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 °C (123 K) down to absolute zero (-273 °C or 0 K)**, the temperature at which molecular motion comes as close as theoretically possible to ceasing completely

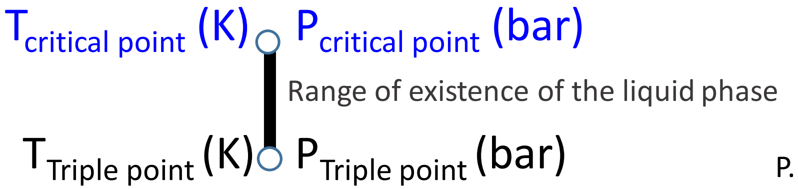
Five main application of cryogenics

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

Element	T_{liq} (K) @1 bar
Oxygen	90.2
Nitrogen	**77.4**
Neon	27.1
Hydrogen	20.4
Helium	**4.2**

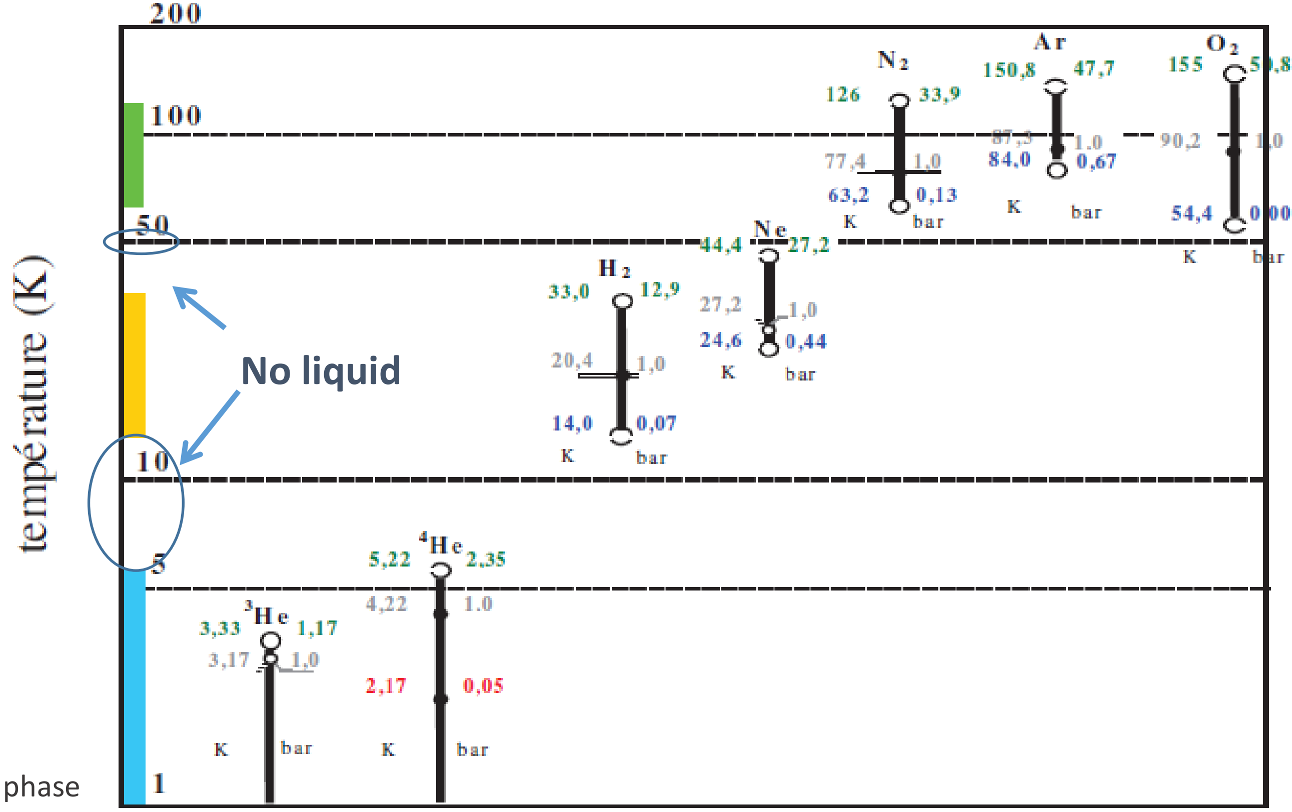


$T_{critical\ point}$ (K) $P_{critical\ point}$ (bar)

Range of existence of the liquid phase

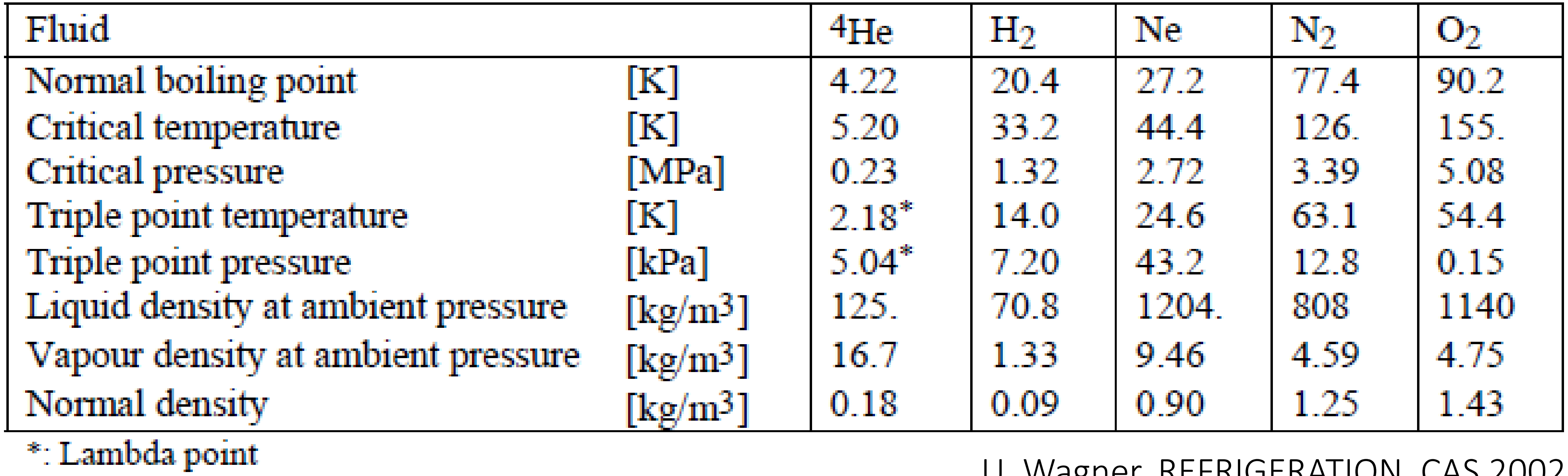
$T_{Triple\ point}$ (K) $P_{Triple\ point}$ (bar)

Domain of existence of cryofluids



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

Cryogenics fluids properties



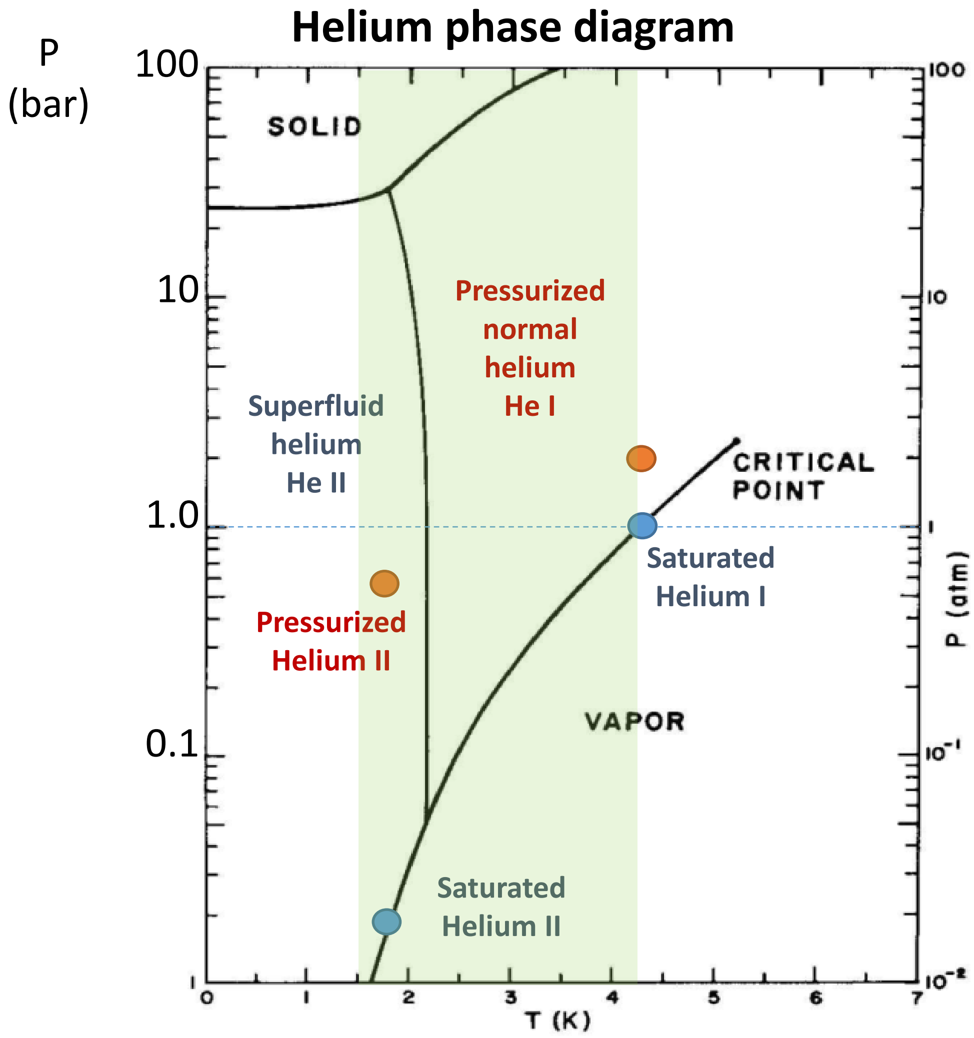
Fluid		^{4}He	H_2	Ne	N_2	O_2
Normal boiling point	[K]	4.22	20.4	27.2	77.4	90.2
Critical temperature	[K]	5.20	33.2	44.4	126.	155.
Critical pressure	[MPa]	0.23	1.32	2.72	3.39	5.08
Triple point temperature	[K]	2.18*	14.0	24.6	63.1	54.4
Triple point pressure	[kPa]	5.04*	7.20	43.2	12.8	0.15
Liquid density at ambient pressure	[kg/m^3]	125.	70.8	1204.	808	1140
Vapour density at ambient pressure	[kg/m^3]	16.7	1.33	9.46	4.59	4.75
Normal density	[kg/m^3]	0.18	0.09	0.90	1.25	1.43

*: 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 Phase Diagram



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 → (*P*,*T*) to be set
- 🔵 2 phases co-existing: monovariant → *P* (or *T)* to be set and thus *T* (or *P)* related
  P=1 bar for *T* = 4.2 T, *P*=0.031 bar for *T* = 2 K

