Superconductive Materials

Part 1
Introduction to Cryogenics
Why Low Temperature is so exciting?

• Temperature is one of the most important variable parameter

• Mechanical, thermodynamical, chemical, electronic and phonon properties strongly affect by T

• Lattice vibration are dominant at room temperature

• At very low temperature quantum behavior of matter appears
Cryogenics

Definition

The cryogenic temperature range has been defined as from \(-150 \, ^\circ\text{C} (123 \, \text{K})\) down to absolute zero \((-273 \, ^\circ\text{C} \text{ or } 0 \, \text{K})\), the temperature at which molecular motion comes as close as theoretically possible to ceasing completely.

Five main application of cryogenics

1. Liquefaction and separation of gases
2. Storage and transport of gases
3. Altering material and fluid properties by reduced temperature
4. Biological and medical applications
5. Superconductivity
How to conduct an experiment at Low T?

Cryogenic Bath

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_{\text{liq}}$ (K) @1 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>90.2</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>77.4</td>
</tr>
<tr>
<td>Neon</td>
<td>27.1</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>20.4</td>
</tr>
<tr>
<td>Helium</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Domain of existence of cryofluids

- $T_{\text{critical point}}$ (K)
- $P_{\text{critical point}}$ (bar)
- $T_{\text{Triple point}}$ (K)
- $P_{\text{Triple point}}$ (bar)

P. DUTHIL, Cryogenics for accelerator cavities, EASISchool 2 on Cryogenics - September 30th 2019
Cryogenics fluids properties

<table>
<thead>
<tr>
<th>Fluid</th>
<th>H$_2$</th>
<th>Ne</th>
<th>N$_2$</th>
<th>O$_2$</th>
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<tr>
<td>Normal boiling point</td>
<td>20.4</td>
<td>27.2</td>
<td>77.4</td>
<td>90.2</td>
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<tr>
<td>Critical temperature</td>
<td>33.2</td>
<td>44.4</td>
<td>126.</td>
<td>155.</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>1.32</td>
<td>2.72</td>
<td>3.39</td>
<td>5.08</td>
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<tr>
<td>Triple point temperature</td>
<td>14.0</td>
<td>24.6</td>
<td>63.1</td>
<td>54.4</td>
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<tr>
<td>Triple point pressure</td>
<td>7.20</td>
<td>43.2</td>
<td>12.8</td>
<td>0.15</td>
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<td>Liquid density at ambient</td>
<td>125.</td>
<td>1204.</td>
<td>808.</td>
<td>1140.</td>
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<tr>
<td>Vapor density at ambient</td>
<td>1.33</td>
<td>9.46</td>
<td>4.59</td>
<td>4.75</td>
</tr>
<tr>
<td>Normal density</td>
<td>0.09</td>
<td>0.90</td>
<td>1.25</td>
<td>1.43</td>
</tr>
</tbody>
</table>

*: Lambda point

U. Wagner, REFRIGERATION, CAS 2002

Helium shows the particularity that it has no **triple point**, it may solidify only at pressures above 2.5 MPa. The commonly given **lambda point** refers to the transition from normal to superfluid helium.
Helium shows the particularity that it has no triple point, it may solidify only at pressures above 2.5 MPa. The commonly given lambda point refers to the transition from normal to superfluid helium. The superfluid component has zero viscosity and zero entropy and very high effective thermal conductivity.

- 1 phase: bivariant $\rightarrow (P,T)$ to be set
- 2 phases co-existing: monovariant $\rightarrow P$ (or $T$) to be set and thus $T$ (or $P$) related $P=1$ bar for $T=4.2$ K, $P=0.031$ bar for $T=2$ K
Some history first

Superconductive Materials - Part 1
Introduction to Cryogenics
The race to liquefy Helium (1)

Here starts the story of Superconductivity

- In 1852 the principle of cooling by rapid expansion had been established by James Prescott Joule and William Thomson (aka Lord Kelvin)

