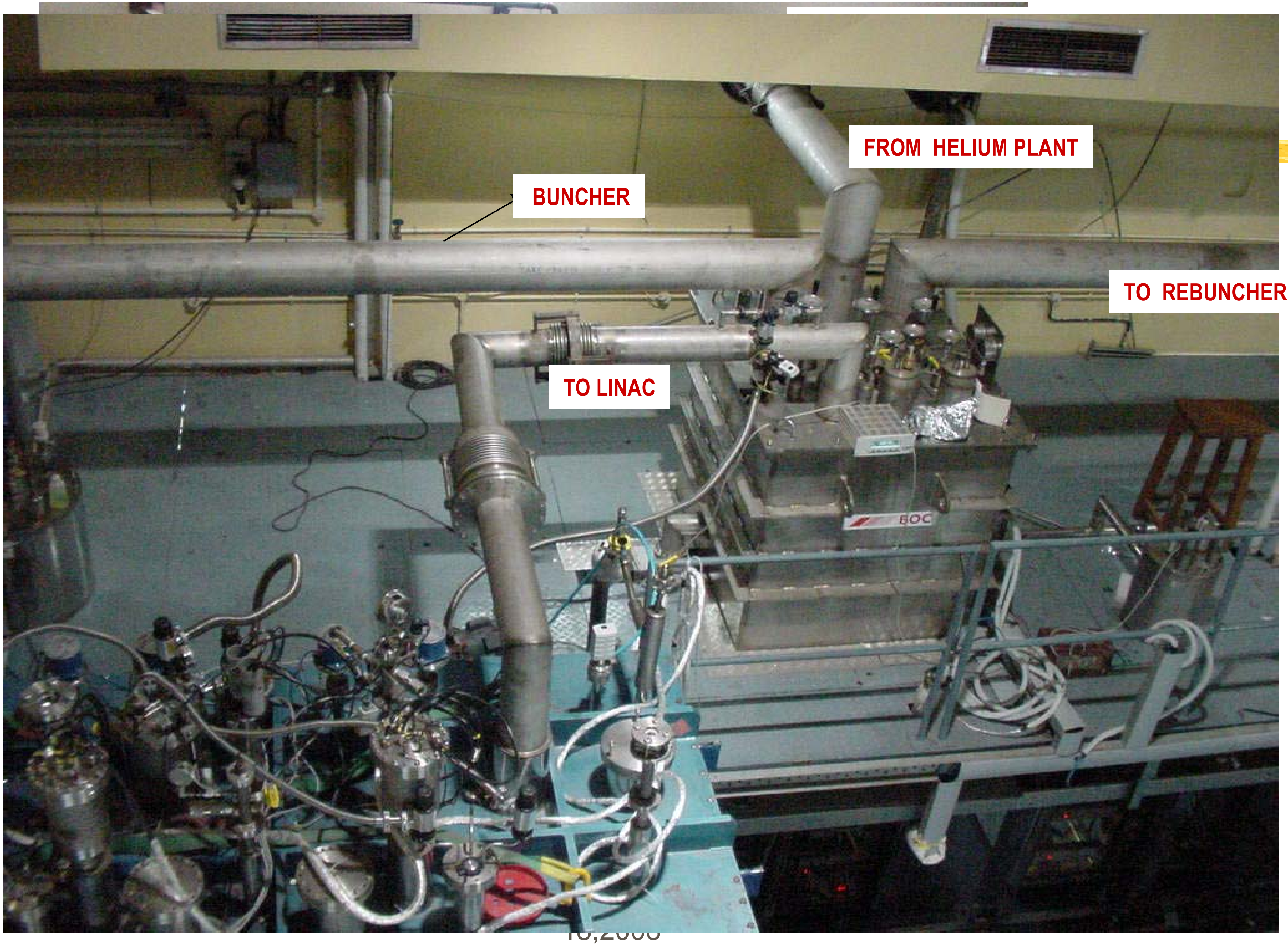
	SS	**G-10**
KdT (: 300- 4.2)	30.6 W/cm	**1.53**
KdT (80- 4.2)	**3.49**	0.18

Yield strength for both is almost same , so Cross sectional area remains same

G- 10 is even better without thermal interception than SS with 80 K thermal interception

G- 10 Difficulty on Fabrication, Cascade better and case to case

LIQUID HELIUM DISTRIBUTION NETWORK


FROM HELIUM PLANT

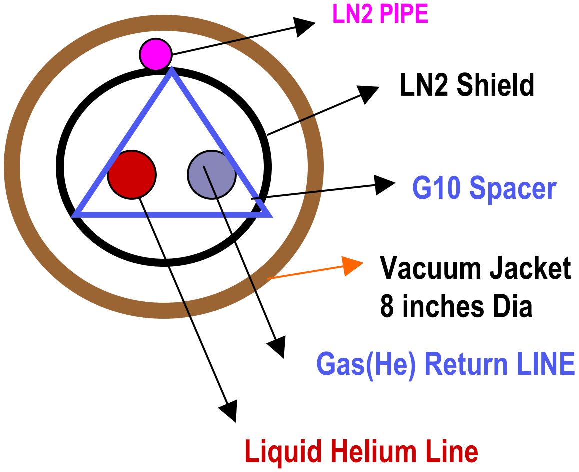
BUNCHER

TO REBUNCHER

TO LINAC

Specification of Lhe Distribution Network

- **Four Valve boxes** : **Weka valves, Vacuum break, Instrumentation, Rectangular & Circular shape, LN2 Shielded**
- **Vacuum jacketed, MLI insulated, LN2 shielded Line, 40 meters length.**
- **Demountable Joints to isolate line from Cryostats**
- **Line without LN2 shielded**

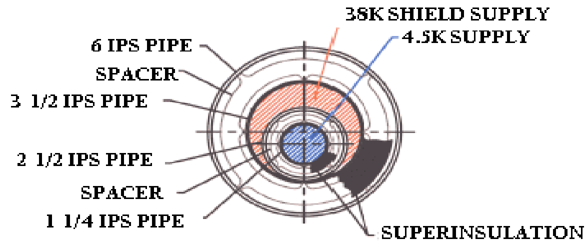


- **MEASURED LOAD : 21 W in 23 meters le**
- **Actual Load in Line : 0.51 W/ m**

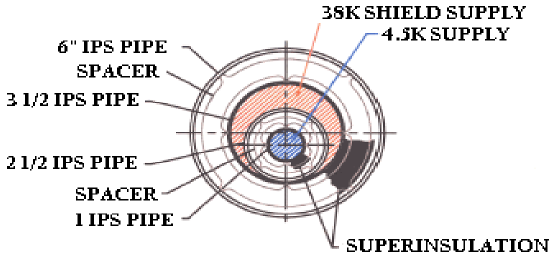
LIQUID HELIUM VALVE BOXES

JLab Designed MSU Distribution Box

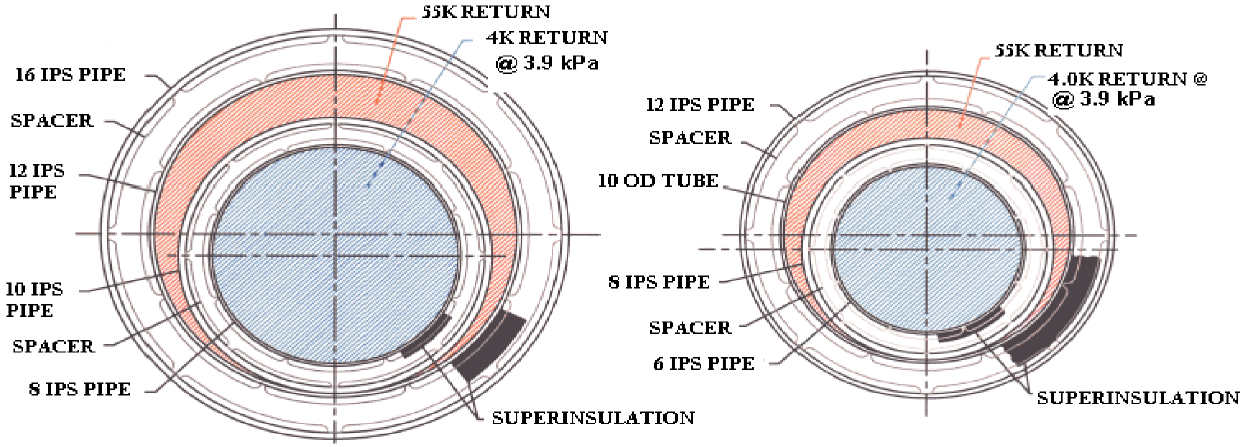
Transfer Line Cross sections (SNS)



CHL SUPPLY TRANSFER LINE



LINAC SUPPLY TRANSFER LINE



CHL RETURN TRANSFER LINE

LINAC RETURN TRANSFER LINE

JLab Transfer Line Bayonets

Designing and Developing any cryogenic apparatus like cryostats, experimental dewar require good knowledge of material properties at low temperature.