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

Some history first

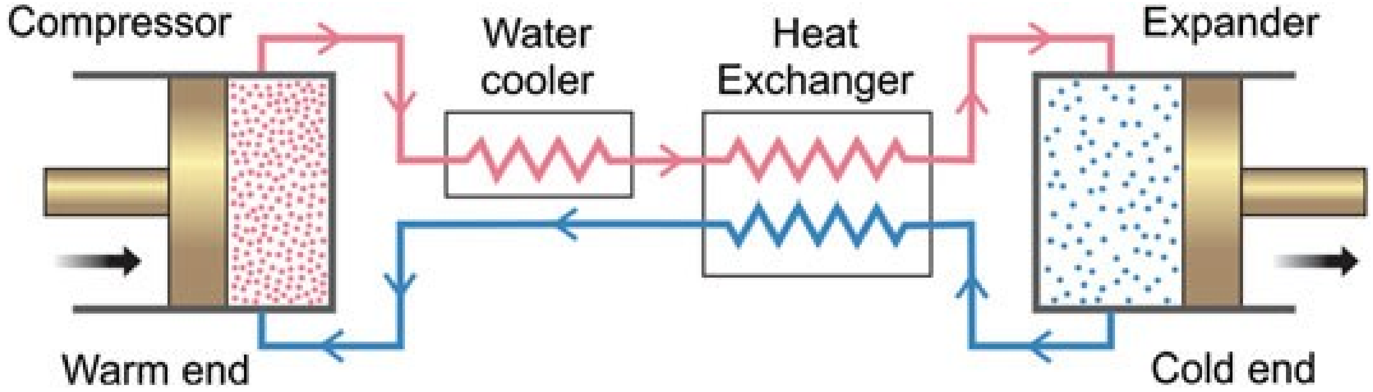
Superconductive Materials - Part 1

The race to liquefy Helium (1)

Here starts the story of Superconductivity

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

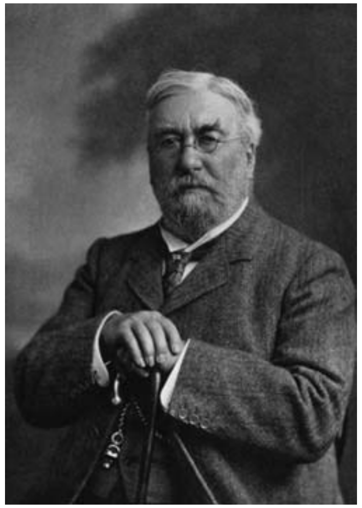
Joule – Thomson effect



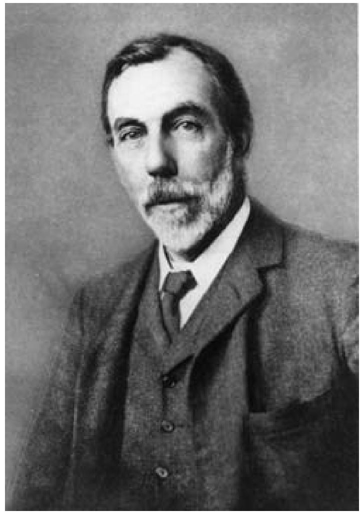
- Carl Paul Gottfried von Linde (professor of Rudolf Diesel) patented and installed in 1873 the first commercial refrigeration system
- In 1879 he founded 'Linde's Ice Machine Company', which is now the Linde group
- Zygmunt Florenty **Wroblewski** and Karol **Olszewski** in March **1883 produced liquid Oxigen**
- **They succeded 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



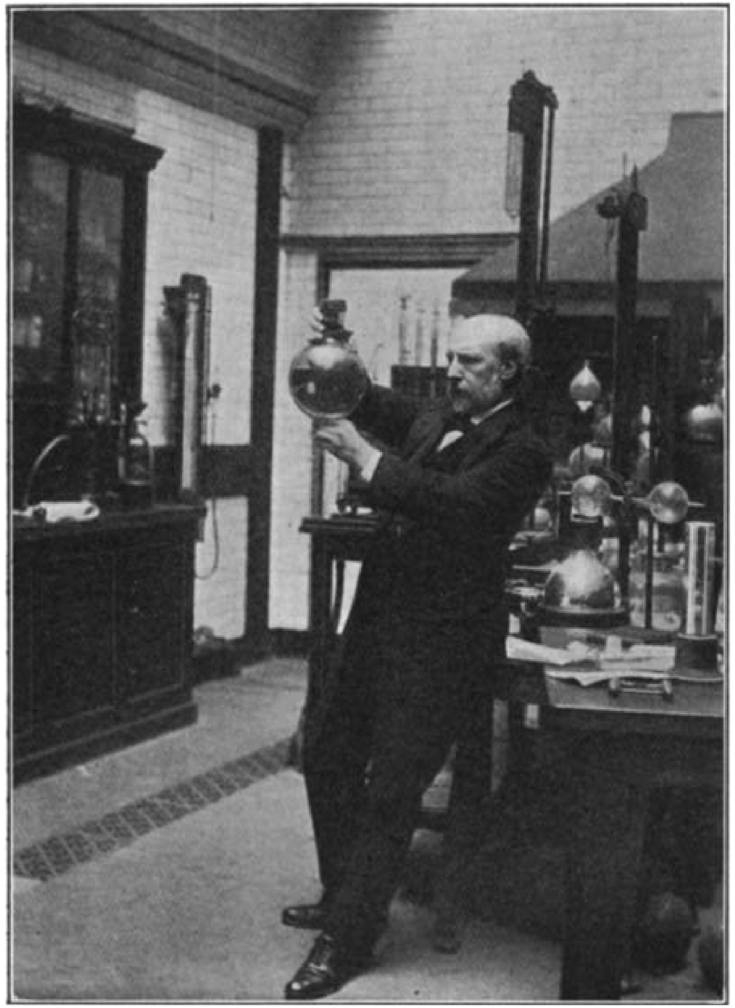
Sir Joseph Norman Lockyer



Sir William Ramsay

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

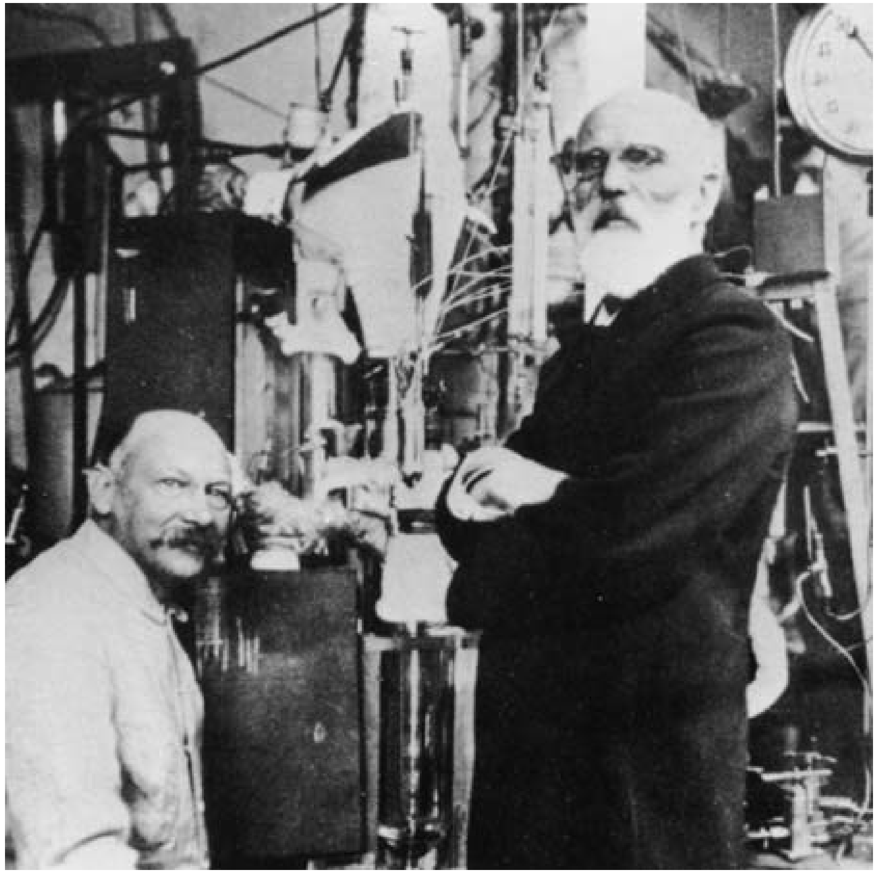


Sir James Dewar

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, cand 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

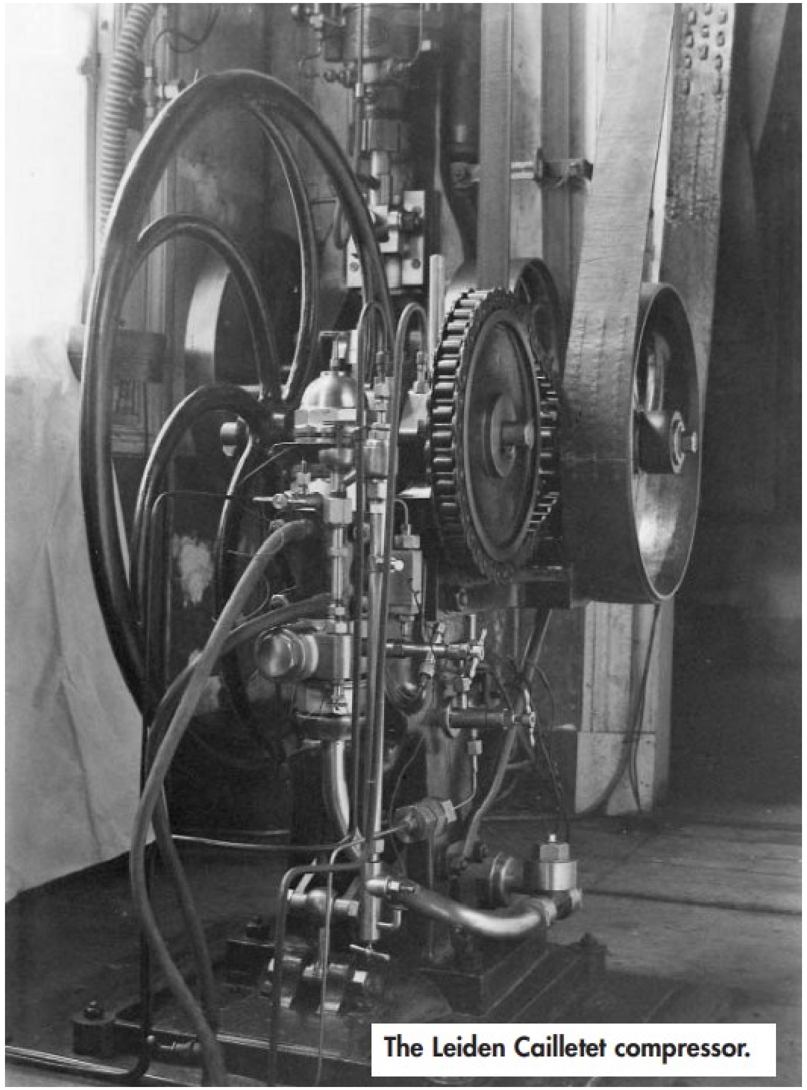


Kamerlingh Onnes (seated, left) and Johannes van der Waals

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


The Leiden Cailletet compressor.