- Carl Paul Gottfried von Linde (professor of Rudolf Diesel) patented and installed in 1873 the first commercial refrigeration system
- In 1879 he founded ‘Linde’s Ice Machine Company’, which is now the Linde group
- Zygmunt Florenty Wroblewski and Karol Olszewski in March 1883 produced liquid Oxygen
- They succeeded also with nitrogen. Krakow became the world-leading centre of low-T physics
- By the mid-1880s, the most important known gases had been liquefied, apart from one: hydrogen
The race to liquefy Helium (2)

- In 1868 Pierre Janssen noticed a bright yellow line with a wavelength of 587.49 nm studying the spectrum of solar light during a total solar eclipse.
- Norman Lockyer (later to be the first editor of Nature) concluded that this spectral line must be due to a new element, unknown on Earth but present on the Sun.
- Norman Lockyer and Edward Frankland (a Professor of Chemistry at the Royal Institution) named the element helium from the Greek word for the Sun.
- In 1895, the Scottish chemist William Ramsay isolated helium in the laboratory of University College London by treating the mineral cleveite with mineral acids.
- Helium is trapped in various minerals because of radioactivity: helium is being continually produced inside the Earth due to radioactive decay processes (alpha particles).
- Ramsay received the Nobel Prize in 1904 ‘in recognition of his services in the discovery of the inert gaseous elements in air, and his determination of their place in the periodic system’, reflecting not only his discovery of helium but also that of the other noble gases: argon, neon, krypton, and xenon.
The race to liquefy Helium (3)

- **James Dewar** comes into the race and in 1886 succeeded in producing solid oxygen.

- In 1893, Dewar unveiled his famous double-walled container which became known as a vacuum flask or a ‘dewar’.

- On 10 May 1898, Dewar produced about twenty cubic centimetres (about five teaspoonfuls) of liquid hydrogen (20.28K or -252.87°C).

- Even when solidified, the hydrogen (14K, -259°C) **Helium remained gaseous**.

- Possible dream team with Ramsey at Royal Institution in London, but because of the “Olszewsky case” they never collaborate together.
Sir James Dewar demonstrating his recent successful liquefaction of hydrogen at a Friday evening lecture in 1899 at the Royal Institution, London. The painting, by Henry Jamyn Brooks (1865–1926), is reproduced with the permission of the Royal Institution and the Bridgeman Art Library.
The race to liquefy Helium (4)

- **Kamerlingh Onnes** studied under Robert Bunsen and Gustav Kirchhoff in Heidelberg and after the PhD he became acquainted with Johannes Diderik van der Waals

- In 1881 built his world-famous low T physics laboratory

- The laboratory motto was therefore the poetic *Door meten totcweten* (‘Through measurement to knowledge’). Onnes was one of the first people to really understand that advances in this field depended critically on having first-rate technicians, expert glass blowers, and skilled craftsmen to build and maintain the delicate equipment and provide support for the technically demanding experiments

- Onnes founded a Society for the Promotion of Training of Instrument Makers which was crucial for building up the necessary skilled workforce
The race to liquefy Helium (5)

- Onnes only succeeded in liquefying hydrogen in 1906, (8 years after Dewar) but Leiden’ apparatus produced much larger quantities and was much more reliable.

- His younger brother was director of the Office of Commercial Intelligence in Amsterdam and in 1905 was able to procure large quantities of monazite sand from North Carolina; helium gas could be extracted from the mineral monazite. Onnes had over 300 litres of helium gas at his disposal.

- On **10 July 1908**, after 14 hours of work, the temperature stopped falling at 4.2K.

- Onnes wrote: ‘It was a wonderful sight when the liquid, which looked almost unreal, was seen for the first time . . . Its surface stood sharply against the vessel like the edge of a knife.’

- The Nobel Prize for Physics in 1913 was awarded to Kamerlingh Onnes ‘for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium.’
Leiden, the coldest place on earth

Here is how the location looked like in the 1980's
Working with cryogenics

Superconductive Materials - Part 1
Introduction to Cryogenics
What information we are looking for?