Why do you need to know ?

Most of the properties may vary by orders of magnitude between ambient and cryogenic condition

Why does the Property vary?

At room temperature the atoms are vibrating very rapidly. Higher the Temp.greater is the amplitude of Oscillation. As the substance is cooled down, the amp. Of atomic vibration is reduced (thermal energy reduces)

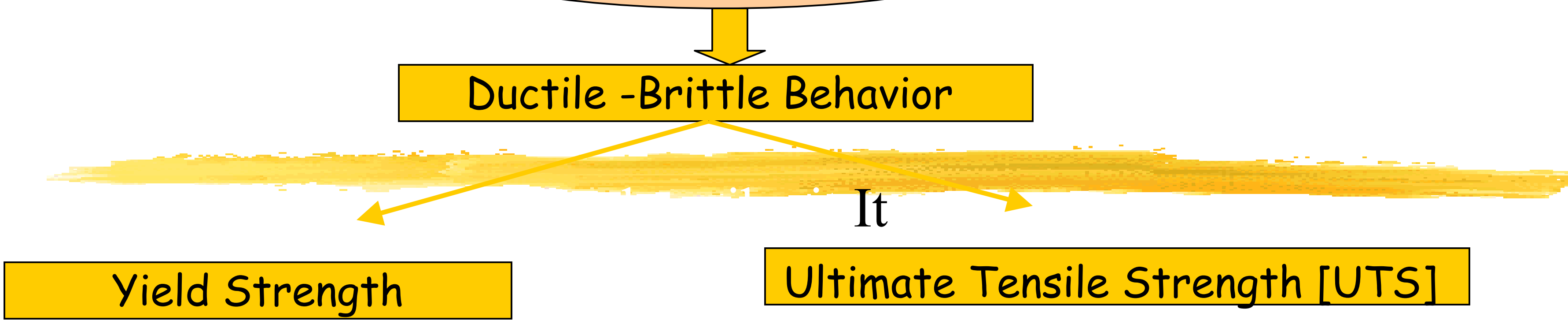
Thus all the properties which dependent on interactions with the atomic vibration (or Lattice) will change at low temperature

The decrease in the various types of interaction will show up as variation in the mechanical properties. Thermal properties and electrical properties

Properties Concerned

- Mechanical
  - **Ductility**
  - **Yield Strength**
  - **Ultimate Tensile strength**
- Electrical
  - **Not so important as far as cryogenics is concerned**
- Thermal
  - **Thermal Contraction**
  - **Thermal Conductivity**
  - **Specific Heat**

