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 :

T.S. Datta : JAS-08 :
RRCAT.Indore : January 7-18,2008
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**

- **LIQUEFIER**
- **DEWAR**
- **Storage**

**CRYOSTAT**

**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

<table>
<thead>
<tr>
<th>Property</th>
<th>He</th>
<th>H₂</th>
<th>N₂</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point</td>
<td>4.2K</td>
<td>20K</td>
<td>78K</td>
<td>373K</td>
</tr>
<tr>
<td>Density</td>
<td>0.12kg/liter</td>
<td>0.07kg/litre</td>
<td>0.81kg/litre</td>
<td>1kg/litre</td>
</tr>
<tr>
<td>Heat of Vaporisation</td>
<td>20KJ/kg</td>
<td>428</td>
<td>198</td>
<td>2250</td>
</tr>
<tr>
<td>Liquid evaporated on</td>
<td>140 l/hr</td>
<td>12 l/hr</td>
<td>2.2 l/hr</td>
<td>0.16 l/hr</td>
</tr>
<tr>
<td>100 W Heat input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 W HEAT LOAD EVAPORATES 34 LITRES Lhe in ONE DAY

THANKS TO MLI (MULTILAYER INSULATION TECHNOLOGY)

EVAPORATION RATE ONLY 1 LITRES/DAY
HEAT TRANSFER TO CRYO VESSEL/CRYOSTAT

Simple Configuration

Design Goal:
- Reduce Heat Flux from Outside
- Structural Stability
- Avoid Collapsing
- Safety Features

LHe (4.2K)

INSULATION (Radiation)

VACUUM (Gas Conduction)

NECK (Conduction)

Outer Jacket (300 K)

SUPPORT (Conduction)

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The 3 modes of heat transfer

- **Conduction**: heat transported in solids or fluids at rest
  \[ Q = -k(T)A \text{ grad } T \]
  
  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:

\[ Q = K \frac{A}{L} \left( T_h - T_c \right) \]

\[ A_c = \text{Cross sectional area (example for a rod of dia (d), } A_c = \pi \frac{d^2}{4} , \]

\[ \text{Similarly for a pipe of outer diameter d and thickness 't', } A_c = \pi dt \]

\[ L = \text{Length of rod/pipe,} \]

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Conductivity $k_m = F(T)$

$$k_m = \left[ \int \frac{k \,dT}{(T_h - T_c)} \right]$$

$$Q = \left(\frac{A_c}{L}\right) \int k \,dT.$$ 

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

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

**CONDUCTION REDUCED BY;**

1. Low Crosssectional Area
2. Long Length
3. Low conductivity pipe (SS/FRP)
4. Thermal interception
### Thermal conductivity integrals