• How to reduce the thermal losses of a cryostat

• How to have a stable working temperature
Thermal Conduction in Solids

\[ \vec{q} = -k(T) \nabla T \]  

*Fourier Law*

- \( q \) is the heat flux density \((W \cdot m^{-2})\)
- \( k \) is the thermal conductivity \((W \cdot m^{-1} \cdot K^{-1})\)
- \( T \) is the temperature \((K)\)

Thermal Conduction in Solids

\[ \vec{q} = -k(T) \vec{\nabla}T \quad \text{Fourier Law} \]

\[ q = -k(T) \frac{dT}{dx} \Rightarrow Q \int_0^L \frac{dx}{A} = \int_{T_{\text{cold}}}^{T_{\text{hot}}} k(T) dT \]

- \( q \) is the heat flux density (\( W \cdot m^{-2} \))
- \( k \) is the thermal conductivity (\( W \cdot m^{-1} \cdot K^{-1} \))
- \( T \) is the temperature (\( K \))

\( A \) is the cross-section of the domain
\( Q \) is the power (\( W \))
Thermal Conduction in Solids

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In the case where \( A \) is constant
Thermal Conduction in Solids

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In the case where \( A \) is constant

\[ q = -k(T) \frac{dT}{dx} \Rightarrow Q = \frac{1}{L} \int_{T_{\text{cold}}}^{T_{\text{hot}}} k(T)\,dT \]

The definition of heat flux in a one-dimensional domain
Thermal conductivity

\[ \int_{T_{cold}}^{T_{hot}} k(T) \, dT \]

- Thermal conductivity of most materials varies strongly with temperature.
- Nb behavior close to SS.

![Graph showing thermal conductivity of various materials vs. temperature.](image)
Thermal conductivity, exercise

• Three 304 stainless steel rods suspend a He bath cooled system
  • $T_{\text{top flange}} = 300 \text{ K}$
  • $T_{\text{He Bath}} = 4.2 \text{ K}$
  • $L_{\text{rod}} = 1 \text{ m}$
  • $\Phi_{\text{rod}} = 10 \text{ mm}$

• Heat leak?
Thermal conductivity, exercise

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• Heat leak?

$$Q_{4K} = \frac{A}{L} \int_{4.2}^{300} k_{SS}(T) \,dT =$$
Thermal conductivity, exercise

- Three 304 stainless steel rods suspend a He bath cooled system
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- Heat leak?

$$Q_{4K} = \frac{A}{L} \int_{4.2}^{300} k_{SS}(T) dT = \frac{2.36 \times 10^{-4}}{1} \times 3.07 \times 10^3 \approx 0.7 \text{ W}$$
Thermal conductivity, exercise

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\[ Q_{4K} = \frac{A}{L} \int_{4.2}^{300} k_{CuRRR20}(T) dT = \frac{2.36 \times 10^{-4}}{1} 1.26 \times 10^5 \approx 20 \, W \]
Thermal conductivity, exercise

\[ Q_{4K} = \frac{A}{L} \int_{4.2}^{3.00} k_{SS}(T) \, dT = \frac{2.36 \times 10^{-4}}{1} \cdot 3.07 \times 10^3 \approx 0.7 \, W \]

\[ Q_{4K} = \frac{A}{L} \int_{4.2}^{3.00} k_{Cu_{RRR20}}(T) \, dT = \frac{2.36 \times 10^{-4}}{1} \cdot 1.26 \times 10^5 \approx 20 \, W \]

\[ Q_{4K} = \frac{A}{L} \int_{4.2}^{3.00} k_{G10}(T) \, dT = \frac{2.36 \times 10^{-4}}{1} \cdot 127 \approx 0.026 \, W \]
1 W = ? l liquid helium evaporated?

- In a phase transition:

\[ Q_{ev} = \lambda_{ev} m \]

\( Q_{ev} \) is amount of energy absorbed during the evaporation (kJ)
\( \lambda_{ev} \) is the specific latent heat of evaporation (kJ·kg\(^{-1}\))
\( m \) is the evaporated mass (kg)
1 W = ? l liquid helium evaporated?