Mechanical Properties

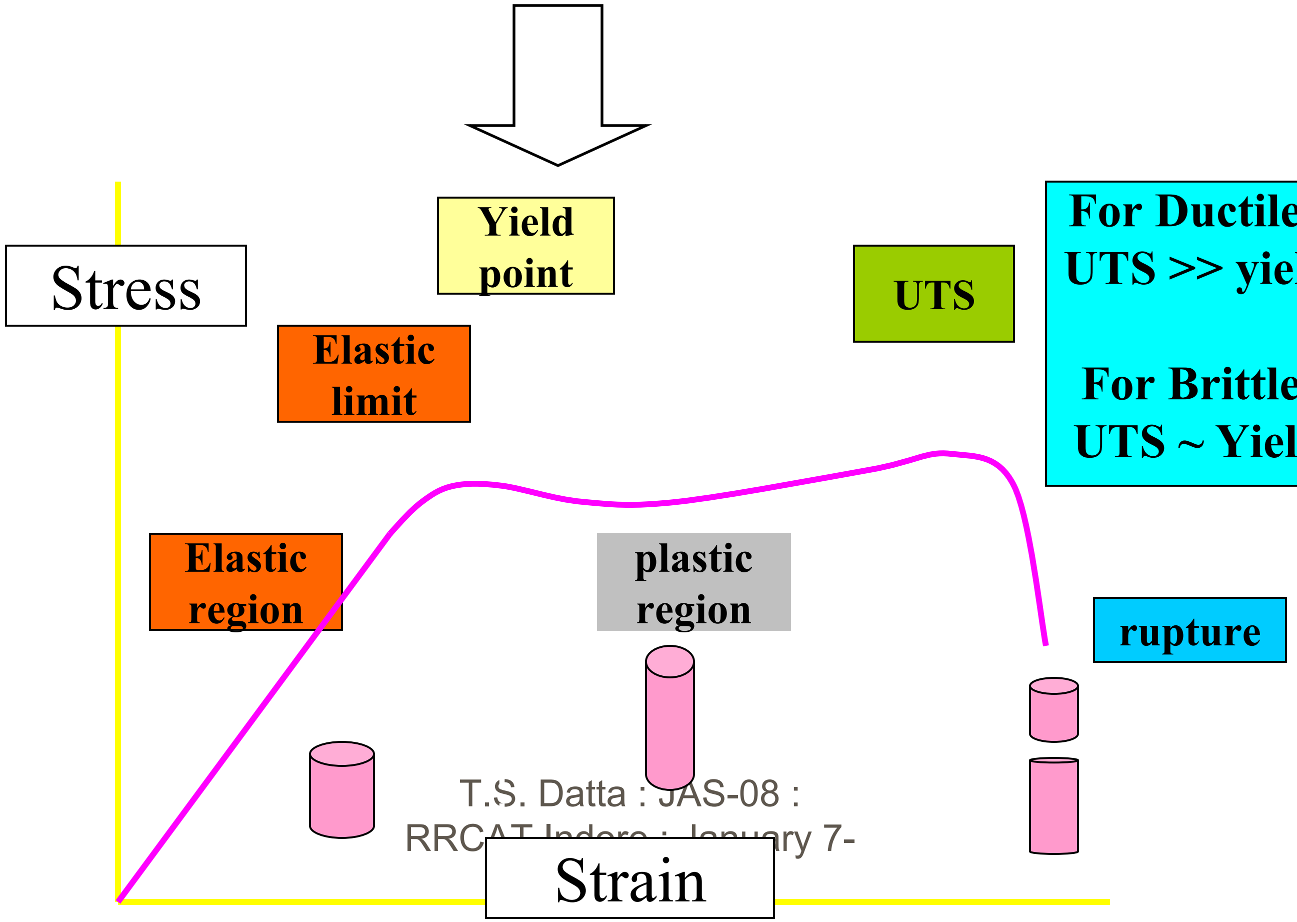


Ductile -Brittle Behavior

It

Yield Strength

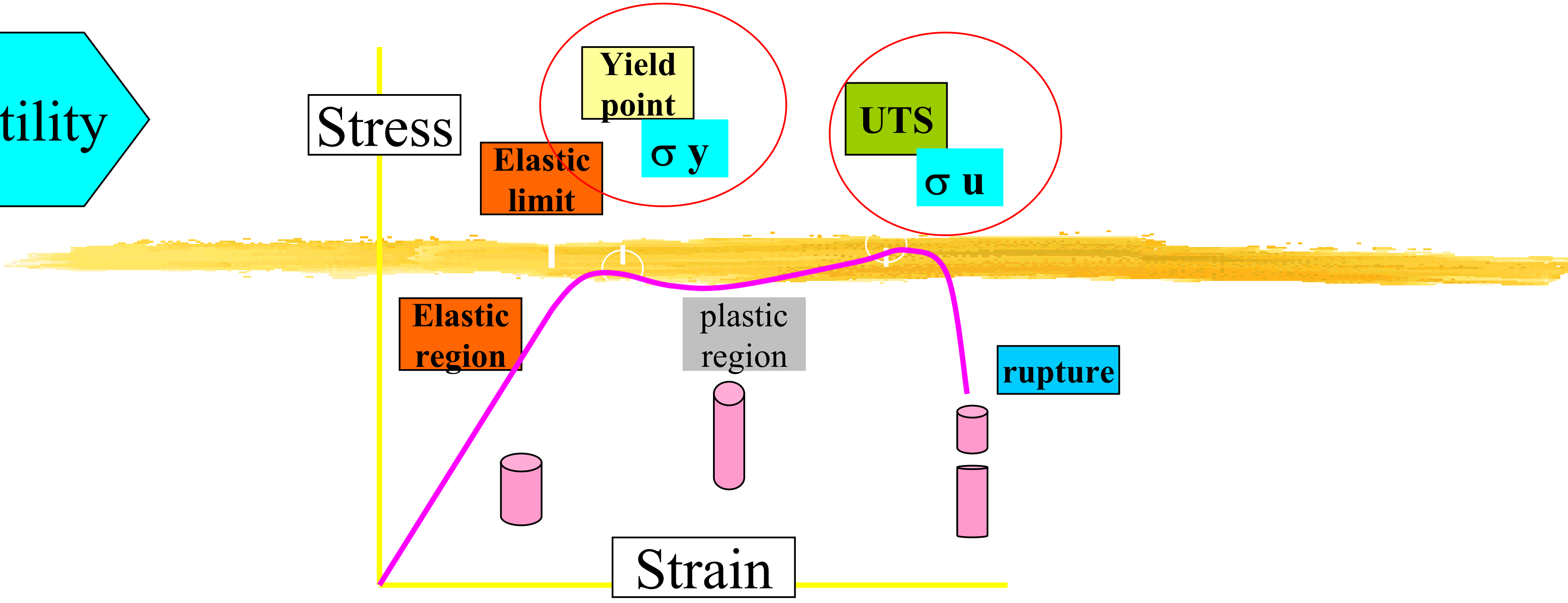
Ultimate Tensile Strength [UTS]



For Ductile Material:
UTS >> yield Strength

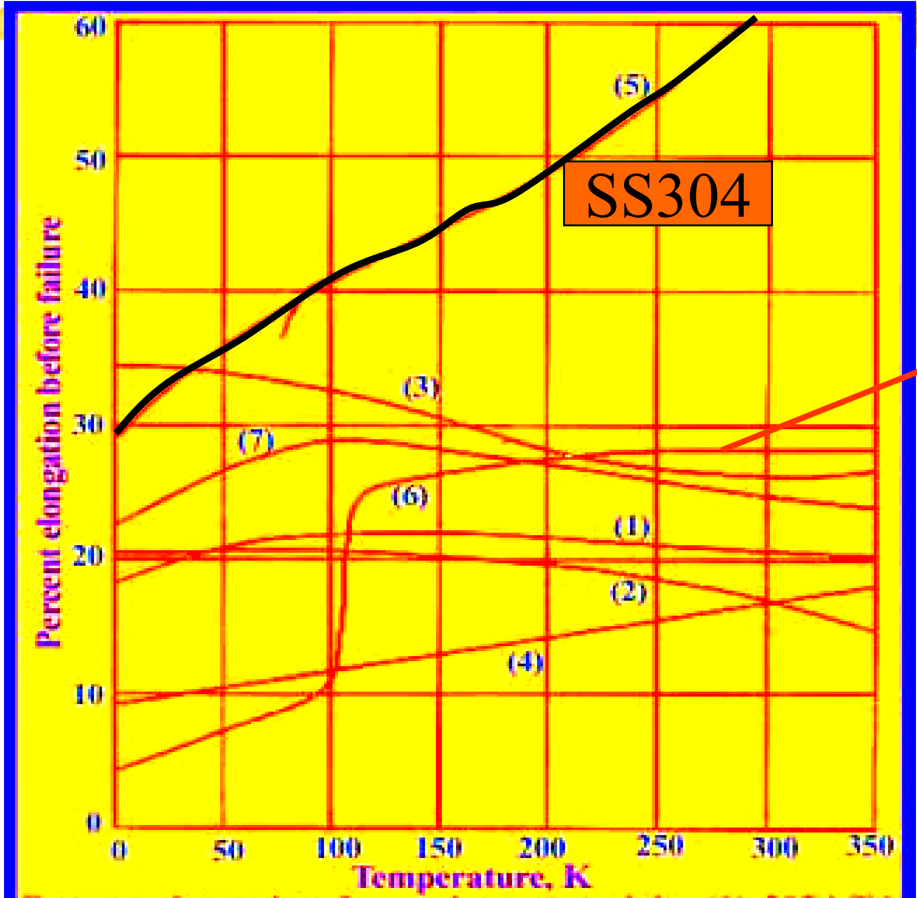
For Brittle Material:
UTS ~ Yield Strength

Ductility



N/m2	σ y (4.2K)	σ u (4.2K)	σ y (80K)	σ u (80K)	σ y (300K)	σ u (300K)
SS304	**547**	**1660**	**460**	**1509**	**406**	**659**
Al -6061	**345**	**497**	**332**	**422**	**282**	**312**
OFHC Cu	**90**	**418**	**88**	**360**	**75**	**222**
G-10	**758**	**758**	**703**	**703**	**414**	**414**

Elongation Before Failure



SS304

Carbon Steel Became Brittle at 120 K

Percent elongation for various materials: (1) 2024-T4 aluminium; (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel; (7) 9 percent Ni steel.

Thermal Properties

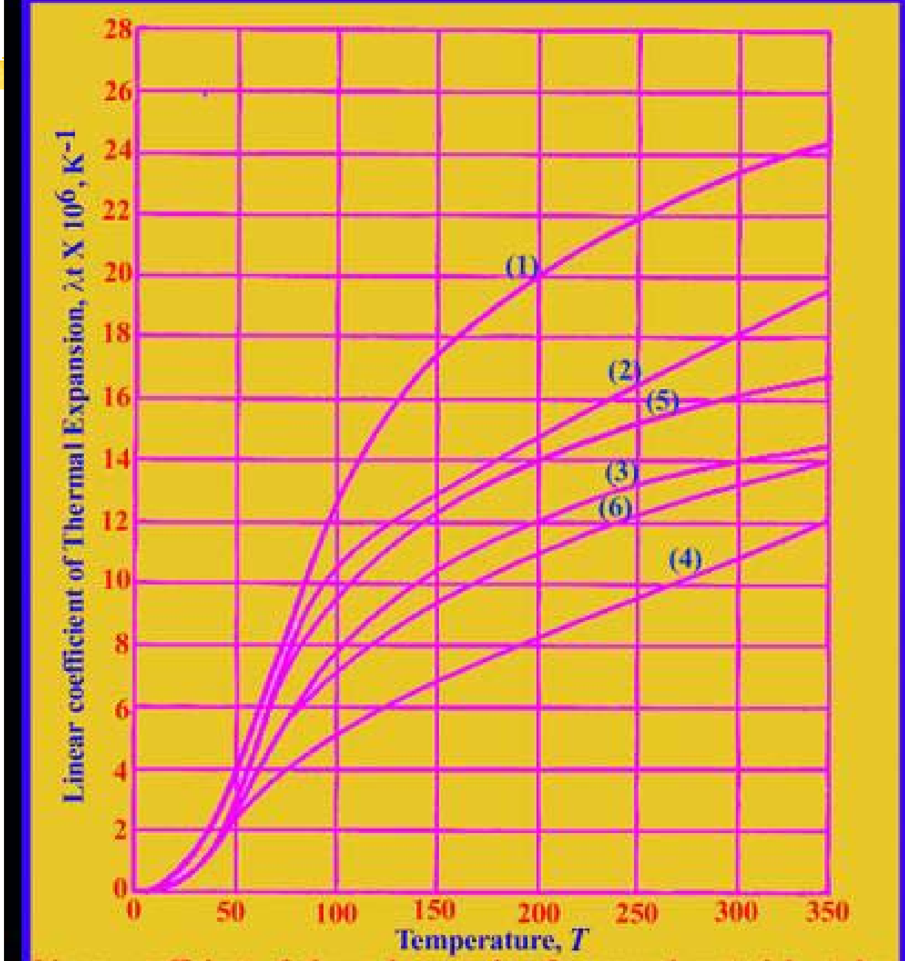
Thermal Contraction

Fractional Change in length per unit change in Temp.

Why do U require “α “ ?