**Tc=4 K**

<table>
<thead>
<tr>
<th>T&lt;sub&gt;2&lt;/sub&gt; [K]</th>
<th>ETP copper [W cm&lt;sup&gt;-1&lt;/sup&gt;]</th>
<th>Aluminium 1100 [W cm&lt;sup&gt;-1&lt;/sup&gt;]</th>
<th>Austenitic stainless steel [W cm&lt;sup&gt;-1&lt;/sup&gt;]</th>
<th>Glass [mW cm&lt;sup&gt;-1&lt;/sup&gt;]</th>
<th>PTFE [mW cm&lt;sup&gt;-1&lt;/sup&gt;]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>33.2</td>
<td>6.07</td>
<td>0.0293</td>
<td>6.81</td>
<td>4.4</td>
</tr>
<tr>
<td>20</td>
<td>140</td>
<td>27.6</td>
<td>0.163</td>
<td>20.0</td>
<td>16.4</td>
</tr>
<tr>
<td>30</td>
<td>278</td>
<td>59.2</td>
<td>0.424</td>
<td>36.8</td>
<td>32.3</td>
</tr>
<tr>
<td>40</td>
<td>406</td>
<td>96.2</td>
<td>0.824</td>
<td>58.6</td>
<td>50.8</td>
</tr>
<tr>
<td>50</td>
<td>508</td>
<td>134</td>
<td>1.35</td>
<td>84.6</td>
<td>71.6</td>
</tr>
<tr>
<td>60</td>
<td>587</td>
<td>170</td>
<td>1.98</td>
<td>115</td>
<td>93.6</td>
</tr>
<tr>
<td>70</td>
<td>651</td>
<td>202</td>
<td>2.70</td>
<td>151</td>
<td>116</td>
</tr>
<tr>
<td>80</td>
<td>707</td>
<td>232</td>
<td>3.49</td>
<td>194</td>
<td>139</td>
</tr>
<tr>
<td>90</td>
<td>756</td>
<td>258</td>
<td>4.36</td>
<td>240</td>
<td>163</td>
</tr>
<tr>
<td>100</td>
<td>802</td>
<td>284</td>
<td>5.28</td>
<td>292</td>
<td>187</td>
</tr>
<tr>
<td>120</td>
<td>891</td>
<td>330</td>
<td>7.26</td>
<td>408</td>
<td>237</td>
</tr>
<tr>
<td>140</td>
<td>976</td>
<td>376</td>
<td>9.39</td>
<td>542</td>
<td>287</td>
</tr>
<tr>
<td>160</td>
<td>1060</td>
<td>420</td>
<td>11.7</td>
<td>694</td>
<td>338</td>
</tr>
<tr>
<td>180</td>
<td>1140</td>
<td>464</td>
<td>14.1</td>
<td>858</td>
<td>390</td>
</tr>
<tr>
<td>200</td>
<td>1220</td>
<td>508</td>
<td>16.6</td>
<td>1030</td>
<td>442</td>
</tr>
<tr>
<td>250</td>
<td>1420</td>
<td>618</td>
<td>23.4</td>
<td>1500</td>
<td>572</td>
</tr>
<tr>
<td>300</td>
<td>1620</td>
<td>728</td>
<td>30.6</td>
<td>1990</td>
<td>702</td>
</tr>
</tbody>
</table>

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

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Intermediate heat interception

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

No Thermal interception \( Q = 0.24 \, \text{W} \) (3.14 x 2.54 x 1 x 30.6/100)

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

80 K Thermal Interception at 10 Cm, \( Q = 0.27 \, \text{W} \) (3.14 x 2.54 x 1 x 3.49/10)
## Refrigeration properties of cryogens

<table>
<thead>
<tr>
<th>Property</th>
<th>He</th>
<th>N₂</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal boiling Pt</td>
<td>4.2</td>
<td>77</td>
<td>373</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>5.2</td>
<td>126</td>
<td>647</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>2.3</td>
<td>34</td>
<td>221</td>
</tr>
<tr>
<td>Liquid density/ Vapor density*</td>
<td>7.4</td>
<td>175</td>
<td>1600</td>
</tr>
<tr>
<td>Heat of vaporization [Jg⁻¹]</td>
<td>20.4</td>
<td>199</td>
<td>2260</td>
</tr>
<tr>
<td>Liquid viscosity *</td>
<td>3.2</td>
<td>152</td>
<td>283</td>
</tr>
<tr>
<td>Enthalpy increase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>between T₁ and T₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T₁ = 4.2 K</td>
<td>384</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T₂ = 77 K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T₁ = 4.2 K</td>
<td></td>
<td>1157</td>
<td>228</td>
</tr>
<tr>
<td>T₂ = 300 K</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*at normal boiling point

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

Highly effective for self-sustained vapor cooling!
Shielding potential of cold vapours

Pure conduction heat losses evacuated at the coldest temperature

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

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

Heat evacuation across a small \( \Delta T \) thermodynamically much more efficient

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Shielding potential of cold vapours

heat balance, perfect exchange

\[ Q = k(T)A \frac{dT}{dx} - mC_p(T - T_i) \]

self-sustained evaporation of fluid

\[ Q = mL_v \]

\[ Q = \frac{A}{L} \int_{T_i}^{T_2} \frac{k(T)dT}{1 + (T - T_i)C_p/L_v} \]