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

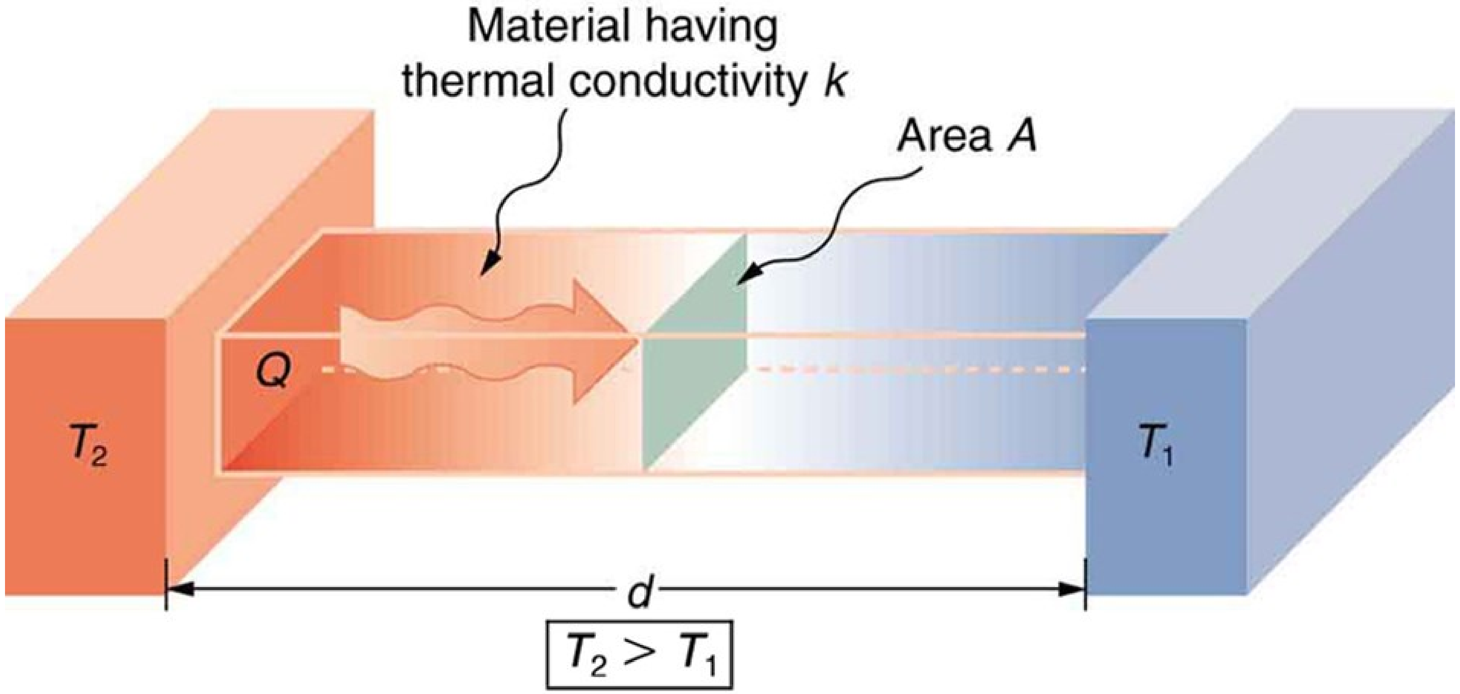
- How to have a stable working temperature

Thermal Conduction in Solids

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

Fourier Law

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



https://www.khanacademy.org/science/physics/thermodynamics/specific-heat-and-heat-transfer/a/what-is-thermal-conductivity

Thermal Conduction in Solids

$$\vec{q} = -k(T)\vec{\nabla}T$$ *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)*

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

A is the cross-section of the domain
Q is the power *(W)*

Thermal Conduction in Solids

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

In the case where ***A*** is constant

Thermal Conduction in Solids

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In the case where ***A*** is constant

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

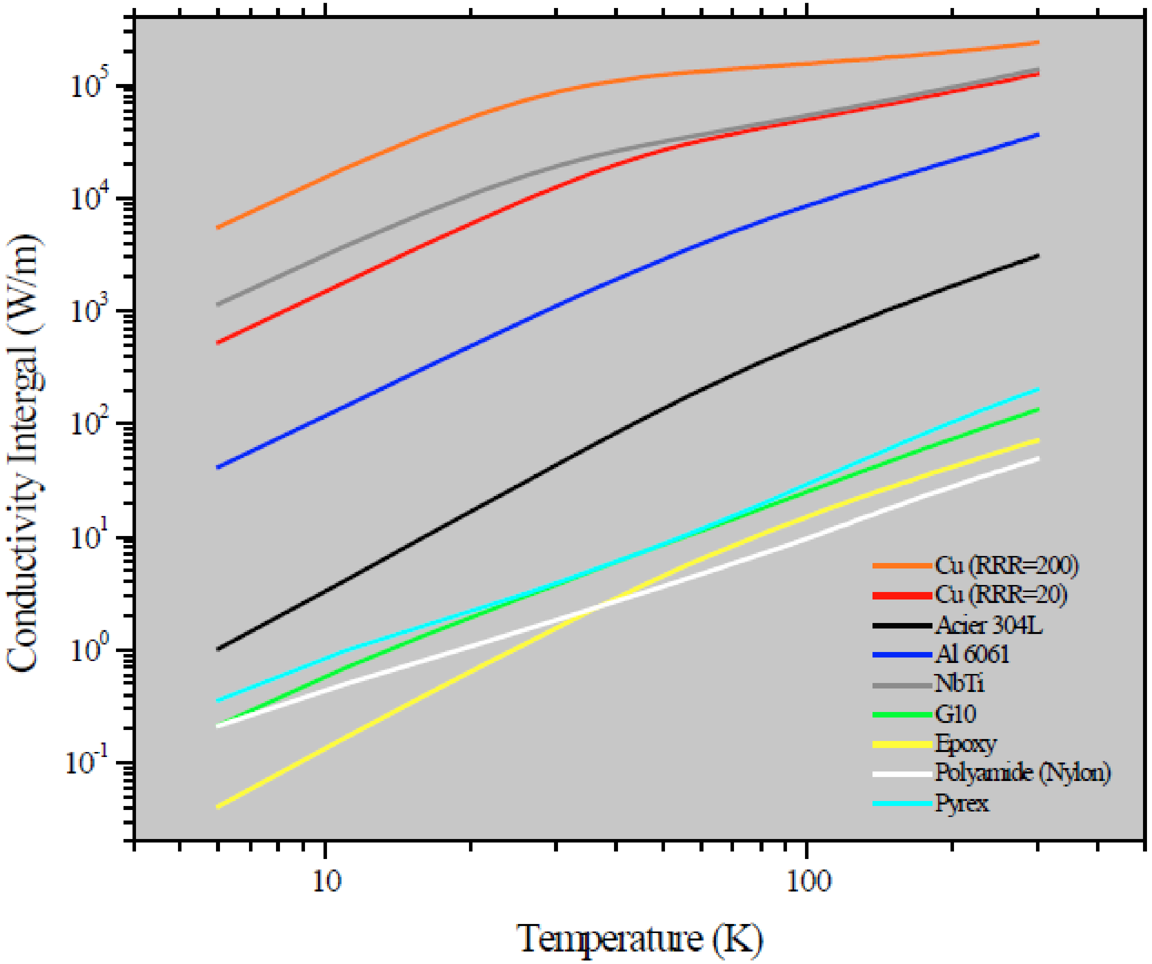
The definition of heat flux
in a one-dimensional domain

Thermal conductivity

$$\int_{T_{cold}}^{T_{hot}} k(T)dT$$

- Thermal conductivity of most materials varies strongly with temperature

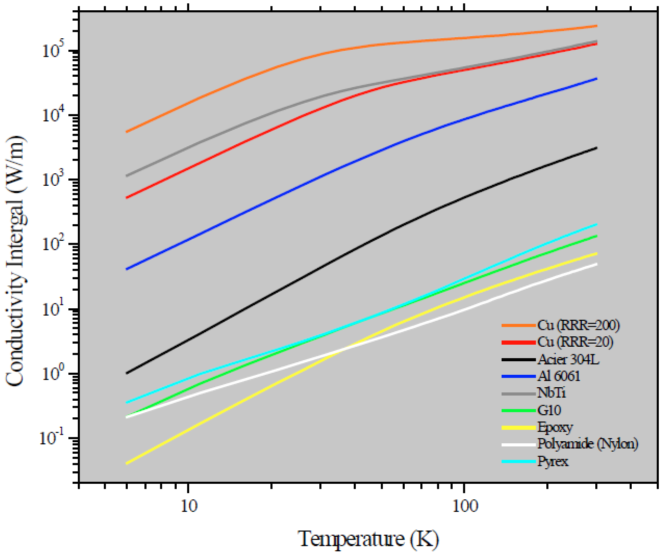
- Nb behavior close to SS

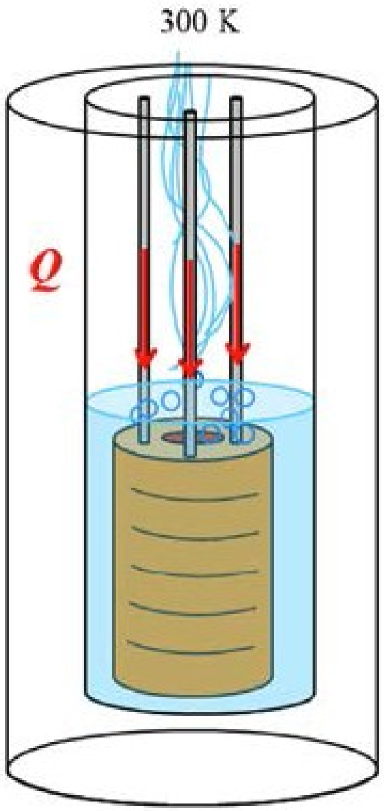


Thermal conductivity, exercise

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

- Heat leak?





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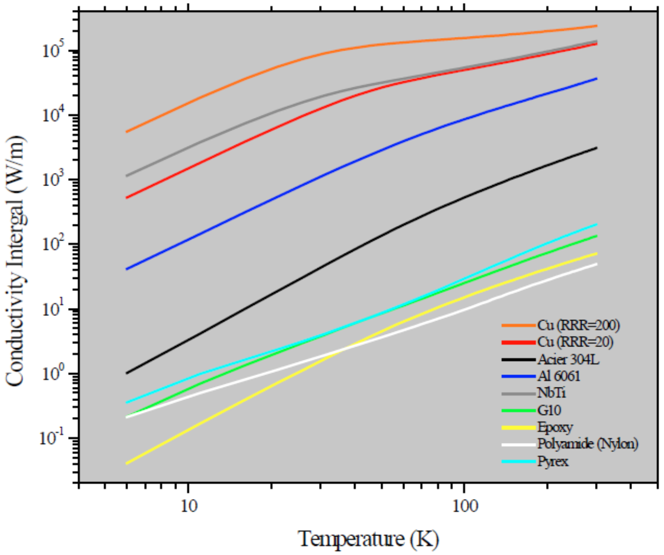

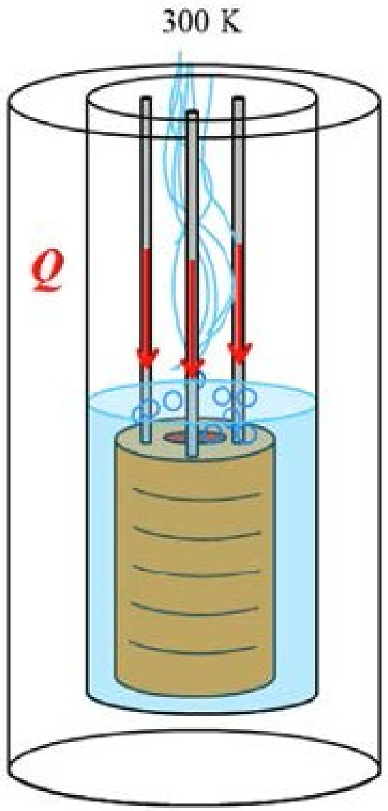

- Heat leak?