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1 W = ? l liquid helium evaporated?

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  \( m \) is the evaporated mass (kg)

- With SS bars, the liquid helium consumption is:
  \[ \frac{Q_{ev}}{\lambda_{ev}} = \frac{0.7 \cdot 10^{-3}}{20.42} = 0.034 \cdot 10^{-3} \frac{kg}{s} \sim 1 \frac{l}{h} \]

- With Cu bars \( \sim 31 \) l/h
- With G10 bars \( \sim 0.04 \) l/h

\( Q_{SS\ bar} = 0.7 \) W
\( Q_{Cu\ bar} = 22 \) W
\( Q_{G10\ bar} = 0.026 \) W

1 W = 1 J/s

He density = 0.125 kg/l
\( \lambda_{ev, He} = 20.42 \) kJ/kg
Cost?

- With SS bars ~ 1 l/h
- With Cu bars ~ 31 l/h
- With G10 bars ~ 0.04 l/h

<table>
<thead>
<tr>
<th>Gas Compressi</th>
<th>Recipiente</th>
<th>Prezzo</th>
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</tr>
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<tbody>
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<tr>
<td>Azoto liquido 5,0</td>
<td>tank criogenico</td>
<td>€ 0,50</td>
<td>litro</td>
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</tbody>
</table>
### Cost?

- With SS bars ~ 1 l/h
- With Cu bars ~ 31 l/h
- With G10 bars ~ 0.04 l/h

<table>
<thead>
<tr>
<th>Gas Compressi</th>
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</table>

| Elio liquido        | € 14,00    | litro  |
| Azoto liquido 5.0   | € 0,50     | litro  |

- With SS bars ~ 14 €/h
- With Cu bars ~ 434 €/h
- With G10 bars ~ 0.56 €/h

€ 50 / liter !!!

![SIAD Logo](image)
Heat Interception
Heat Interception

\[ Q_{4K} = \frac{A}{L} \int_{4.2}^{77} k_{SS}(T) dT = \frac{2.36 \times 10^{-4}}{0.75} \times 325 \approx 0.1 \, W \]

consumption of 0.14 l·h⁻¹ of liquid helium (*7 times less*) ~ 2 €/h
Heat Interception

\[ Q_{4K} = \frac{A}{L} \int_{4.2}^{77} k_{SS}(T) dT = \frac{2.36 \times 10^{-4}}{0.75} \times 325 \approx 0.1 \text{ W} \]

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\[ Q_{77K} = \frac{A}{L} \int_{77}^{300} k_{SS}(T) dT = \frac{2.36 \times 10^{-4}}{0.25} \times 2.75 \times 10^3 \approx 2.6 \text{ W} \]
Heat Interception

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consumption of 0.06 l·h⁻¹ of liquid nitrogen \( \sim 0.03 \text{ €/h} \)

<table>
<thead>
<tr>
<th></th>
<th>He(^4)</th>
<th>N(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal boiling point (K)</td>
<td>4.22</td>
<td>77.3</td>
</tr>
<tr>
<td>Liquid density (kg/m(^3))</td>
<td>125</td>
<td>809</td>
</tr>
<tr>
<td>Liquid density/vapour density</td>
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<td>175</td>
</tr>
<tr>
<td>Enthalpy of vaporisation (kJ/kg)</td>
<td>20.42</td>
<td>199</td>
</tr>
</tbody>
</table>

| Elio liquido | dewars | € 14,00 | litro |
| Azoto liquido 5.0 | tank criogenico | € 0,50 | litro |
Heat Interception

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consumption of 0.14 l·h\(^{-1}\) of liquid helium (7 times less) \(\sim 2 \, €/h\)

\[ Q_{77K} = \frac{A}{L} \int_{77}^{300} k_{SS}(T) dT = \frac{2.36 \times 10^{-4}}{0.25} \times 2.75 \times 10^3 \approx 2.6 \, W \]

consumption of 0.06 l·h\(^{-1}\) of liquid nitrogen

The optimization depends on many parameters:
- thermalization temperature
- material properties
- geometry of the system
- ...
Thermal resistance $R_{th}$