Thermal conductivity integral

<table>
<thead>
<tr>
<th>Material</th>
<th>([W \text{ cm}^{-1}])</th>
<th>([W \text{ cm}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETP copper</td>
<td>128</td>
<td>1620</td>
</tr>
<tr>
<td>OFHC copper</td>
<td>110</td>
<td>1520</td>
</tr>
<tr>
<td>Aluminium 1100</td>
<td>39.9</td>
<td>728</td>
</tr>
<tr>
<td>AISI 300 st.steel</td>
<td><strong>0.92</strong></td>
<td><strong>30.6</strong></td>
</tr>
</tbody>
</table>
**Conductivity of gases:**

### Molecular:
- \( \lambda = 115 \cdot \frac{\mu}{p} \sqrt{\frac{T}{M}} \)
- Mean free path vs wall distance \( L \)
- \( p \) proportional to \( p \)
- \( q \) independent from \( L \)

<table>
<thead>
<tr>
<th>P [Pa]</th>
<th>10^{-2}</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>0.63 cm</td>
<td>6.3 ( 10^{-5} )</td>
</tr>
<tr>
<td>( N_2 )</td>
<td>1.8</td>
<td>1.8 ( 10^{-4} )</td>
</tr>
<tr>
<td>He</td>
<td>0.60</td>
<td>6.0 ( 10^{-5} )</td>
</tr>
</tbody>
</table>

### Viscous:
- \( q \) independent from \( p \)
- \( q = k q T L \)
- \( k \) 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

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

where \( \gamma = \frac{C_p}{C_v} \) is the ratio of specific heats.

\( \alpha \) is the accommodation coefficient, \( 0 < \alpha < 1 \), indicating the degree of thermal equilibrium between molecules and the wall. For heavy gases, \( \alpha \approx 0.7 - 1 \).

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

\[ \alpha = \frac{\alpha_1 \alpha_2}{\alpha_2 + \alpha_1 (1 - \alpha_2)} \frac{A_1}{A_2} \]

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Residual gas conduction:

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

\[ Q_{gc} = C \alpha P (T_h - T_c) \]

\[ C = \text{constant}, \quad \alpha = \text{accommodation coefficient}, \quad P = \text{Gas pressure} \]

Residual gas conduction can be reduced
1. Clean surface (low \( \alpha \)) 2. by high vacuum.

<table>
<thead>
<tr>
<th>Gas</th>
<th>( C )</th>
<th>( \alpha )</th>
<th>( P ) (Torr)</th>
<th>( T_2/T_1 )</th>
<th>( Q_{gc} ) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.02</td>
<td>0.8 ( 10^{-5} )</td>
<td>300/78</td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td>Air</td>
<td>0.02</td>
<td>0.8 ( 10^{-3} )</td>
<td>78/4.2</td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>Air</td>
<td>0.02</td>
<td>0.8 ( 10^{-3} )</td>
<td>300/78</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>Helium</td>
<td>0.03</td>
<td>0.35 ( 10^{-3} )</td>
<td>300/4.2</td>
<td></td>
<td>0.31</td>
</tr>
<tr>
<td>Helium</td>
<td>0.03</td>
<td>0.35 ( 10^{-5} )</td>
<td>78/4.2</td>
<td></td>
<td>0.07</td>
</tr>
</tbody>
</table>
RADIATION

Any surface T>0K absorbs (\(\alpha\)) and emits (\(\varepsilon\)) energy as electromagnetic radiation:
depending on direction and wavelength

incident \(P\) reflected \(\rho P\)
transmitted \(\tau P\)
absorbed \(\alpha P\)

Energy conservation \(\rho + \alpha + \tau = 1\)
Opaque medium \(\rho + \alpha = 1\)

BLACK-BODY:
The whole incident radiation is absorbed: \(\alpha = 1\)
Heat transfer between 2 real surfaces

\[ \Phi = \sigma A_1 \varepsilon_{12} \left( T_2^4 - T_1^4 \right) \varepsilon_{12} \]

effective emissivity (emissivities + view factor)

**Parallel plates**

\[ \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + (1 - \varepsilon_2) \varepsilon_1} \]

**Spheres and long cylinders**

self-contained, not concentrical/coaxial

\[ \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_2 + \frac{A_1}{A_2} (1 - \varepsilon_2) \varepsilon_1} \]