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

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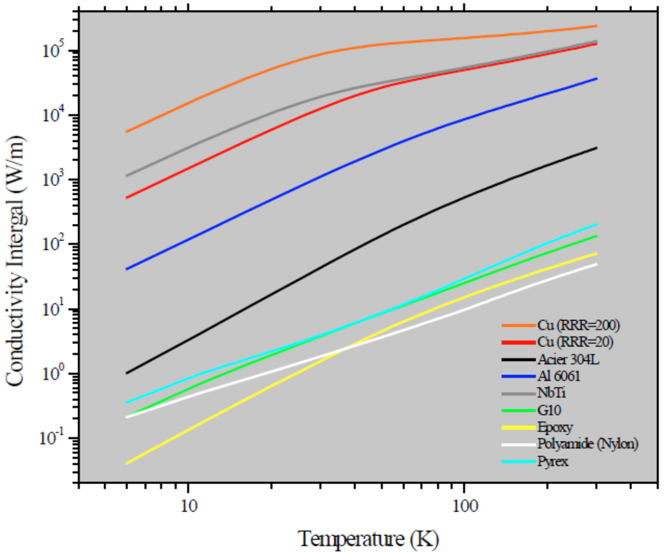

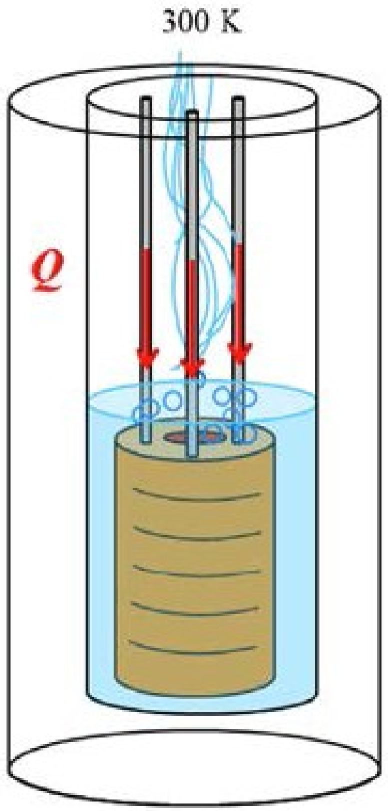

- Heat leak?

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

Thermal conductivity, exercise

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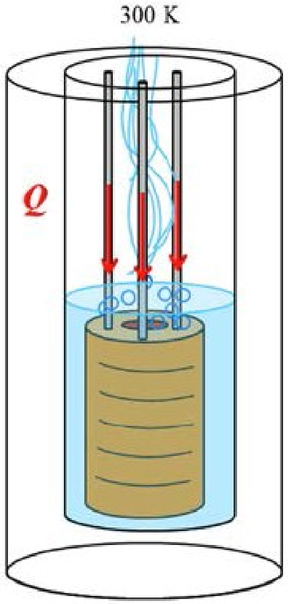
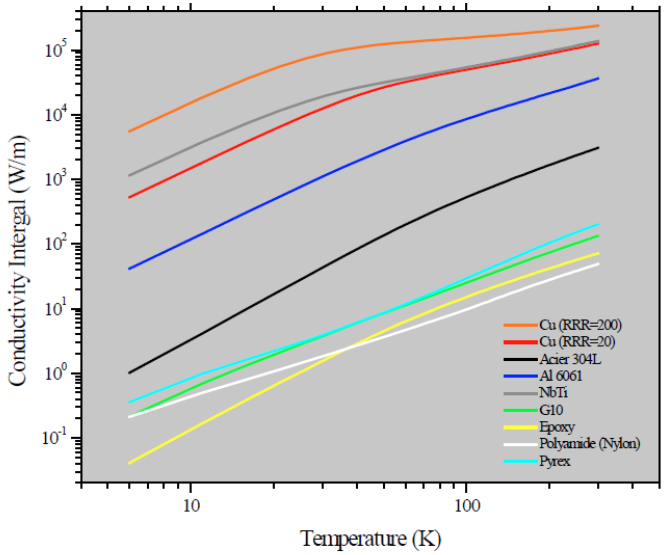
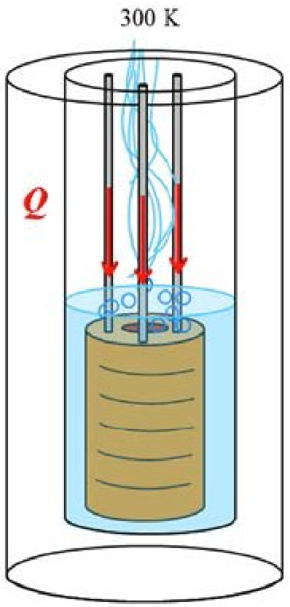




Thermal conductivity, exercise



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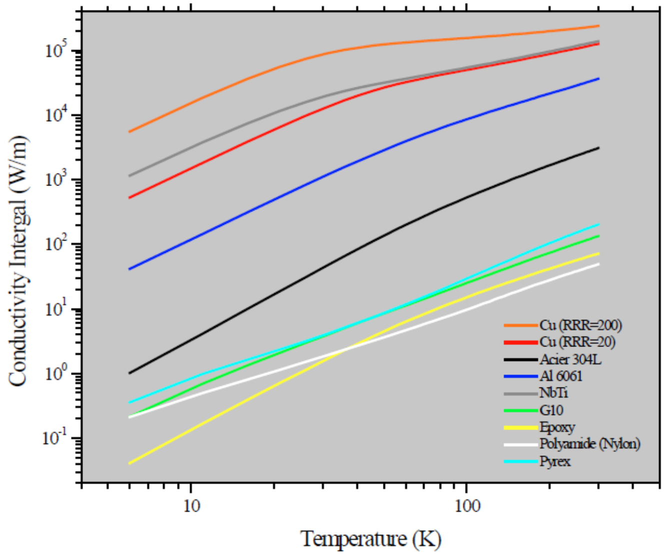
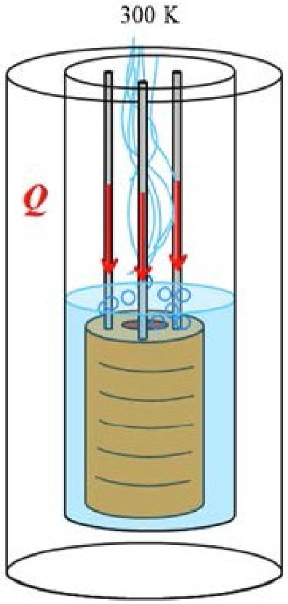
$$Q_{4K} = \frac{A}{L}\int_{4.2}^{300} \boldsymbol{k_{Cu\ RRR20}}(T)dT = \frac{2.36\times10^{-4}}{1}1.26\times10^{5} \approx 20\,W$$



Thermal conductivity, exercise



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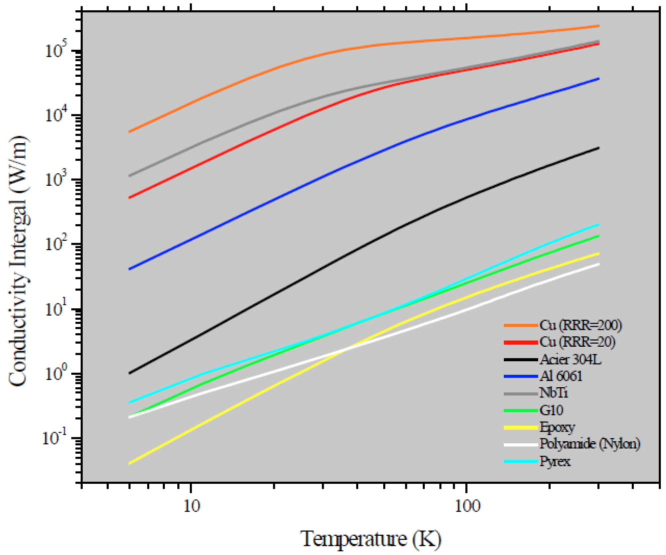
$$Q_{4K} = \frac{A}{L}\int_{4.2}^{300} \boldsymbol{k_{G10}}(T)dT = \frac{2.36 \times 10^{-4}}{1} 127 \approx 0.026\ W$$

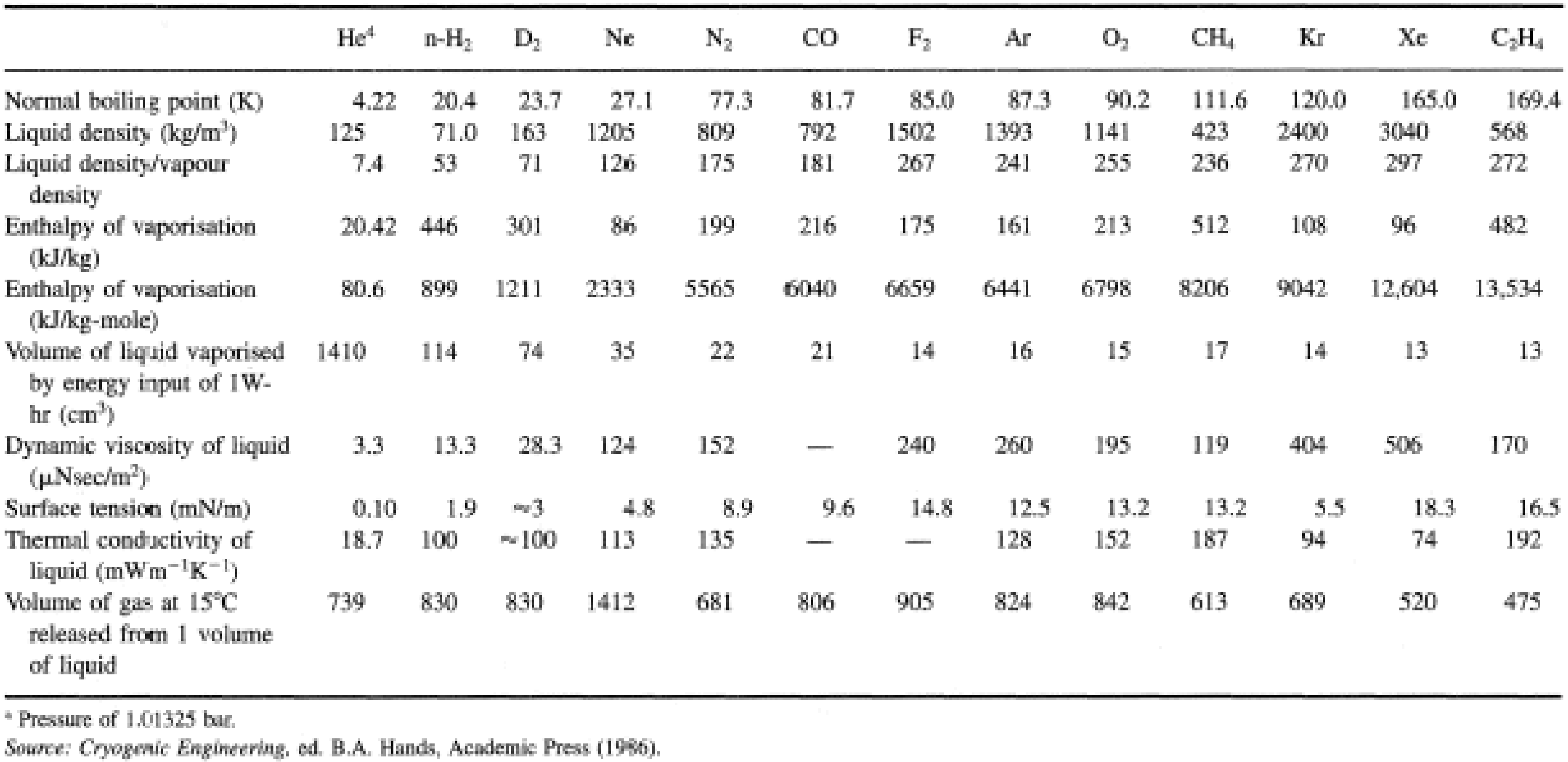


1 W = ? l liquid helium evaporated?

- In a phase transition:

$$Q_{ev} = \lambda_{ev} m$$

$\boldsymbol{Q_{ev}}$ is amount of energy absorbed during the evaporation *(kJ)*
$\boldsymbol{\lambda_{ev}}$ is the specific latent heat of vaporation *(kJ·kg⁻¹)*
m is the evaporated mass *(kg)*