- Used to evaluate the thermal losses of the system
- Thermal resistance is characteristic of each material

- From:  
  \[ q = -k(T) \frac{dT}{dx} \Rightarrow \frac{Q}{A} = \frac{1}{L} \int_{T_{cold}}^{T_{hot}} k(T) dT \]

- In the steady state regime
- No internal dissipation

\[ Q \int_{z_1}^{z_2} \frac{dz}{A(z)} = - \int_{T_1}^{T_2} k(T) dT = \bar{k}(T_1 - T_2) \Rightarrow R_{th} = \frac{T_1 - T_2}{Q} = \frac{1}{k} \int_{z_1}^{z_2} \frac{dz}{A(z)} \left[ \frac{K}{W} \right] \]

$\bar{k} = \text{average conductivity}$
Thermal resistance $R_{th}$

$$ Q \int_{z_1}^{z_2} \frac{dz}{A(z)} = - \int_{T_1}^{T_2} k(T)dT = \bar{k}(T_1 - T_2) \Rightarrow R_{th} = \frac{T_1 - T_2}{Q} = \frac{1}{k} \int_{z_1}^{z_2} \frac{dz}{A(z)} \left[ \frac{K}{W} \right] $$

$\bar{k} = \text{average conductivity}$

- for a slab a constant section $A = A_1 = A_2$ and a thickness $L$
  $$R_{th} = \frac{L}{kA}$$

- for a slab a cylinder with radius $R_1$ and $R_2$, with a length $L$
  $$R_{th} = \frac{\ln R_2 / R_1}{\bar{k}2\pi L}$$

- a convective boundary thermal resistance can be simulated by considering a heat transfer coefficient $h$ and a heat transfer area $A$ as
  $$R_{th} = \frac{1}{hA}$$
Different Materials System

**SERIES case**

\[ R_{total} = \sum R_i \]

\[ Q = \frac{T_h - T_c}{\sum \frac{1}{R_i}} = A \frac{T_h - T_c}{\left( \frac{1}{h_h} + \frac{1}{k_1} + \frac{1}{k_2} + \frac{1}{k_3} + \frac{1}{h_c} \right)} \]

**PARALLEL case**

\[ R_{total} = \sum \frac{1}{R_i} \]

\[ Q = A \frac{T_h - T_c}{\left( \frac{1}{h_h} + \frac{1}{k_1} + \frac{2}{k_2 + k_3} + \frac{1}{k_4} + \frac{1}{h_c} \right)} \]

A convective boundary thermal resistance can also be simulated by considering a heat transfer coefficient \( h \) and a heat transfer area \( A \) as \( R_{th} = \frac{1}{hA} \).
Contact Thermal Resistance

- Surfaces are not perfect
- **Contact at the interface is not perfect:**
  - Roughness
  - Defects

- Thermal resistance increase significantly:
  - **Kapitza resistance** (phonon scattering at the solid–solid contact)
  - Heat transfer via eventual *interstitial elements*

\[
R_c = \frac{T_2 - T_1}{Q}
\]
How to reduce $R_c$?

- Decrease with $T$
- Increase with applied force

- **Insertion of conductive and malleable fillers**
  (charged grease, indium, or surface coatings)

  Fundamental for a good thermometer contact
Thermometer contact

Indium wire

Thermometer (Cernox)
Transient conduction process and Thermal Diffusivity

In a cryostat design it is often important to include the transient conduction process. Using an energy conservation equation:

\[ \rho C \frac{\partial T}{\partial t} = \nabla \cdot ( - k(T) \nabla T ) + Q \]

\[ \frac{\partial T}{\partial t} = \frac{k}{\rho C} \frac{\partial^2 T}{\partial x^2} + Q \]

\[ \tau \approx \frac{4 L^2}{\pi^2 D} \]

\( \tau \) characteristic diffusion time (95% \( T_{\text{fin}} = 3 \tau \))