Thermal Contraction of different material vary considerably. Therefore differential thermal contraction has to be taken care of

Thermal expansion Coefficient



Linear coefficient of thermal expansion for several materials at low temperatures (1) 2024-T4 aluminium; (2) beryllium copper;(3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel.

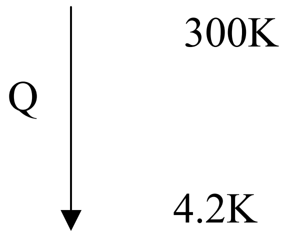
Thermal Properties

Thermal Contraction

Thermal Conductivity

Heat transfer rate per unit area per unit thermal gradient which causes the heat flow

Why Do You Require "K" ?

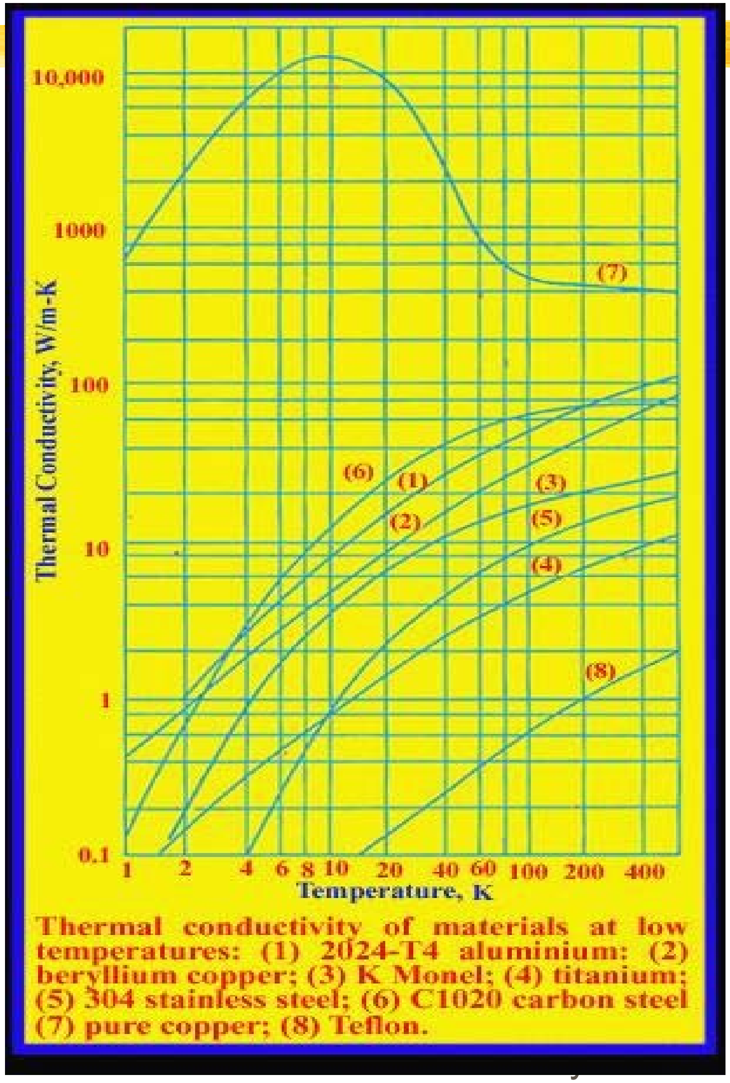


300K

Q

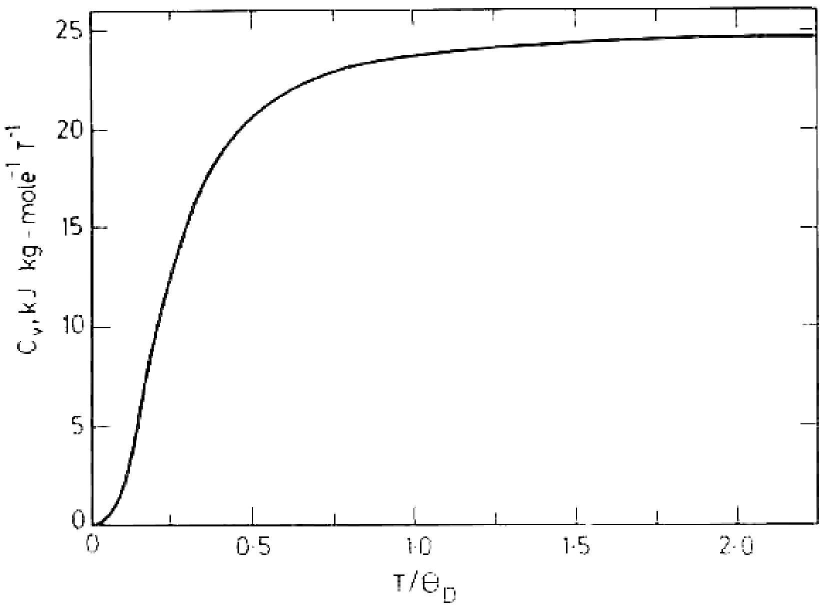
4.2K

Thermal Conductivity



Thermal conductivity of materials at low temperatures: (1) 2024-T4 aluminium: (2) beryllium copper; (3) K Monel; (4) titanium; (5) 304 stainless steel; (6) C1020 carbon steel (7) pure copper; (8) Teflon.

Specific heat of structural materials



C_v heat capacity per kg mole approximately described by the

Debye function

$$C_v = 9R\left(\frac{T}{\theta_D}\right)^3 \int_0^{\theta/T} \frac{x^4 e^x}{(e^x - 1)^2} dx$$

θ_D Debye temperature, a material's property

Nb: T_c/θ_D=0.04

Material	θ_D (K)	Material	θ_D (K)
Aluminium	385	Lead	85
Carbon (graphite)	760	Nickel	440
Copper	310	Niobium	265
Gold	180	Silver	220
Indium	105	Titanium	355
Iron	460	Quartz	255

Thermal Properties

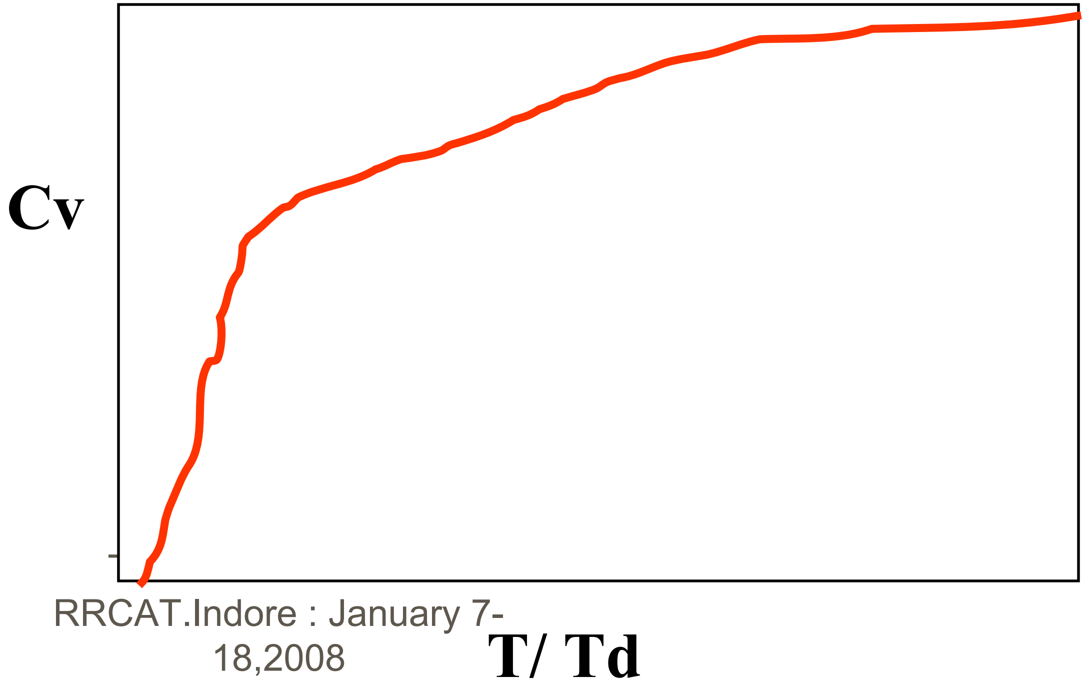
Thermal Contraction

Specific Heat

Thermal Conductivity

Energy Required to change the temperature of 1 g substance by one degree

Why do you require "Cp"?