	He^4	n-H_2	D_2	Ne	N_2	CO	F_2	Ar	O_2	CH_4	Kr	Xe	C_2H_4
Normal boiling point (K)	4.22	20.4	23.7	27.1	77.3	81.7	85.0	87.3	90.2	111.6	120.0	165.0	169.4
Liquid density (kg/m^3)	125	71.0	163	1205	809	792	1502	1393	1141	423	2400	3040	568
Liquid density/vapour density	7.4	53	71	126	175	181	267	241	255	236	270	297	272
Enthalpy of vaporisation (kJ/kg)	20.42	446	301	86	199	216	175	161	213	512	108	96	482
Enthalpy of vaporisation (kJ/kg-mole)	80.6	899	1211	2333	5565	6040	6659	6441	6798	8206	9042	12,604	13,534
Volume of liquid vaporised by energy input of 1W-hr (cm^3)	1410	114	74	35	22	21	14	16	15	17	14	13	13
Dynamic viscosity of liquid (μNsec/m^2)	3.3	13.3	28.3	124	152	—	240	260	195	119	404	506	170
Surface tension (mN/m)	0.10	1.9	~3	4.8	8.9	9.6	14.8	12.5	13.2	13.2	5.5	18.3	16.5
Thermal conductivity of liquid (mWm^{-1}K^{-1})	18.7	100	~100	113	135	—	—	128	152	187	94	74	192
Volume of gas at 15°C released from 1 volume of liquid	739	830	830	1412	681	806	905	824	842	613	689	520	475

[a] Pressure of 1.01325 bar.

Source: Cryogenic Engineering, ed. B.A. Hands, Academic Press (1986).

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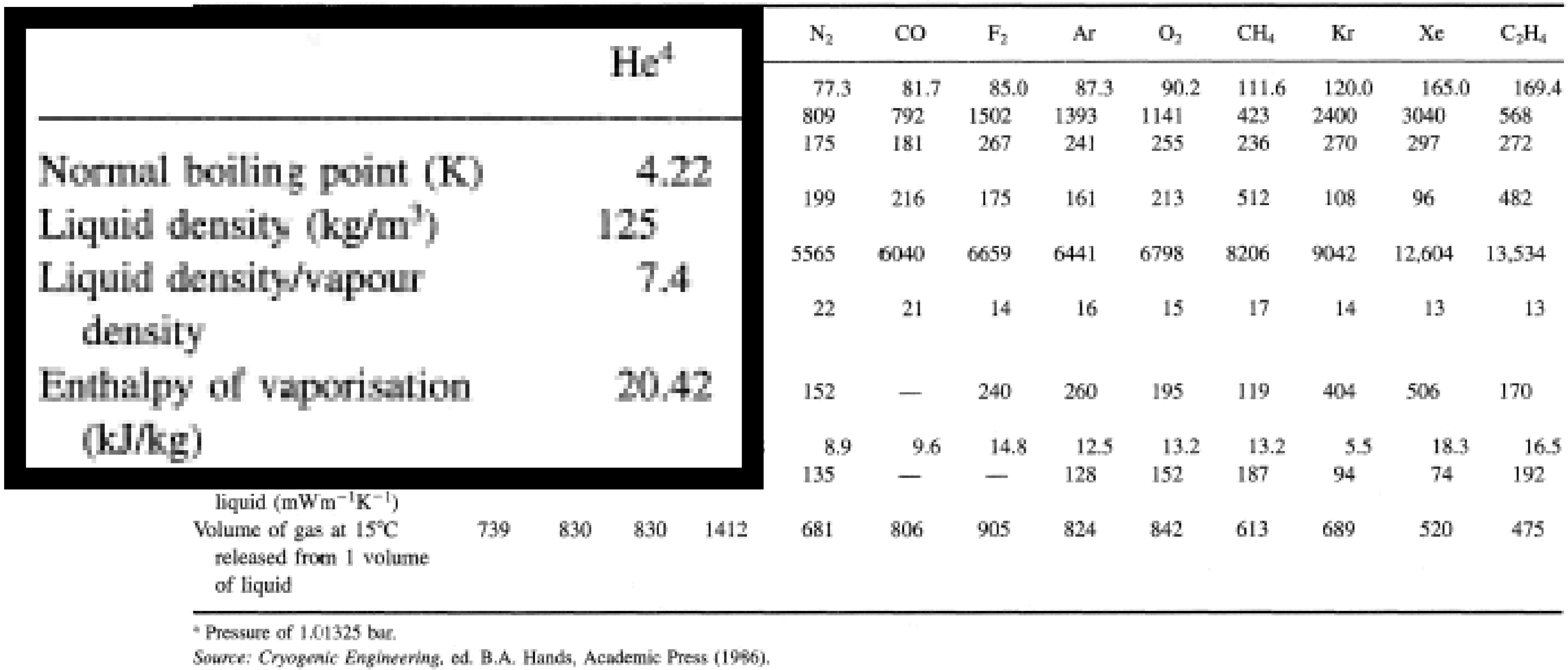

	He^4
Normal boiling point (K)	4.22
Liquid density (kg/m^3)	125
Liquid density/vapour density	7.4
Enthalpy of vaporisation (kJ/kg)	20.42

					N_2	CO	F_2	Ar	O_2	CH_4	Kr	Xe	C_2H_4
					77.3	81.7	85.0	87.3	90.2	111.6	120.0	165.0	169.4
					809	792	1502	1393	1141	423	2400	3040	568
					175	181	267	241	255	236	270	297	272
					199	216	175	161	213	512	108	96	482
					5565	6040	6659	6441	6798	8206	9042	12,604	13,534
					22	21	14	16	15	17	14	13	13
					152	—	240	260	195	119	404	506	170
					8.9	9.6	14.8	12.5	13.2	13.2	5.5	18.3	16.5
liquid ($mWm^{-1}K^{-1}$)					135	—	—	128	152	187	94	74	192
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m is the evaporated mass *(kg)*

- **With SS bars, the liquid helium consumption is:**

$$\frac{Q_{ev}}{\lambda_{ev}} = \frac{0.7 \cdot 10^{-3}}{20.42} = 0.034 \cdot 10^{-3} \frac{kg}{s} \sim 1 \frac{\boldsymbol{l}}{\boldsymbol{h}}$$

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

1 W = 1 J/s

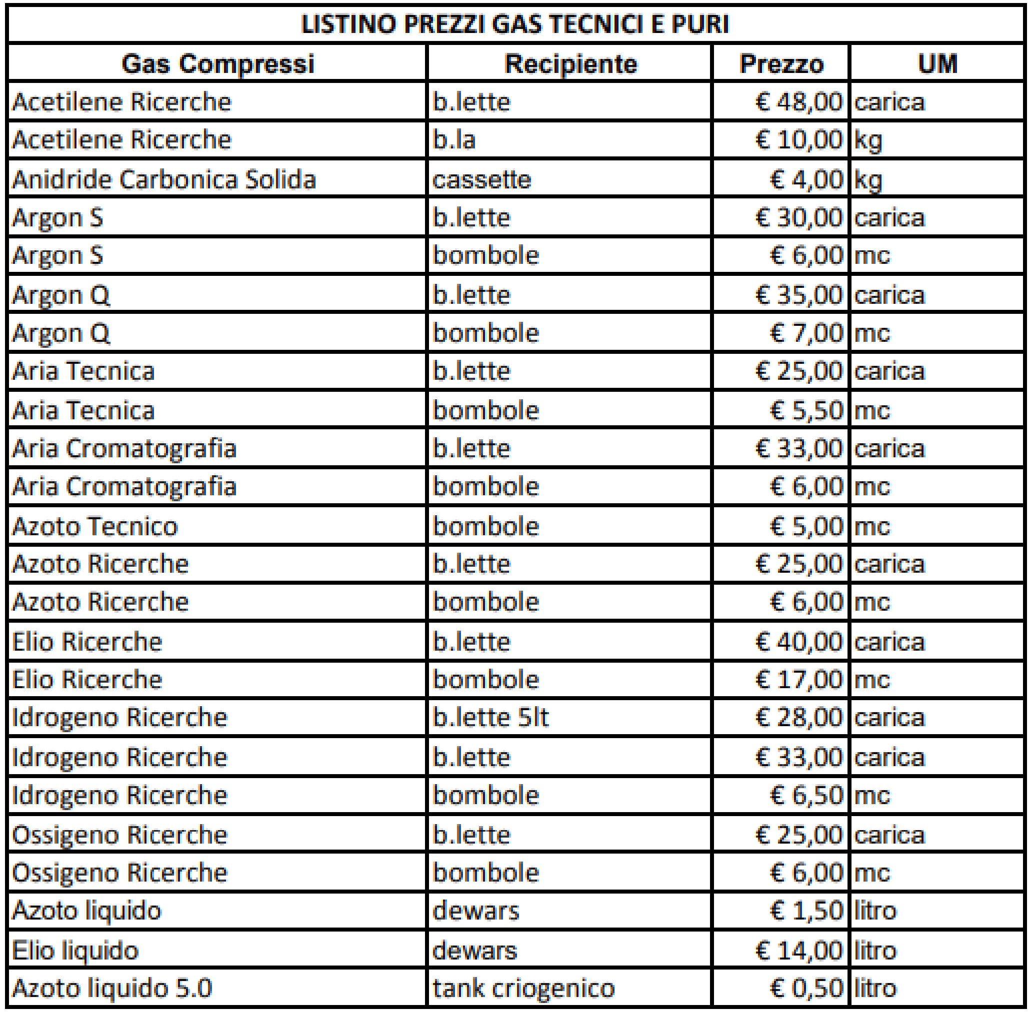
He density = 0.125 kg/l
λ_{ev} ***He = 20,42 kJ/kg***

- **With Cu bars ~ 31 l/h**
- **With G10 bars ~ 0.04 l/h**

Cost?