(A1<A2)

\( A_2 >> A_1 \) equivalent to \( A_2 \) black: black-body radiation fills the cavity between the two surfaces and is collected by \( A_1 \) proportionally to \( \varepsilon_1 \)
Radiation:

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

Radiant heat transfer rate between two parallel surfaces

\[ Q = F_e F_{1-2} \sigma A (T_2^4 - T_1^4) \]

\[ F_e = \text{Effective emmissivity}, \quad F_{1-2} = \text{Geometry factor} = 1, \quad \sigma = \text{Stefen Boltzmann constant} = 5.6 \times 10^{-8} \text{ w/ m}^2 \text{ K}. \]

\[ A_1 = \text{Surface area of inner vessel}. \]

\[ 1/F = 1/e + A_1/A_2 (1/e -1), \quad e : \text{emmissivity for inner and outer surface}. \]
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 $200 \sim (300/80)^4$*

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.**

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

<table>
<thead>
<tr>
<th>T&lt;sub&gt;2&lt;/sub&gt; (K)</th>
<th>T&lt;sub&gt;1&lt;/sub&gt; (K)</th>
<th>Heat flux (W/m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Evaporation rate (l/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>78</td>
<td>45</td>
<td>1 litre/hr liquid Nitrogen</td>
</tr>
<tr>
<td>200</td>
<td>78</td>
<td>9</td>
<td>0.2 litre/hr</td>
</tr>
<tr>
<td>300</td>
<td>20</td>
<td>45</td>
<td>5 litres/hr liquid Hydrogen</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>0.23</td>
<td>0.026 litre/hr</td>
</tr>
<tr>
<td>300</td>
<td>4.2</td>
<td>45</td>
<td>65 litres/hr liquid Helium</td>
</tr>
<tr>
<td>80</td>
<td>4.2</td>
<td>0.23</td>
<td>0.33 litres/hr</td>
</tr>
</tbody>
</table>

**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

\[ T_w - T_c \]

\[ \varepsilon \]

\[ \frac{\varepsilon}{2 - \varepsilon} (T_w^4 - T_c^4) \]

\[ T^4 = \frac{1}{2} (T_w^4 + T_c^4) \]

\[ \frac{1}{n+1} \left( \frac{\varepsilon}{2 - \varepsilon} \right) (T_w^4 - T_c^4) \]

\[ T_i^4 = T_c^4 + \frac{T_w^4 - T_c^4}{i + 1} \]
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 degrading 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

\[ N = 15 \text{ cm}^{-1} \]

\[ T_c = 4.2 \text{ K}, \quad \epsilon = 0.03 \]

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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

Kennard's law
Performance Comparison of Al tape and MLI w.r.t Vacuum (80-4.2 K)

Heat load measurement repeated with different vacuum (5x 10^{-7} Torr to 5x 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 3x 10^{-6} Torr.
Multilayer Insulation (MLI)
CRYOGENIC INSULATION

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

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

B. POWDER : (Evacuated Perlite Powder)

Apparent 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

\[ Q = \frac{\sigma e A (T_2^4 - T_1^4)}{2(N+1)} \]
Typical heat inleaks in a cryostat

...between flat plates, at vanishingly low temperature

<table>
<thead>
<tr>
<th>Description</th>
<th>[W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black-body radiation from 290 K</td>
<td>400</td>
</tr>
<tr>
<td>Black-body radiation from 80 K</td>
<td>2.3</td>
</tr>
<tr>
<td>Residual gas conduction (100mPa helium) from 290 K</td>
<td>19</td>
</tr>
<tr>
<td>Residual gas conduction (1mPa helium) from 290 K</td>
<td>0.19</td>
</tr>
<tr>
<td>Multi-layer insulation (30 layers) from 290 K, pressure below 1mPa</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Multi-layer insulation (10 layers) from 80 K, pressure below 1mPa</td>
<td>0.05</td>
</tr>
<tr>
<td>Multi-layer insulation (10 layers) from 80 K, residual pressure 100mPa</td>
<td>0.2</td>
</tr>
<tr>
<td>Residual Gas conduction (100mPa) from 80 K</td>
<td>6.8</td>
</tr>
<tr>
<td>Residual gas conduction (1mPa) from 80 K</td>
<td>0.07</td>
</tr>
</tbody>
</table>
### A. Thermal Conductivity Integrals of common material