Role of Specific Heat on Cool Down

To cool 1 gm mass from Room temperature to 4.2 K

Q = m Cp (300- 4.2) J , Cp = f(T)

At low temperature Cp is less, less heat to be extracted at low Temperature

How much Cryogen (Mc) is required to cool 1 Kg mass

Mc. L = m. Cp (300- 4.2)

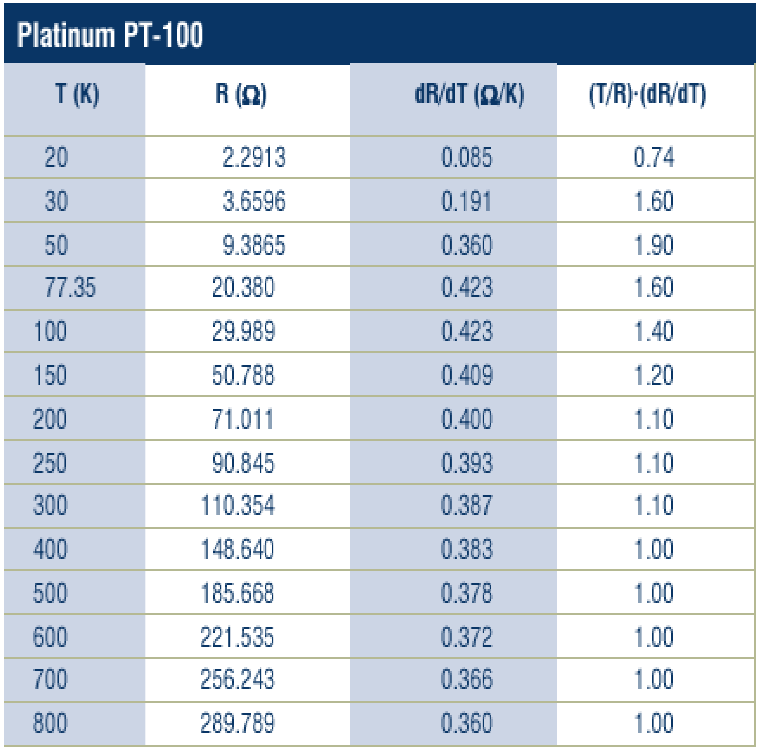
Requirement of Cryogen To cool Down

Material	300- 4.2 (Lhe)	78- 4.2 K	With cold gas (300- 4.2)	300-80 (LN2)
SS	33 litres/ kg	1.44 litres/kg	0.80 litres/kg	0.53 litres/kg
Al	66	3.2	1.60	1.0

Measuring Instruments at Low Temperature

- **Temperature** : **Platinum, Diode, Thermocouple**
- **Liquid Level** : **Capacitance, Superconducting, Differential Pressure**
- **Flow rate** : **Orifice meter, Turbine flow**
- **Quality** : **Capacitance Type (Liquid/ gas)**

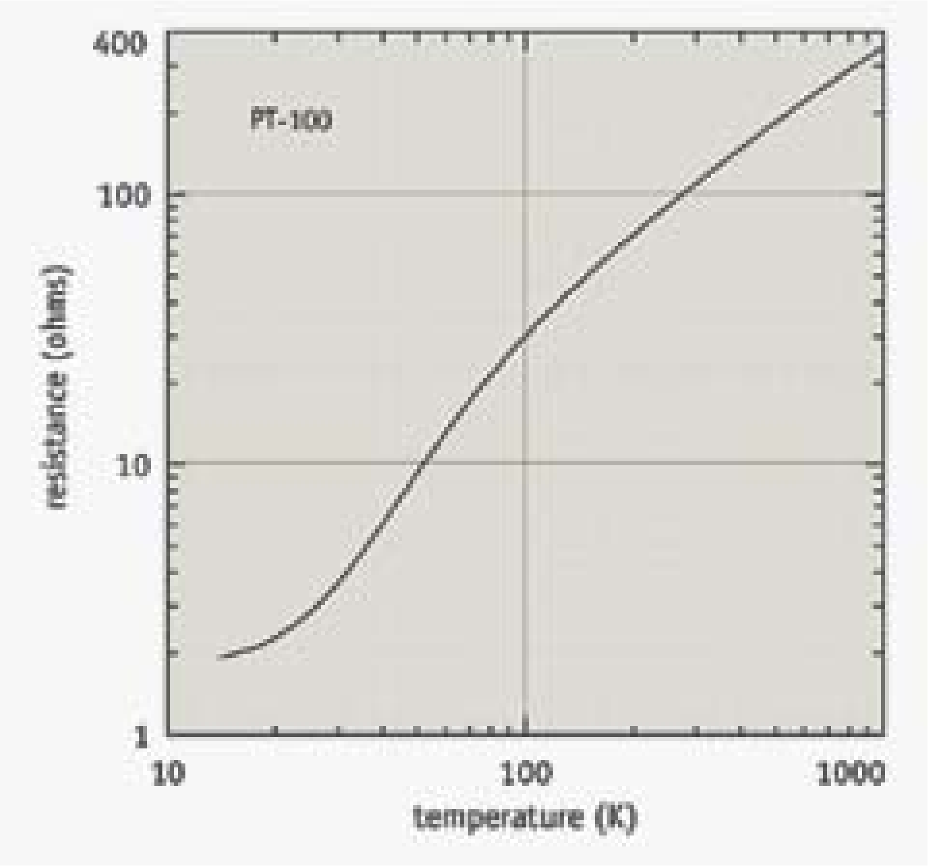
Platinum Resistance Thermometer

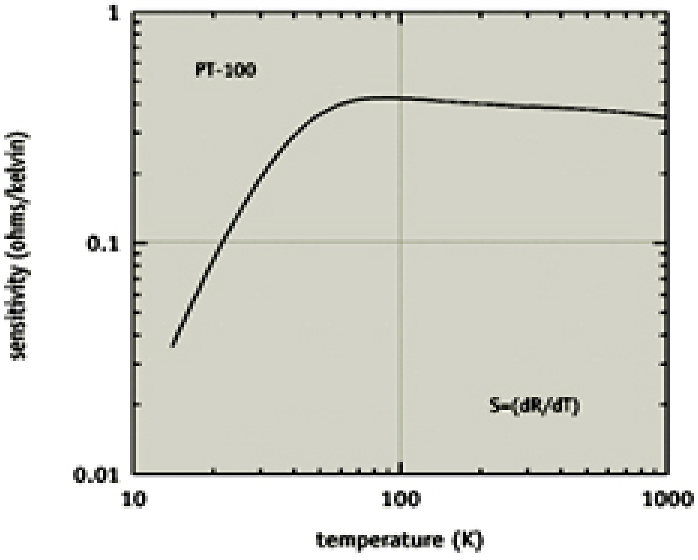


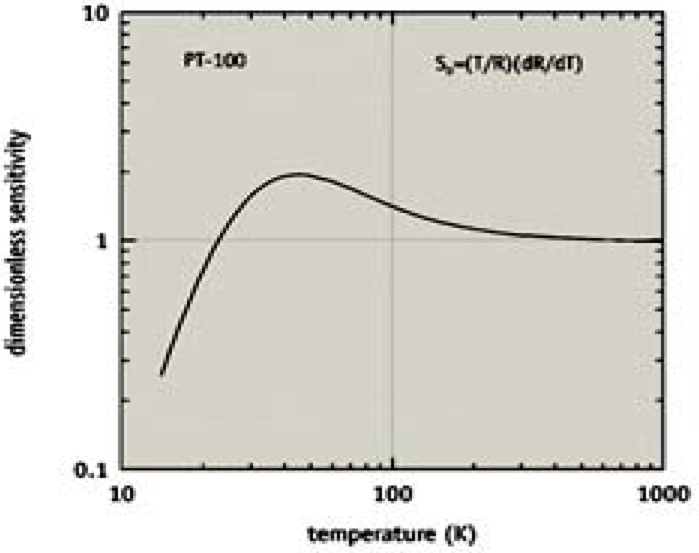
Platinum PT-100

T (K)	R (Ω)	dR/dT (Ω/K)	(T/R)·(dR/dT)
20	2.2913	0.085	0.74
30	3.6596	0.191	1.60
50	9.3865	0.360	1.90
77.35	20.380	0.423	1.60
100	29.989	0.423	1.40
150	50.788	0.409	1.20
200	71.011	0.400	1.10
250	90.845	0.393	1.10
300	110.354	0.387	1.10
400	148.640	0.383	1.00
500	185.668	0.378	1.00
600	221.535	0.372	1.00
700	256.243	0.366	1.00
800	289.789	0.360	1.00