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

SIAD



LISTINO PREZZI GAS TECNICI E PURI

Gas Compressi	Recipiente	Prezzo	UM
Acetilene Ricerche	b.lette	€ 48,00	carica
Acetilene Ricerche	b.la	€ 10,00	kg
Anidride Carbonica Solida	cassette	€ 4,00	kg
Argon S	b.lette	€ 30,00	carica
Argon S	bombole	€ 6,00	mc
Argon Q	b.lette	€ 35,00	carica
Argon Q	bombole	€ 7,00	mc
Aria Tecnica	b.lette	€ 25,00	carica
Aria Tecnica	bombole	€ 5,50	mc
Aria Cromatografia	b.lette	€ 33,00	carica
Aria Cromatografia	bombole	€ 6,00	mc
Azoto Tecnico	bombole	€ 5,00	mc
Azoto Ricerche	b.lette	€ 25,00	carica
Azoto Ricerche	bombole	€ 6,00	mc
Elio Ricerche	b.lette	€ 40,00	carica
Elio Ricerche	bombole	€ 17,00	mc
Idrogeno Ricerche	b.lette 5lt	€ 28,00	carica
Idrogeno Ricerche	b.lette	€ 33,00	carica
Idrogeno Ricerche	bombole	€ 6,50	mc
Ossigeno Ricerche	b.lette	€ 25,00	carica
Ossigeno Ricerche	bombole	€ 6,00	mc
Azoto liquido	dewars	€ 1,50	litro
Elio liquido	dewars	€ 14,00	litro
Azoto liquido 5.0	tank criogenico	€ 0,50	litro

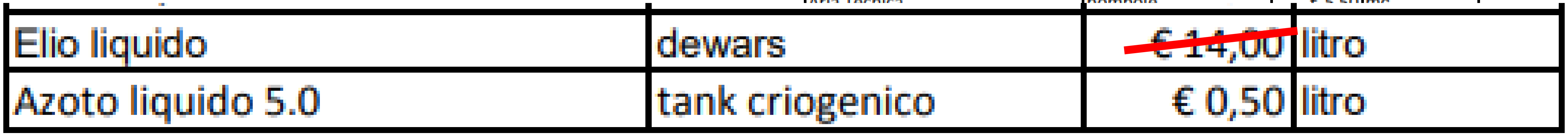
Cost?

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

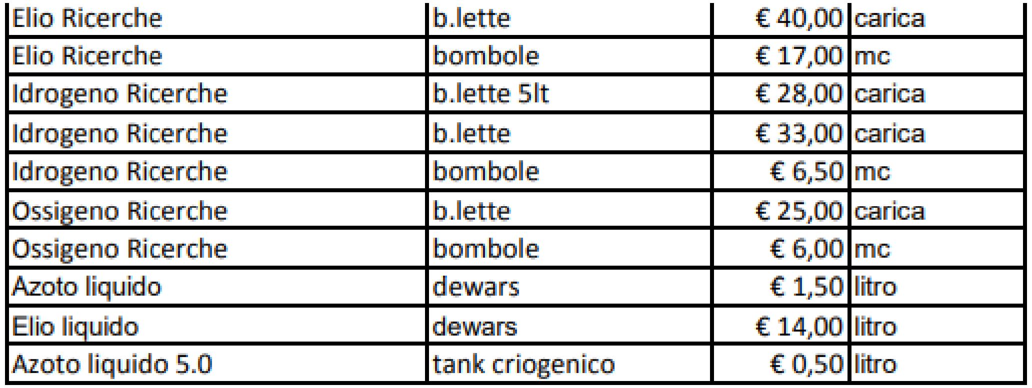
SIAD

LISTINO PREZZI GAS TECNICI E PURI			
Gas Compressi	**Recipiente**	**Prezzo**	**UM**
Acetilene Ricerche	b.lette	€ 48,00	carica
Acetilene Ricerche	b.la	€ 10,00	kg
Anidride Carbonica Solida	cassette	€ 4,00	kg
Argon S	b.lette	€ 30,00	carica
Argon S	bombole	€ 6,00	mc
Argon Q	b.lette		
Argon Q	bombol		
Aria Tecnica	b.lette		
Aria Tecnica	bombole	€ 5,50	mc

€ 50 / liter !!!



Elio liquido	dewars	~~€ 14,00~~	litro
Azoto liquido 5.0	tank criogenico	€ 0,50	litro



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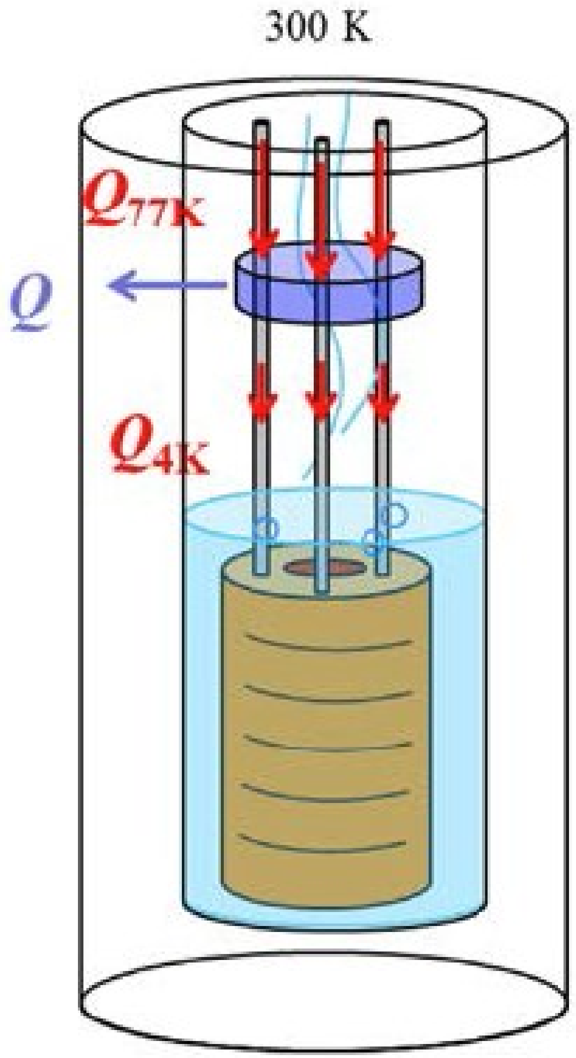
Ossigeno Ricerche	b.lette	€ 25,00	carica
Ossigeno Ricerche	bombole	€ 6,00	mc
Azoto liquido	dewars	€ 1,50	litro
Elio liquido	dewars	€ 14,00	litro
Azoto liquido 5.0	tank criogenico	€ 0,50	litro

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

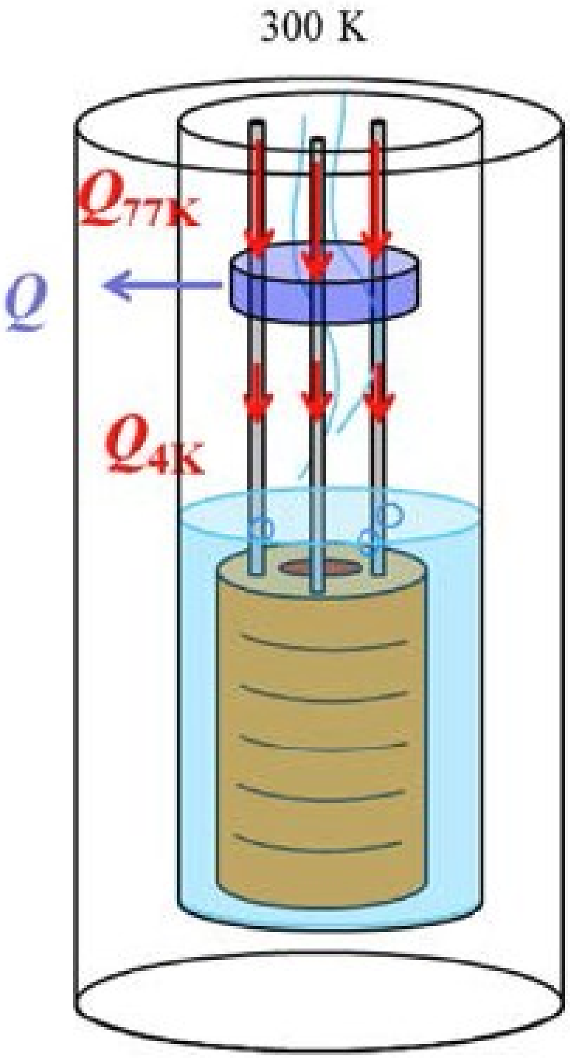
Heat Interception



Heat Interception

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

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



Heat Interception

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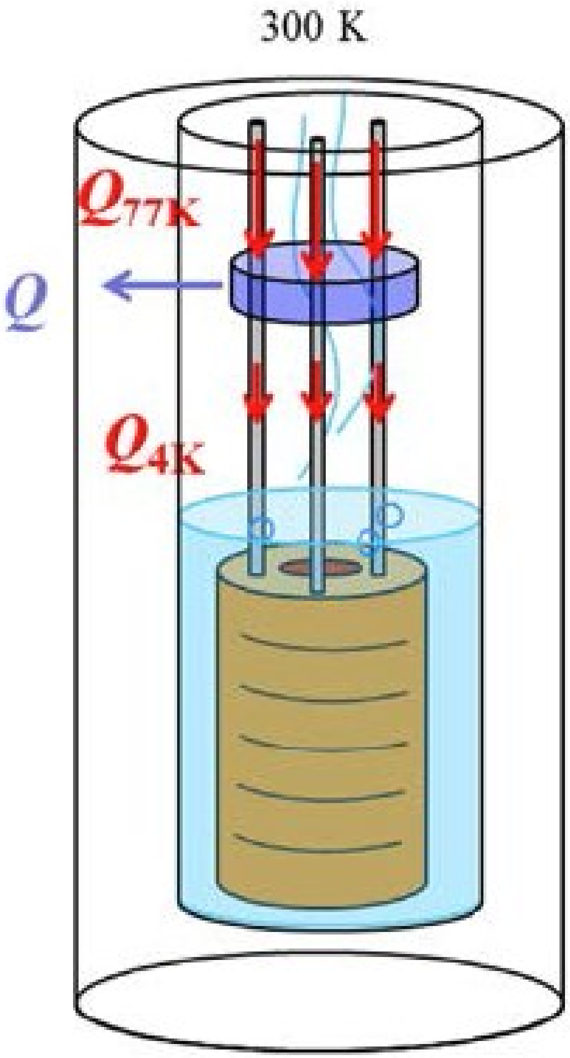
$$Q_{77K} = \frac{A}{L}\int_{77}^{300} k_{SS}(T)dT = \frac{2.36 \times 10^{-4}}{0.25} 2.75 \times 10^{3} \approx 2.6\ W$$



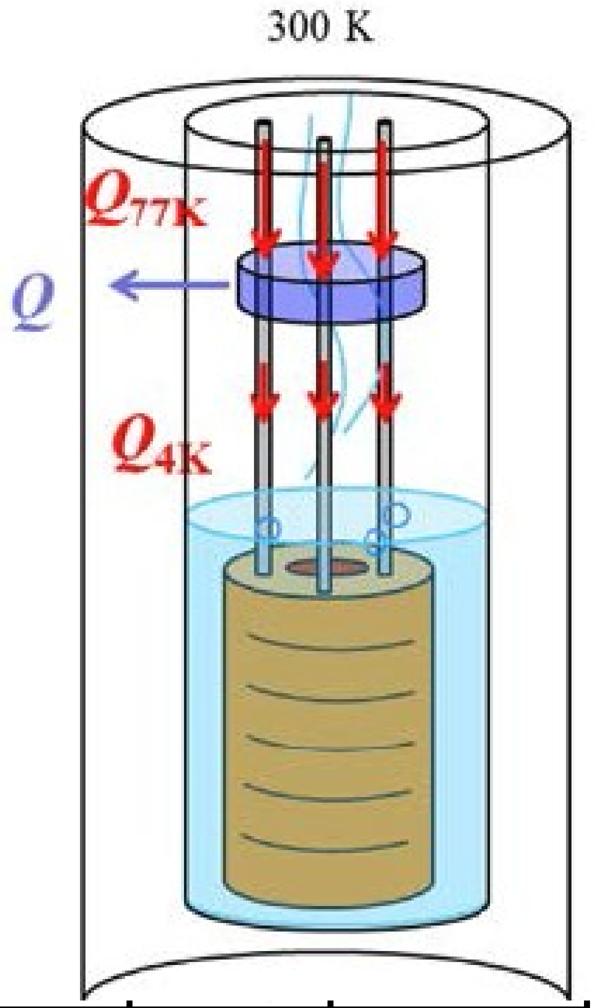
Heat Interception

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

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

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

consumption of 0.06 l·h^{-1} of liquid nitrogen ***~ 0,03 €/h***



	He^4	N$_2$
Normal boiling point (K)	4.22	77.3
Liquid density (kg/m^3)	125	809
Liquid density/vapour density	7.4	175
Enthalpy of vaporisation (kJ/kg)	20.42	199