\( L \) characteristic thermal length of the solid

\( \rho \) is the density (kg·m\(^{-3}\))

\( C \) specific heat of the solids (J·kg\(^{-1}\)·K\(^{-1}\))

\( k \) thermal conductivity (W·m\(^{-3}\)·K\(^{-1}\))

\( Q \) heat source (W·m\(^{-3}\))

\[ D = \frac{k}{\rho C} \left[ \text{m}^2 \cdot \text{s}^{-1} \right] \text{ DIFFUSIVITY} \]

**Table 1: The thermal diffusivity of different materials at different temperatures in cm\(^2\)·s\(^{-1}\) [1]**

<table>
<thead>
<tr>
<th>Material</th>
<th>300 K</th>
<th>77 K</th>
<th>4 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu OFHC (RRR = 150)</td>
<td>1.2</td>
<td>3.2</td>
<td>11 700</td>
</tr>
<tr>
<td>Pure Al (RRR = 800)</td>
<td>1</td>
<td>4.7</td>
<td>42 000</td>
</tr>
<tr>
<td>Commercial Al (6061)</td>
<td>0.7</td>
<td>1.3</td>
<td>1 200</td>
</tr>
<tr>
<td>SS 304L</td>
<td>0.04</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Nb–Ti</td>
<td>0.03</td>
<td>0.02</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Thermal Conductivity ($k$) in different media

![Diagram showing thermal conductivity in different media](image-url)
Thermal Conductivity (k) in different media

**SOLIDS**

Thermal conductivity of some cryogens at atmospheric pressure (W·m⁻¹·K⁻¹)

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature</th>
<th>k (W·m⁻¹·K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ (T = 90 K)</td>
<td>0.152</td>
<td></td>
</tr>
<tr>
<td>N₂ (T = 77 K)</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>H₂ (T = 20 K)</td>
<td>0.072</td>
<td></td>
</tr>
<tr>
<td>He (T = 4.2 K)</td>
<td>0.019</td>
<td></td>
</tr>
</tbody>
</table>

**LIQUIDS**

Bad thermal conductors

Except superfluid helium:

\[ k \approx 10^5 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} \]

**GAS**

Depends on mean free path \( \lambda \) and the distance \( L \) (related to \( P \))
Thermal radiation

- Principal source of energy transfer in vacuum
Emissivity

From Plank’s law, for a blackbody we can obtain the **Stefan-Boltzmann law**

\[
E^0 = \int_0^\infty \frac{C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} d\lambda = \sigma T^4
\]

\[
\sigma = 5.67 \cdot 10^{-8} \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}
\]

Stefan-Boltzmann constant

For real surface materials, emissive power is a fraction of the blackbody Emissive power for real surface materials is defined as:

\[
E^0 = \varepsilon \sigma T^4
\]

Emissivity

\[
\Phi_\lambda
\]

Spectral distribution \( \lambda \)

\[
\Phi_\Omega
\]

Directional distribution

\[
\text{Cristian Pira}
\]

**Superconductive Materials**
Emissivity

\[ E^0 = \varepsilon \sigma T^4 \]

- \( \varepsilon \) decreases with \( T \)
- \( \varepsilon \) increases with oxidation, impurities, dirt, ...
- Highly polished and highly conductive clean surfaces allow to achieve the lowest emissivity values

<table>
<thead>
<tr>
<th>Material</th>
<th>300 K</th>
<th>78 K</th>
<th>4.2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M black paint (80 µm) on a copper surface</td>
<td>0.94</td>
<td>0.91</td>
<td>0.89</td>
</tr>
<tr>
<td>Polished aluminium (33 µm roughness)</td>
<td>0.05</td>
<td>0.023</td>
<td>0.018</td>
</tr>
<tr>
<td>Polished copper (41 µm roughness)</td>
<td>0.10</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>304 Polished stainless steel (27 µm roughness)</td>
<td>0.17</td>
<td>0.13</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The total emissivity of various metals at three different temperatures

The total emissivity from ambient temperature down to liquid helium temperature (4.2 K)
Passive thermal shielding