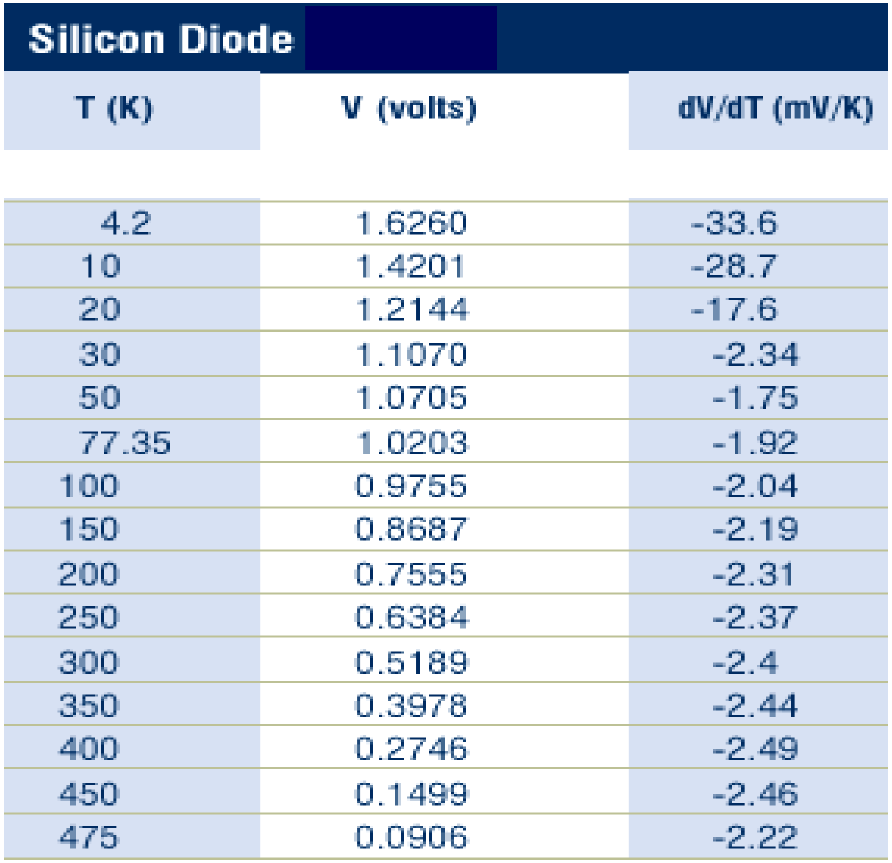
Platinum Resistance Thermometer







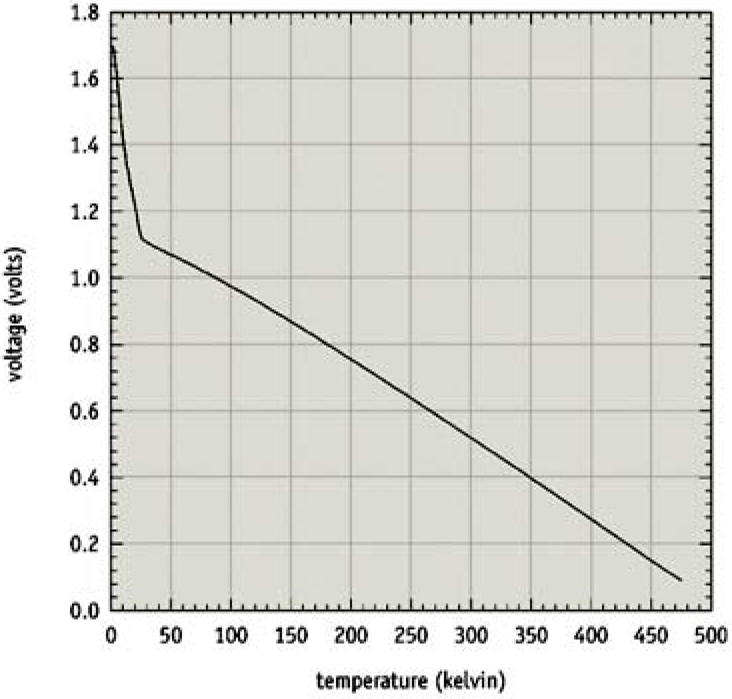
Silicone Diode Thermometer

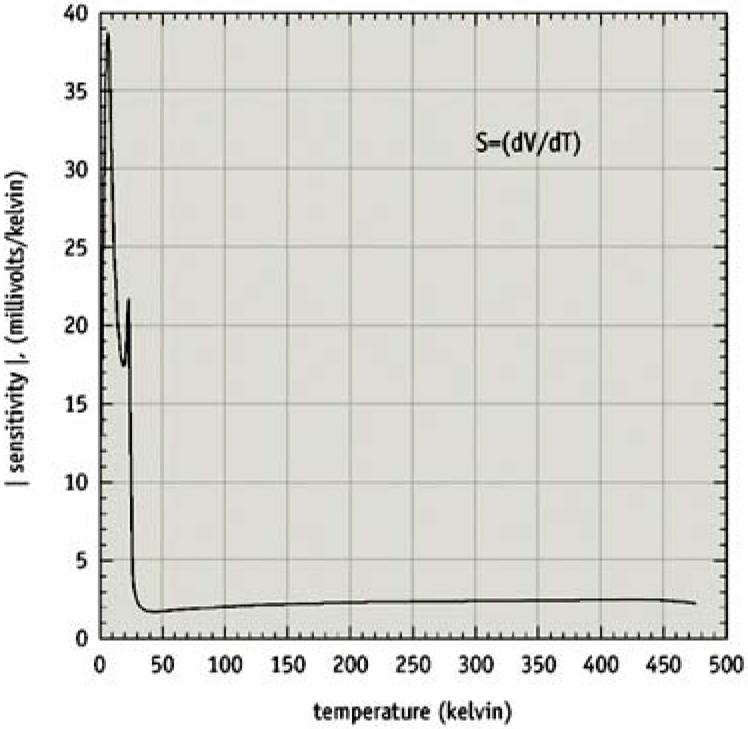


Silicon Diode

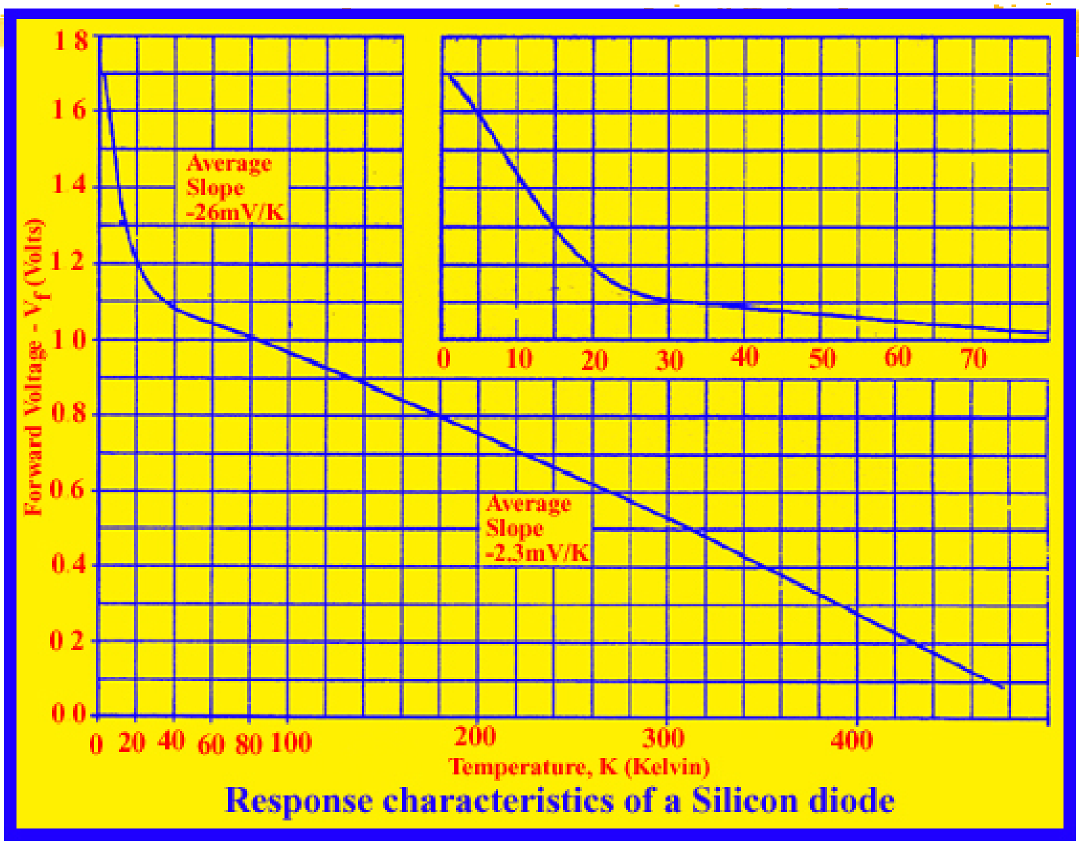
T (K)	V (volts)	dV/dT (mV/K)
4.2	1.6260	-33.6
10	1.4201	-28.7
20	1.2144	-17.6
30	1.1070	-2.34
50	1.0705	-1.75
77.35	1.0203	-1.92
100	0.9755	-2.04
150	0.8687	-2.19
200	0.7555	-2.31
250	0.6384	-2.37
300	0.5189	-2.4
350	0.3978	-2.44
400	0.2746	-2.49
450	0.1499	-2.46
475	0.0906	-2.22