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

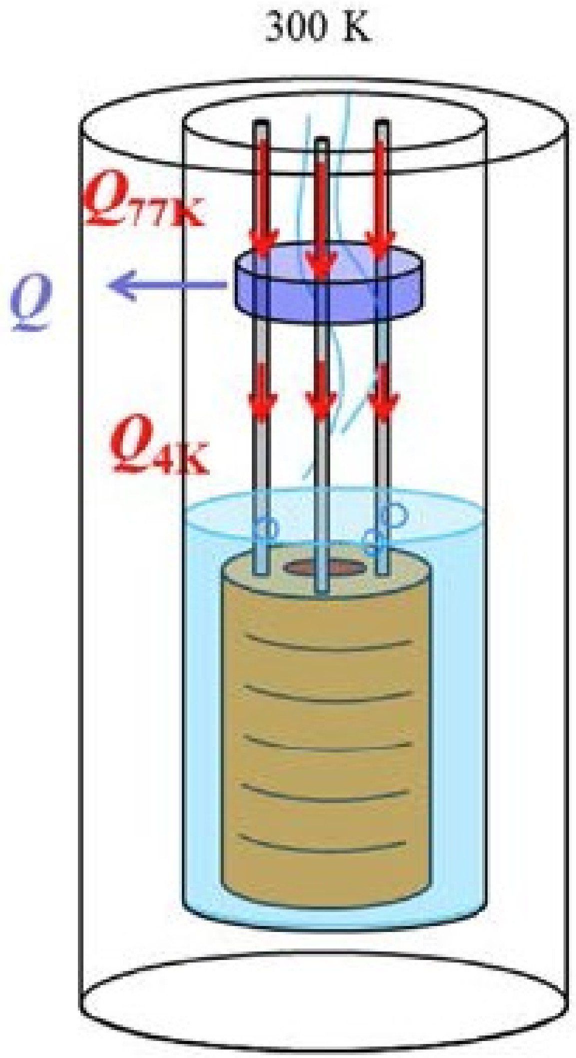
Heat Interception

$$Q_{4K} = \frac{A}{L}\int_{4.2}^{77} k_{SS}(T)dT = \frac{2.36\times10^{-4}}{0.75}325 \approx 0.1\ W$$

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

$$Q_{77K} = \frac{A}{L}\int_{77}^{300} k_{SS}(T)dT = \frac{2.36\times10^{-4}}{0.25}2.75\times10^{3} \approx 2.6\ W$$

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

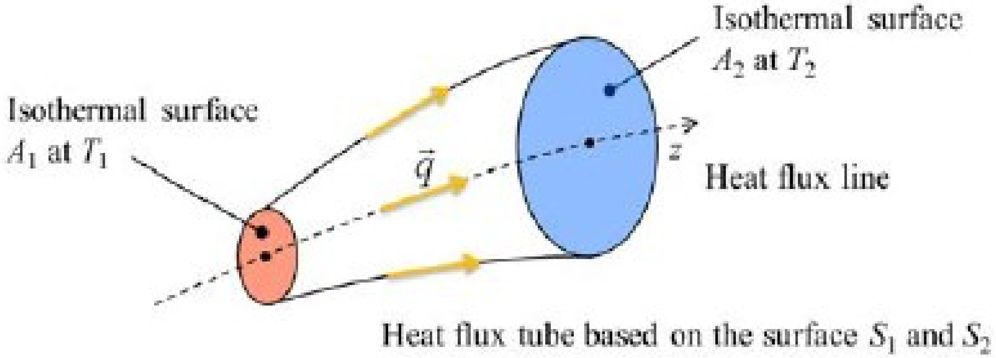


The optimization depends on many parameters:

- **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

$$Q\int_{z_1}^{z_2}\frac{dz}{A(z)} = -\int_{T_1}^{T_2} k(T)dT = \bar{k}(T_1 - T_2) \Rightarrow \boldsymbol{R_{th}} = \boldsymbol{\frac{T_1 - T_2}{Q}} = \boldsymbol{\frac{1}{\bar{k}}\int_{Z_1}^{Z_2}\frac{dz}{A(z)}\left[\frac{K}{W}\right]}$$

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

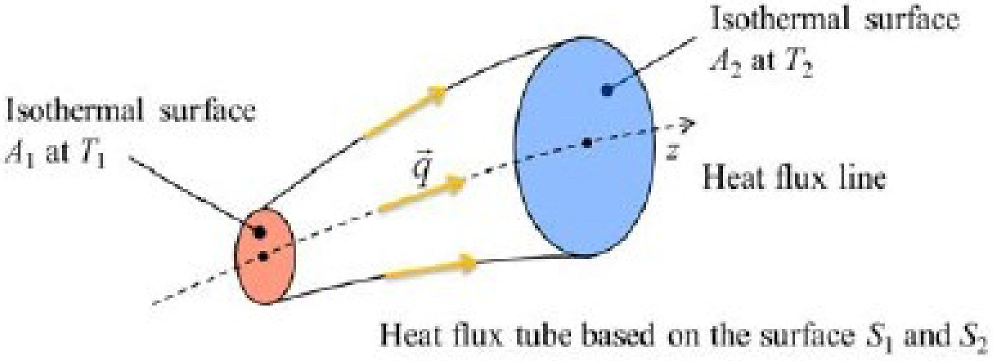
Thermal resistance R_{th}

$$Q\int_{z_1}^{z_2}\frac{dz}{A(z)} = -\int_{T_1}^{T_2}k(T)\,dT = \bar{k}(T_1 - T_2) \Rightarrow \boldsymbol{R_{th}} = \frac{\boldsymbol{T_1 - T_2}}{\boldsymbol{Q}} = \frac{\boldsymbol{1}}{\boldsymbol{\bar{k}}}\int_{Z_1}^{Z_2}\frac{\boldsymbol{dz}}{\boldsymbol{A(z)}}\left[\frac{\boldsymbol{K}}{\boldsymbol{W}}\right]$$

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

- for a slab a constant section A = A1 = A2 and a thickness L

$$\boldsymbol{R_{th}} = \frac{\boldsymbol{L}}{\boldsymbol{\bar{k}A}}$$



Heat flux tube based on the surface S_1 and S_2

- for a slab a cylinder with radio R1 and R2, with a length L

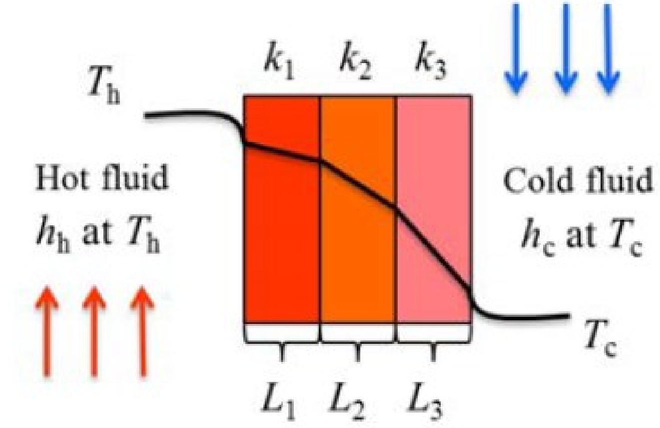
$$\boldsymbol{R_{th}} = \frac{\boldsymbol{\ln R_2/R_1}}{\boldsymbol{\bar{k}2\pi L}}$$

- a convective boundary thermal resistance can be simulated by considering a heat transfer coefficient h and a heat transfer area A as

$$\boldsymbol{R_{th}} = \frac{\boldsymbol{1}}{\boldsymbol{hA}}$$

Different Materials System

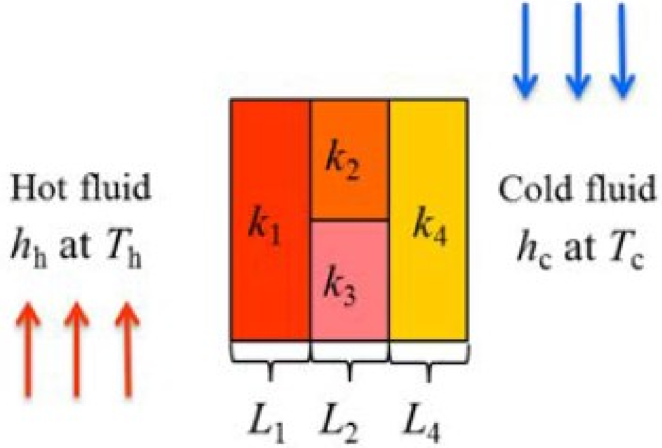
A **convective boundary thermal resistance** can also be simulated by considering a **heat transfer coefficient *h*** and a **heat transfer area *A*** as **$R_{th} = 1/hA$**



SERIES case

$$R_{total} = \sum R_i$$

$$Q = \frac{T_\mathrm{h} - T_\mathrm{c}}{\sum_i R_i} = A\frac{T_\mathrm{h} - T_\mathrm{c}}{(1/h_\mathrm{h}) + (L_1/\bar{k}_1) + (L_2/\bar{k}_2) + (L_3/\bar{k}_3) + \boxed{(1/h_\mathrm{c})}}$$

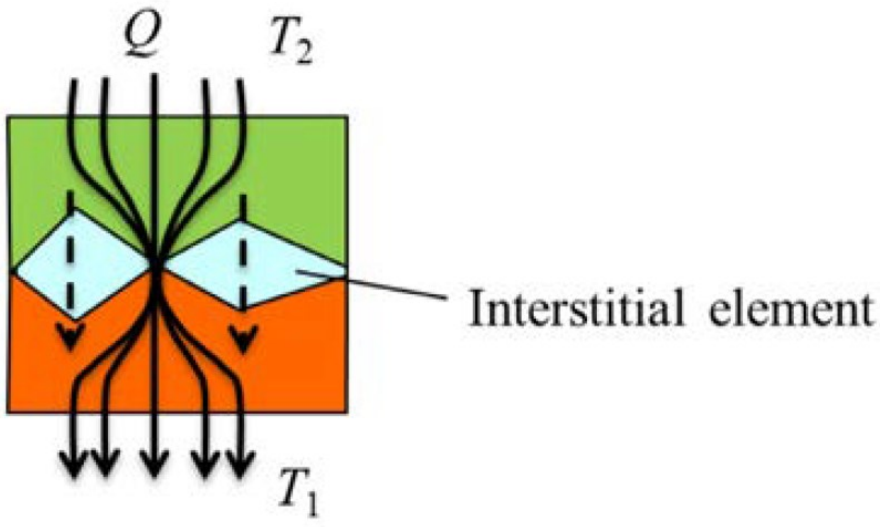


PARALLEL case

$$R_{total} = \sum \frac{1}{R_i}$$

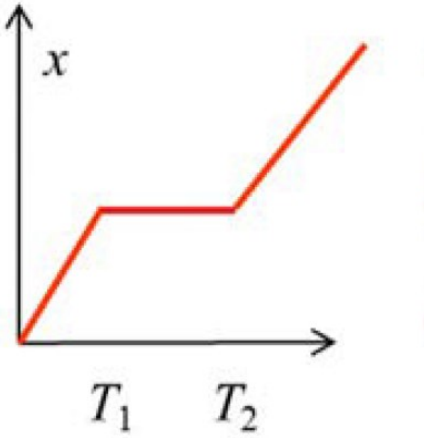
$$Q = A\frac{T_\mathrm{h} - T_\mathrm{c}}{(1/h_\mathrm{h}) + (L_1/\bar{k}_1) + (2L_2/(\bar{k}_2 + \bar{k}_3)) + (L_4/\bar{k}_4) + (1/h_\mathrm{c})}$$

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 Rc?