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>OFHC Copper</th>
<th>AISI 304 SS</th>
<th>G - 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 K To 80 K</td>
<td>600 w/cm</td>
<td>3.49</td>
<td>0.18</td>
</tr>
<tr>
<td>80 K To 300K</td>
<td>1600</td>
<td>30.6</td>
<td>1.53</td>
</tr>
</tbody>
</table>

### B. Emissivity of Technical materials

<table>
<thead>
<tr>
<th>Material</th>
<th>300- 77K</th>
<th>77- 4.2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS as found</td>
<td>0.34</td>
<td>0.12</td>
</tr>
<tr>
<td>SS Mech polished</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>SS Electropolished</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>SS+ Al foil</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Al Mech polished</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Copper, Mech polished</td>
<td>0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>
A superconducting accelerator magnet

- Thermal Shield
- Vacuum Vessel
- Support
- Heat Exchanger
- Helium pipes
- Cold Mass
- Beam tube
A superconducting 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, \( Q = 2 \times 1.5 = 3 \text{W} \)
2. 80 K Shield (No MLI): \( Q = 2 \times 0.15 = 0.3 \) (one order less)
3. Same with one layer Al Foil \( q = 2 \times 0.02 = 0.04 \text{W} \)

Vacuum Level?

10^-5 mbar \( Q_g = 2 \times 0.07 = 0.15 \text{W} \)
10^-3 mbar, \( Q_g = 2 \times 7 = 14 \text{W} \) (not acceptable)
Heat load Budget - 2

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

\[ Q_g + Q_r = 0.03 + 0.15 = 0.19 \text{ W} \]

Same with vacuum 10^-3 mbar, \( Q = 15 \text{ W} \)

If we wrap with 10 layers of MLI
\( Q = 4 \text{ W} \) (Still 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**

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>G-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>KdT (: 300- 4.2)</td>
<td>30.6 W/cm</td>
<td>1.53</td>
</tr>
<tr>
<td>KdT ( 80- 4.2)</td>
<td>3.49</td>
<td>0.18</td>
</tr>
</tbody>
</table>

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

TO REBUNCHER

TO LINAC

LIQUEIFIER

1000 L DEWAR

VALVE BOX

TO CRYOSTATE ROOM

FROM HELIUM PLANT

TO REBUNCHER

TO LINAC
Specification of the 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 length

**Actual Load in Line**: 0.51 W/m
JLab Designed MSU Distribution Box
Transfer Line Cross sections (SNS)
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).

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

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

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Mechanical Properties

Ductile - Brittle Behavior

Yield Strength

Ultimate Tensile Strength [UTS]

For Ductile Material: UTS >> yield Strength
For Brittle Material: UTS ~ Yield Strength

Yield point

Elastic limit

Elastic region

plastic region

rupture

Yield Strength

Ultimate Tensile Strength [UTS]
### Table: Stress and Strain

<table>
<thead>
<tr>
<th>Material</th>
<th>( \sigma_y ) (4.2K)</th>
<th>( \sigma_u ) (4.2K)</th>
<th>( \sigma_y ) (80K)</th>
<th>( \sigma_u ) (80K)</th>
<th>( \sigma_y ) (300K)</th>
<th>( \sigma_u ) (300K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS304</td>
<td>547</td>
<td>1660</td>
<td>460</td>
<td>1509</td>
<td>406</td>
<td>659</td>
</tr>
<tr>
<td>Al -6061</td>
<td>345</td>
<td>497</td>
<td>332</td>
<td>422</td>
<td>282</td>
<td>312</td>
</tr>
<tr>
<td>OFHC Cu</td>
<td>90</td>
<td>418</td>
<td>88</td>
<td>360</td>
<td>75</td>
<td>222</td>
</tr>
<tr>
<td>G-10</td>
<td>758</td>
<td>758</td>
<td>703</td>
<td>703</td>
<td>414</td>
<td>414</td>
</tr>
</tbody>
</table>

### Diagram:

- **Ductility**: Directions and relationships between stress and strain.
- **Yield point** and **UTS** highlight critical points in material behavior.
- **Elastic limit** and **Elastic region** indicate stress-strain behavior.
- **Plastic region** marks the transition to non-recoverable deformation.
- **Rupture** signifies failure or material breakdown.
Elongation Before Failure

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.