Silicone Diode Thermometer

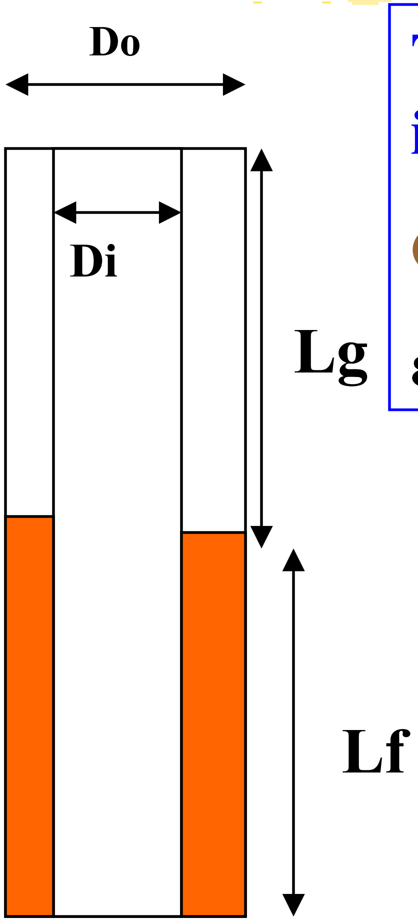




Silicone Diode Thermometer



LIQUID LEVEL METER



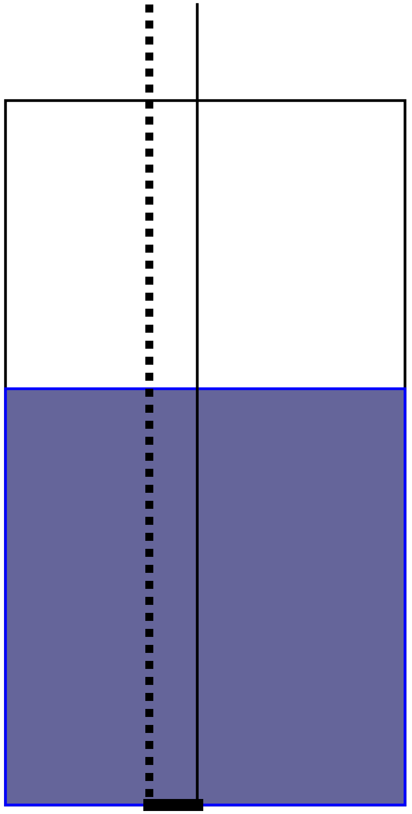
The capacitance of concentric Cylinder tube is

$$C = C_f + C_g = 2\Pi(L_f \varepsilon_f + L_g \varepsilon_g)/\ln(D_o/D_i)$$

ε_f, ε_g : Dielectric Constant for liquid & Gas

This is popular for Liquid nitrogen but not for liquid Helium

Liquid level meter by Superconducting wire



Nb- Ti Conmmercial wire (Tc = 12 K)

The length of the wire immersed in liquid helium will be superconductor. Resistance will be only for (L- Lf) length of wire. By measuring resistance and comparing with total resistance without liquid we will be able to calculate length of liquid helium level

HELIUM GAS STORAGE TANK AT IUAC

Storage Capacity : 2 x 40 + 1 x 60 M3

Op. Pressure : 240 psig

INVENTORY 2100 M3

Eq : 320 Cylinders

Thank You

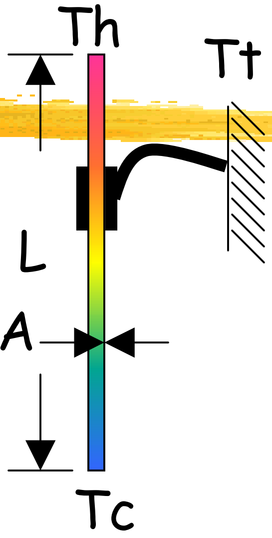
Thank You

Time-independent conduction

1D, constant A

$$G = \left(\int_{x_1}^{x_2} \frac{dx}{A(x)}\right)^{-1}$$

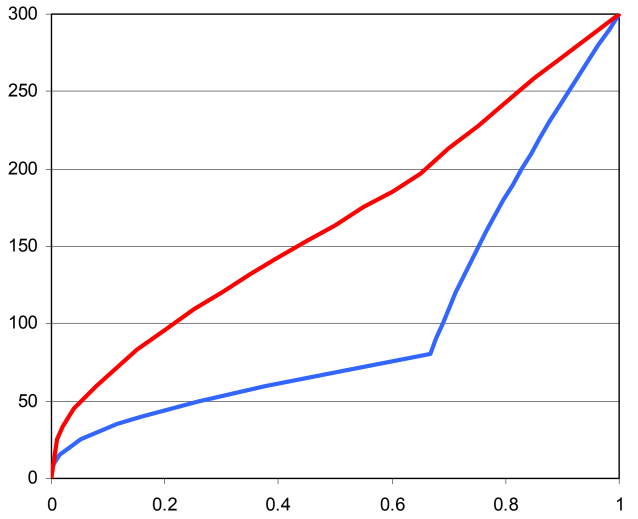
$$\dot{Q} = -k(T)A\frac{dT}{dx} \longrightarrow \dot{Q} = \frac{A}{L}\int_{T_c}^{T_h} k(T)\,dT$$



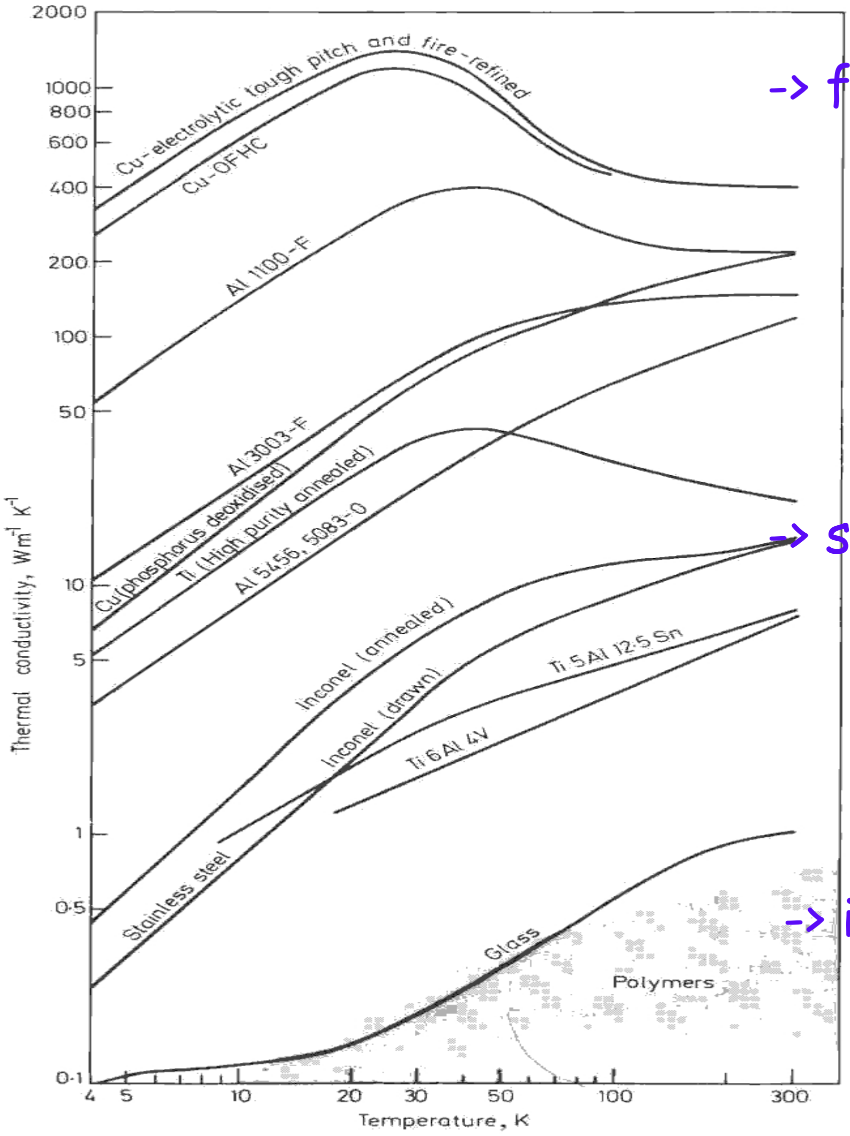
$$\int_{T_c}^{T_h} k(T)\,dT = \text{material's property}$$