• From blackbody radiation: 

\[ q = \sigma (T_{\text{warm}}^4 - T_{\text{cold}}^4) \]

Heat transfer rate

\[ q_{77K} = \sigma (T_{300}^4 - T_{77}^4) = 457 \, W \cdot m^2 \]

\[ q_{4.2K} = \sigma (T_{300}^4 - T_{4.2}^4) = 459 \, W \cdot m^2 \]

Assuming that the surfaces and emissivities are identical for the different reflecting surfaces:

\[ q = \frac{\varepsilon \sigma}{2 - \varepsilon} (T_{\text{warm}}^4 - T_{\text{cold}}^4) \]

\[ q = \frac{1}{2} \frac{\sigma \varepsilon}{2 - \varepsilon} (T_{\text{warm}}^4 - T_{\text{cold}}^4) \]

\[ q = \frac{1}{n+1} \frac{\sigma \varepsilon}{2 - \varepsilon} (T_{\text{warm}}^4 - T_{\text{cold}}^4) \]

Heat transfer rate

\[ T^4 = \frac{T_{\text{warm}}^4 + T_{\text{cold}}^4}{2} \]

\[ T_i^4 = T_{\text{cold}}^4 + \frac{T_{\text{warm}}^4 + T_{\text{cold}}^4}{i+1} \]
Multilayer insulation system (MLI)

- Reflective films (usually aluminium or aluminized polyester film)
- Insulating interlayers (polyester, glass-fibre nets, or paper)
- Operated under vacuum
Cooling techniques at Low Temperature

Direct cooling
Bath cooling

Indirect cooling
Bath as cold source

Indirect cooling
Cryocooler as cold source
Thermal link

Direct cooling
Forced flow

Indirect cooling
Forced flow

Indirect cooling
Two-phase thermosiphon

Indirect cooling
Two-phase thermosiphon
Coupled with a cryocooler
Helium direct cooling bath method
He Cryostat @ LNL

![Cryostat Diagram](image)

- **Cryostat**
- **Vacuum pumps**
- **Liquid N\_2 dewar**
- **He recovery balloon**
- **Compressor Room**

**References**

1. Introduction to Cryogenics
He Cryostat @ LNL
Helium indirect cooling bath method

Quarter Wave Resonators (QWR)


ALPI Cryostat @ LNL
ALPI Cryostat
Helium uses

Helium isn’t just used in balloons, it’s also used to save lives, as well as to power scientific innovation.

**Global Share of Helium Applications**

- **Cryogenics**: 23%
- **Lifting**: 15%
- **Electronics**: 14%
- **Optical Fiber Source USGS**: 11%
- **Optical Fiber**: 9%
- **Leak Detection**: 6%
- **Welding**: 6%
- **Pressure & Purging**: 5%
- **Analytical**: 5%
- **Diving**: 3%
- **Other**: 8%

**Helium Use**

<table>
<thead>
<tr>
<th>Helium Use</th>
<th>Global Share</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenics</td>
<td>23%</td>
<td>Superconductors use ultracold helium liquid.</td>
</tr>
<tr>
<td>Lifting</td>
<td>15%</td>
<td>Used in airships and balloons</td>
</tr>
<tr>
<td>Electronics</td>
<td>14%</td>
<td>Used to manufacture silicon wafers</td>
</tr>
<tr>
<td>Optical Fiber</td>
<td>11%</td>
<td>Necessary to make optical fiber cables</td>
</tr>
<tr>
<td>Welding</td>
<td>9%</td>
<td>Used as a shielding gas for welding</td>
</tr>
<tr>
<td>Leak Detection</td>
<td>6%</td>
<td>Helium particles are small, and can find the tiniest leaks</td>
</tr>
<tr>
<td>Analytics</td>
<td>6%</td>
<td>Used in chromatography and other applications</td>
</tr>
<tr>
<td>Pressure &amp; Purging</td>
<td>5%</td>
<td>Used in rocket systems</td>
</tr>
<tr>
<td>Diving</td>
<td>3%</td>
<td>Mixed into commercial diving tanks for various reasons</td>
</tr>
<tr>
<td>Other</td>
<td>8%</td>
<td>Helium’s diverse properties give it many other minor uses</td>
</tr>
</tbody>
</table>