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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 Conductivity

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

Why Do You Require “K”?  

\[ Q = \frac{K}{A \cdot \frac{dT}{dx}} = \frac{W}{m \cdot K} \]

300K

4.2K

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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

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Specific heat of structural materials

\[ C_v \] heat capacity per kg mole approximately described by the Debye function

\[ C_v = 9R \left( \frac{T}{\theta_D} \right)^3 \int_{0}^{\theta_D/T} \frac{x^4 e^x}{(e^x - 1)^2} \, dx \]

\( \theta_D \) Debye temperature, a material's property

<table>
<thead>
<tr>
<th>Material</th>
<th>( \theta_D ) (K)</th>
<th>Material</th>
<th>( \theta_D ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>385</td>
<td>Lead</td>
<td>85</td>
</tr>
<tr>
<td>Carbon (graphite)</td>
<td>760</td>
<td>Nickel</td>
<td>440</td>
</tr>
<tr>
<td>Copper</td>
<td>310</td>
<td>Niobium</td>
<td>265</td>
</tr>
<tr>
<td>Gold</td>
<td>180</td>
<td>Silver</td>
<td>220</td>
</tr>
<tr>
<td>Indium</td>
<td>105</td>
<td>Titanium</td>
<td>355</td>
</tr>
<tr>
<td>Iron</td>
<td>460</td>
<td>Quartz</td>
<td>255</td>
</tr>
</tbody>
</table>

Nb: \( T_c/\theta_D = 0.04 \)

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Thermal Properties

Thermal Conductivity

Specific Heat

Thermal Contraction

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

Why do you require “Cp”? 

\[ C_v = \text{Energy Required to change the temperature of 1 g substance by one degree} \]

\[ \frac{C_v}{T/T_d} \]
Role of Specific Heat on Cool Down

To cool 1 gm mass from Room temperature to 4.2 K

\[ Q = m \cdot Cp \cdot (300-4.2) \, J \] \(,\) \(\text{Cp} = f(T)\)

At low temperature \(\text{Cp}\) is less, less heat to be extracted at low Temperature

How much Cryogen (\(\text{Mc}\)) is required to cool 1 Kg mass

\[ \text{Mc.} \, L = m \cdot \text{Cp} \cdot (300-4.2) \]

### Requirement of Cryogen To Cool Down

<table>
<thead>
<tr>
<th>Material</th>
<th>300-4.2 (Lhe)</th>
<th>78-4.2 K</th>
<th>With cold gas (300-4.2)</th>
<th>300-80 (LN2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>33 litres/kg</td>
<td>1.44 litres/kg</td>
<td>0.80 litres/kg</td>
<td>0.53 litres/kg</td>
</tr>
<tr>
<td>Al</td>
<td>66</td>
<td>3.2</td>
<td>1.60</td>
<td>1.0</td>
</tr>
</tbody>
</table>
**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