Heat flux reduction by intermediate temperature thermalization:

Temperature profile T(x) of st.steel bar with thermalization 2/3 of length at 80K



Conductivity of solids



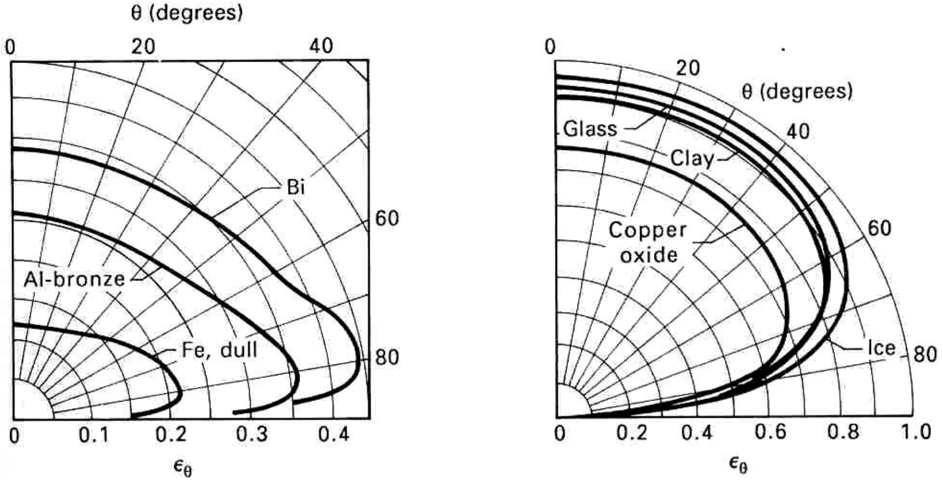
-> form for pure and alloyed metals

-> st.steel

-> increase with T

Emissivity and materials

Real emissivities depend on direction and wavelength



(a) Metal surfaces.

(b) Electric nonconducting surfaces.

- **Polished metals: small ε**
- **Insulators: large ε**
- **ε = ε(T): for real metals, ε~T at low T**
- **Coatings: since ε related to surface, not bulk, resistance, => lower limit on thickness of reflectors ($\rho \cong 1$ above ~40nm)**

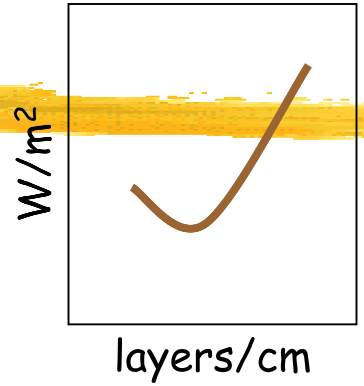
Drude law for ideal metal

$$\varepsilon(\lambda, T) = 0.365\sqrt{\frac{\rho(T)}{\lambda}}$$

MLI: effective conductivity

Effective conductivity $k=aT+bT^3$

Heat transfer rate $q=k/e\,\Delta T$, e = thickness



Optimal density: 10-20 cm^{-1}

Low boundary temperature:

77 K-> 4K

heat transfer rate determined by aT, not by radiation

1 single aluminized foil is sufficient in high vacuum

in bad vacuum, MLI provides sufficient insulation

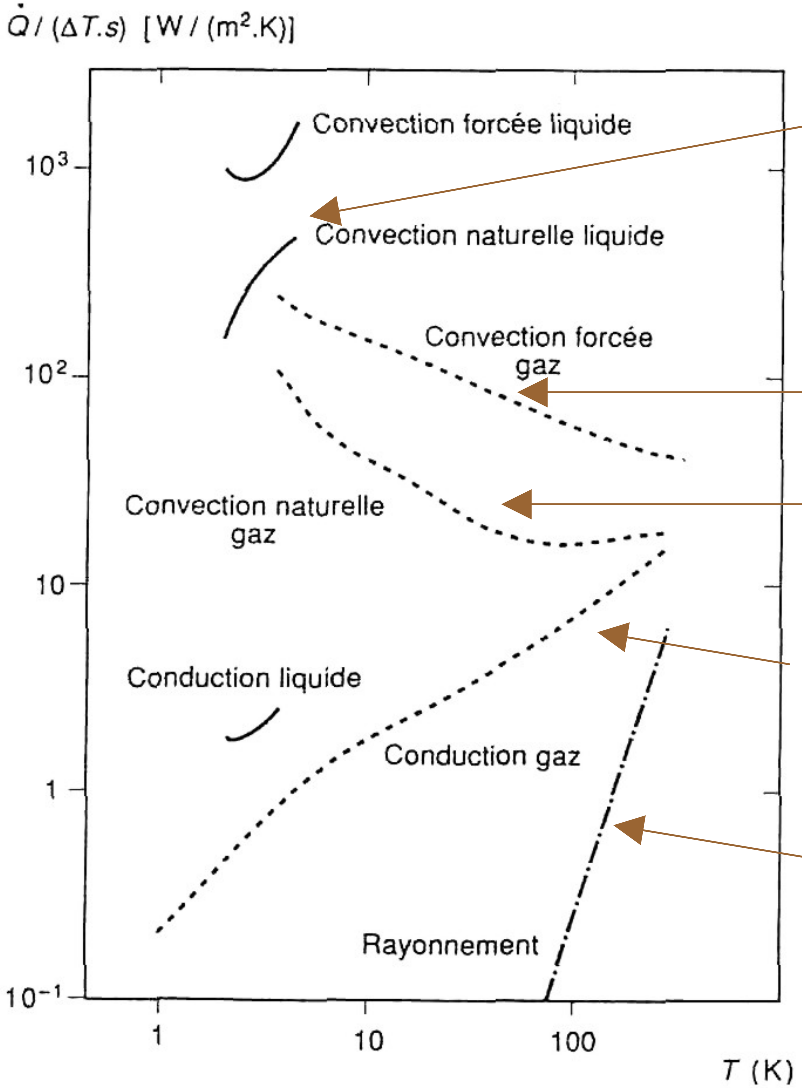
High boundary temperature:

300 K-> 77K

heat transfer rate determined by radiation important reduction with layer's number

bad vacuum: radiation dominates anyway

Cryogenic heat transfer modes



PeakNucleate BoilingFlux

increase of Re for decreasing T

increase of Gr for decreasing T, $h \sim T^{-1/2}$

$k \sim T^{0.7}$

T^3

Conductivity of solids

- Heat carriers: phonons ($k \sim T^3$) and electrons ($k \sim T$)
- Good electrical conductors = good thermal conductors (but not the best ones !)
- Hinder heat transmission at low T ? **DEFECTS**

  difference between pure and alloyed

  effect of modification of the defect content: magnetic impurities, annealing, cold work

- Hinder heat transmission at high T ? **Phonon-phonon**

  Phonon-electron

  no difference between pure and alloyed metals

T behaviour well known