[https://www.visualcapitalist.com/helium-a-valuable-gas-not-to-be-taken-lightly/]
Helium shortage

People walk out of a Party City store with balloons on in Miami, Florida. Party City announced that it will shutter 45 stores in 2019 due to a global helium shortage

https://business.financialpost.com/

Up to 50 €/l in 2022!!! Today ~40 €/l (2024)
Helium shortage reasons


Pandemic situation solves helium shortage issue, but not the price race
How to work with helium today?

Today is mandatory install a **closed re-circulation system** to re-compress helium which comes out of the exhaust of a cryogenic system.

**Reduce** as much as possible the **helium losses**

Just to have an idea: when I test a single Accelerating cavity, I use 200-400 liters of Helium, for a theoretical cost of more than 10000 €!!!
Leiden, the coldest place on earth (from 1908 to 1923)
Leiden, the coldest place on earth (from 1908 to 1923)
Nowadays: CUORE Experiment @ LNGS INFN

• 1 m³, 400 kg @ T=6 mK for 15 days

• A mixture of Helium-3 and Helium-4 that continuously circulates in a specialized cryogenic unit called dilution refrigerator, removing any remnant heat energy from the smallest chamber. The CUORE dilution refrigerator, built by Leiden Cryogenics in Netherlands, is one of the most powerful in the world.
Nowadays: CUORE Experiment @ LNGS INFN
The CUORE detectors and their shielding must be cooled to approximately 10 mK before they can take data. We cool them using one of the largest and most powerful helium dilution refrigerators ever constructed. Our cryostat produces the coldest cubic meter in the known universe.

To reach such a low temperature, the cryostat is cooled in different stages. The first, which allows the cryostat reach a few degrees above absolute zero, can be performed using cryogenic liquids (liquid helium and liquid nitrogen) or pulse tube cryocoolers. For CUORE, we chose the latter, as it ensures that the cryostat will be stable over several years without needing to replace boiled off liquid cryogens, which disturbs the detector operating conditions.

The second stage, that brings the temperature down to a few mK, exploits the unique properties of two isotopes of helium, $^3$He and $^4$He, to cool matter to a fraction of a degree above absolute zero. At very cold temperatures, $^3$He and $^4$He cannot be mixed in an arbitrary ratio; the mixture will spontaneously separate into two phases, much like oil and water. These phases are known as the concentrated phase, containing mostly $^3$He, and the dilute phase, containing mostly $^4$He. A pump outside the cryostat pulls $^3$He across the boundary from the concentrated phase to the dilute phase, an endothermic process that absorbs energy and is the key to the cooling power of the refrigerator. This $^3$He is then returned to the dilute phase, completing the circuit. We pump on the dilute phase to encourage faster phase change from concentrated to dilute, just like blowing across the gas above a cup of tea encourages a phase change from liquid to gas, cooling your tea.

Smaller dilution refrigerators are commonly used in modern low-temperature experimental physics; they typically have working spaces of tens of cubic centimeters. The CUORE detectors, on the other hand, weigh approximately a ton and are approximately a cubic meter in size, and are accompanied by several tons of copper and lead shielding that need to be cooled as well. Also, the CUORE detectors are extremely sensitive to any radioactive background, so the cryostat had to be constructed from extremely radio-pure materials. For these reasons, the design of a cryogenic facility for CUORE was a real challenge.

The cryostat is surrounded by an octagonal lead shield and borated polyethylene neutron shield. Some of the lead used for shielding close to the detector was recovered from an Ancient Roman shipwreck off the coast of Sardinia.
Bibliography of this part

• B. Baudouy, *Heat Transfer and Cooling Techniques at Low Temperature*
  CERN Accelerating School (CAS): Course on Superconductivity for Accelerators (2013)
  https://cds.cern.ch/record/1507630