<table>
<thead>
<tr>
<th>T (K)</th>
<th>R (Ω)</th>
<th>dR/dT (Ω/K)</th>
<th>(T/R)-(dR/dT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.2913</td>
<td>0.085</td>
<td>0.74</td>
</tr>
<tr>
<td>30</td>
<td>3.6556</td>
<td>0.191</td>
<td>1.60</td>
</tr>
<tr>
<td>50</td>
<td>9.3865</td>
<td>0.360</td>
<td>1.90</td>
</tr>
<tr>
<td>77.35</td>
<td>20.380</td>
<td>0.423</td>
<td>1.60</td>
</tr>
<tr>
<td>100</td>
<td>29.989</td>
<td>0.423</td>
<td>1.40</td>
</tr>
<tr>
<td>150</td>
<td>50.788</td>
<td>0.409</td>
<td>1.20</td>
</tr>
<tr>
<td>200</td>
<td>71.011</td>
<td>0.400</td>
<td>1.10</td>
</tr>
<tr>
<td>250</td>
<td>90.845</td>
<td>0.393</td>
<td>1.10</td>
</tr>
<tr>
<td>300</td>
<td>110.354</td>
<td>0.387</td>
<td>1.10</td>
</tr>
<tr>
<td>400</td>
<td>148.640</td>
<td>0.383</td>
<td>1.00</td>
</tr>
<tr>
<td>500</td>
<td>185.668</td>
<td>0.378</td>
<td>1.00</td>
</tr>
<tr>
<td>600</td>
<td>221.535</td>
<td>0.372</td>
<td>1.00</td>
</tr>
<tr>
<td>700</td>
<td>256.243</td>
<td>0.366</td>
<td>1.00</td>
</tr>
<tr>
<td>800</td>
<td>289.789</td>
<td>0.360</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Platinum Resistance Thermometer

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**Silicone Diode Thermometer**

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

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Silicone Diode Thermometer

Response characteristics of a Silicon diode
The capacitance of concentric Cylinder tube is

\[ C = C_f + C_g = \frac{2\pi (L_f \varepsilon_f + L_g \varepsilon_g)}{\ln(D_o/D_i)} \]

\( \varepsilon_f, \varepsilon_g \): Dielectric Constant for liquid & Gas

This is popular for Liquid nitrogen but not for liquid Helium
Liquid level meter by Superconducting wire

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

Nb- Ti Commercial wire (\(T_c = 12\) K)
HELUM 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
Time-independent conduction

1D, constant \( A \)

\[
\dot{Q} = -k(T) A \frac{dT}{dx} \quad \rightarrow \quad \dot{Q} = \frac{A}{L} \int_{T_c}^{T_h} k(T) dT
\]

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

Heat flux reduction by intermediate temperature thermalization:

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

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Conductivity of solids

-> form for pure and alloyed metals

-> st.steel

-> increase with T
Emissivity and materials

Real emissivities depend on direction and wavelength

- **Polished metals**: small $\varepsilon$
- **Insulators**: large $\varepsilon$
- $\varepsilon = \varepsilon(T)$: for real metals, $\varepsilon \sim T$ at low $T$
- **Coatings**: since $\varepsilon$ related to surface, not bulk, resistance, $\Rightarrow$ lower limit on thickness of reflectors ($\rho \approx 1$ above $\sim 40\text{nm}$)

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

Drude law for ideal metal
MLI: effective conductivity

Effective conductivity \( k = aT + bT^3 \)

Heat transfer rate \( q = \frac{k}{e} \Delta T, \ e = \text{thickness} \)

Optimal density: 10-20 cm\(^{-1}\)

Low boundary temperature:
- heat transfer rate determined by \( aT \), not by radiation
- 77 K -> 4 K
  - 1 single aluminized foil is sufficient in high vacuum
  - in bad vacuum, MLI provides sufficient insulation

High boundary temperature:
- heat transfer rate determined by radiation
- important reduction with layer’s number
- 300 K -> 77 K
  - bad vacuum: radiation dominates anyway
Cryogenic heat transfer modes

\[ \frac{\dot{Q}}{\Delta T \cdot s} \quad [\text{W/(m}^2\text{.K})] \]

- Convection forcée liquide
- Convection naturelle liquide
- Convection forcée gaz
- Convection naturelle gaz
- Conduction liquide
- Conduction gaz
- Rayonnement

- **PeakNucleate BoilingFlux**
- Increase of Re for decreasing T
- Increase of Gr for decreasing T, \( h \sim T^{-1/2} \)
- \( k \sim T^{0.7} \)
- \( T^3 \)

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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 $T$? Difference between pure and alloyed.
  Effect of modification of the defect content: magnetic impurities, annealing, cold work

- Hinder heat transmission at high $T$? No difference between pure and alloyed metals

- Phonon-phonon
- Phonon-electron

- Behaviour well known

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