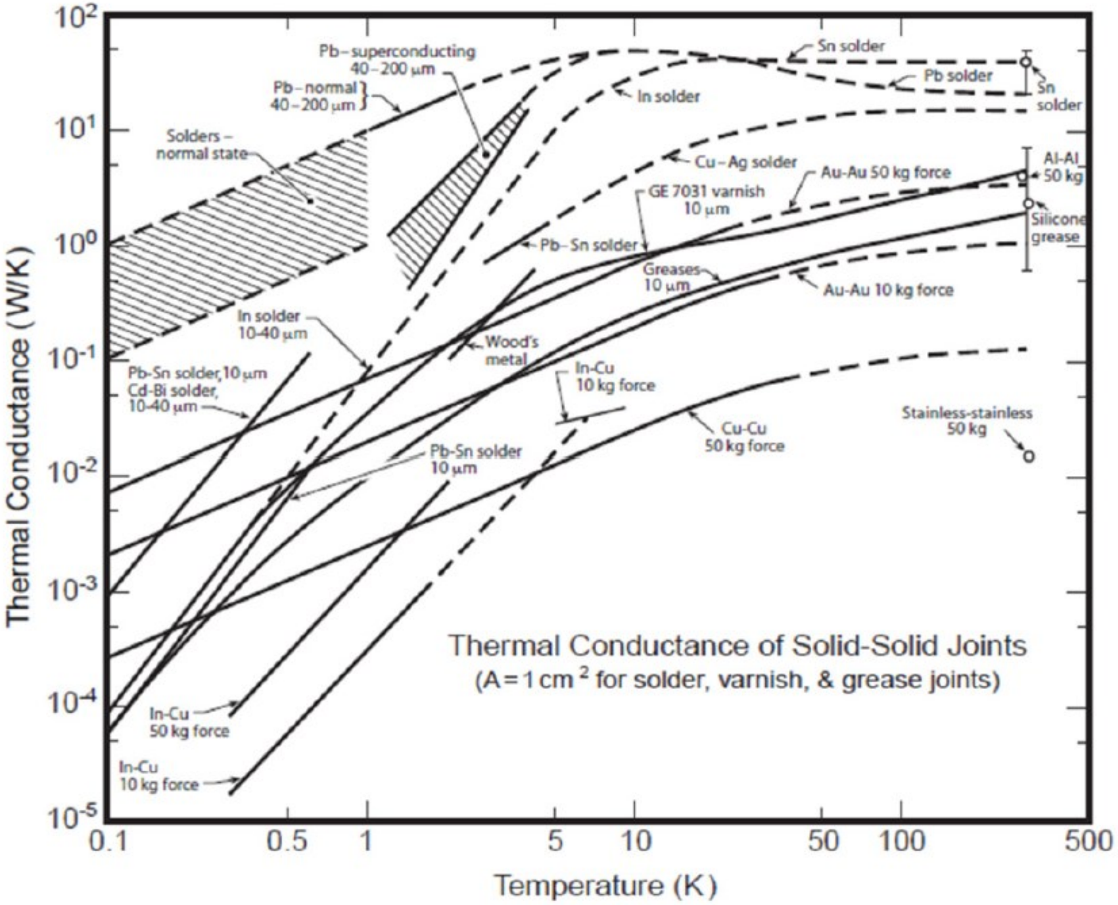
- Decrease with T
- Increase with applied force

- **Insertion of conductive and malleable fillers**

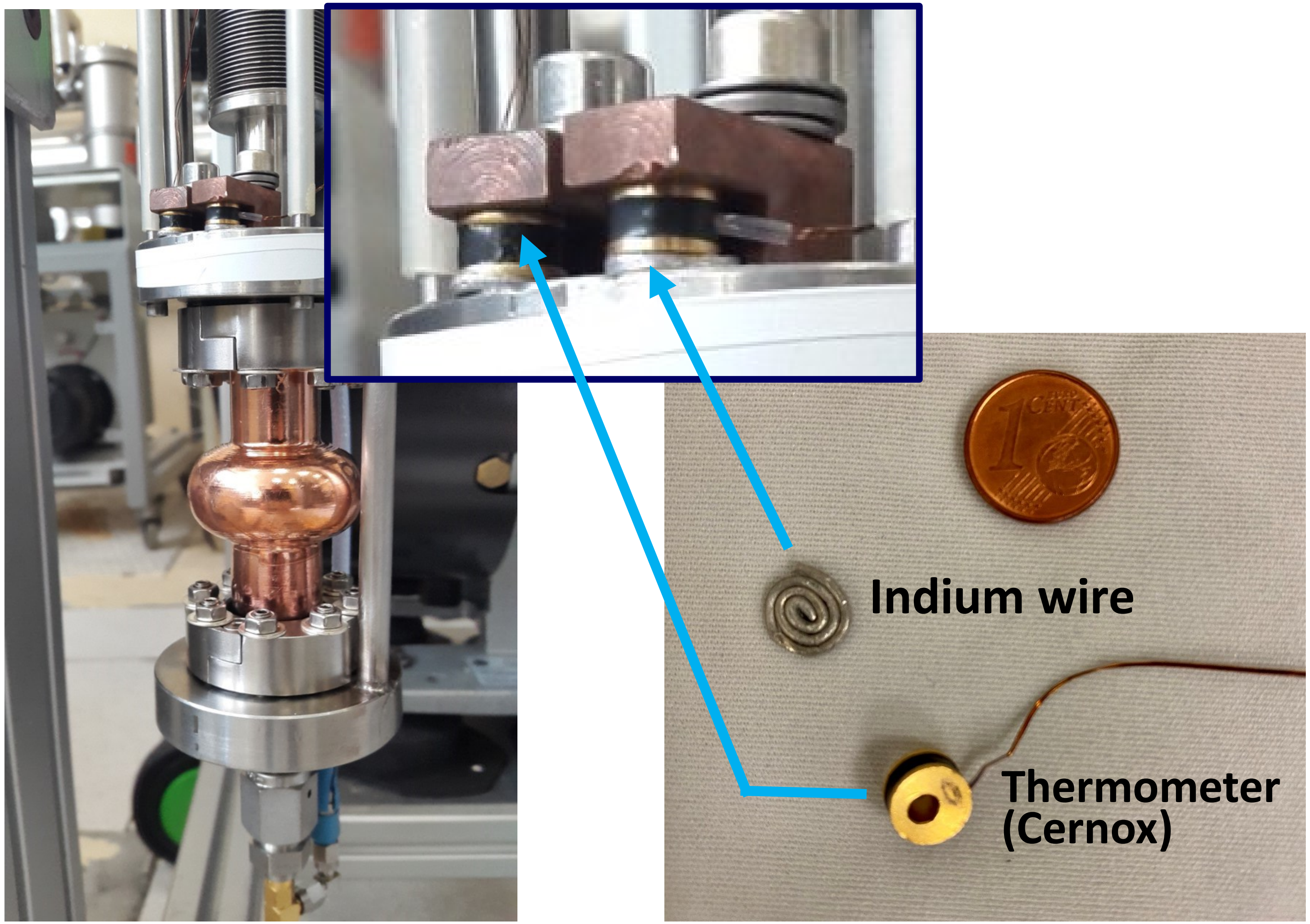
(charged grease, indium, or surface coatings)

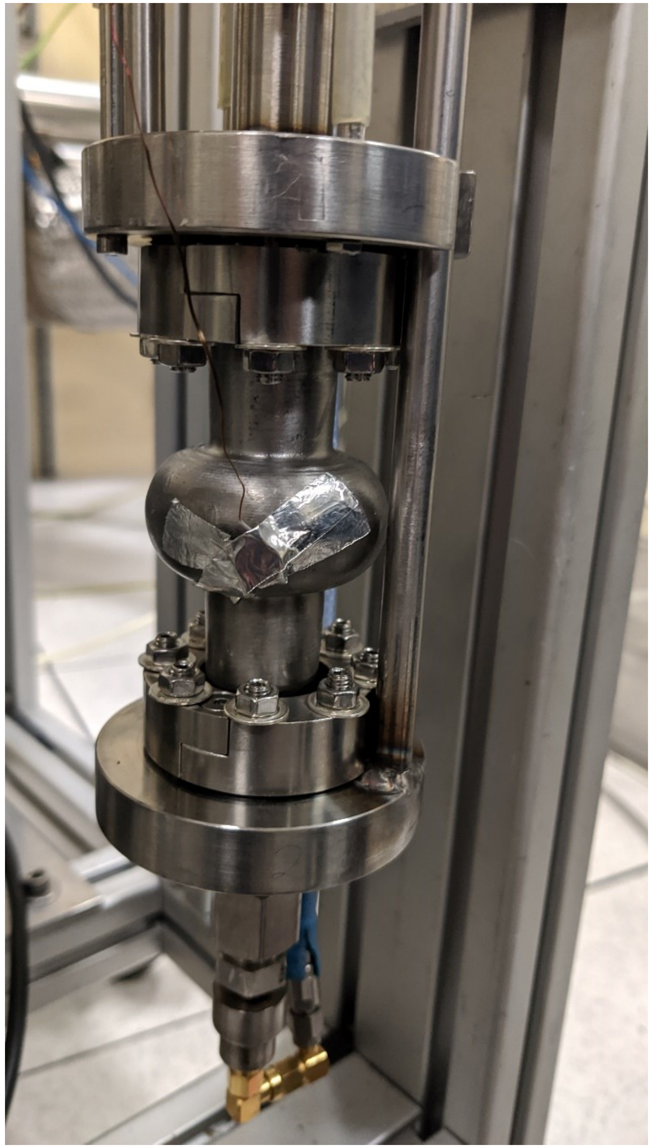
⬇

Fundamental for
a good thermometer contact



Thermometer contact



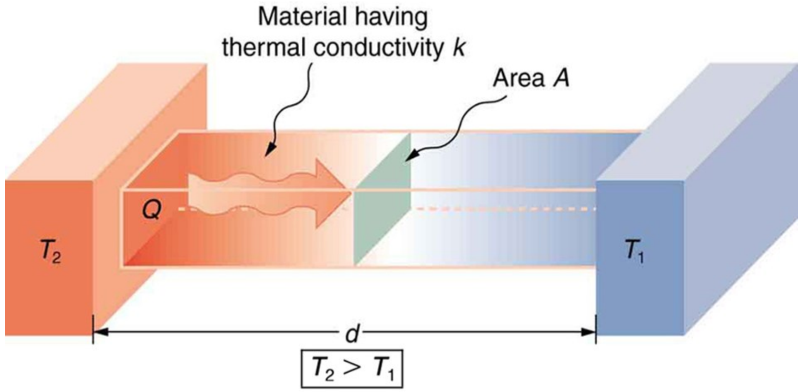


Transient conduction process and Thermal Diffusivity

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

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot \left(-k(T)\vec{\nabla} T \right) + Q$$

ρ is the density (kg$\cdot$m^{-3})
C specific heat of the solids (J$\cdot$kg$^{-1}\cdot$K^{-1})
k thermal conductivity (W$\cdot$m$^{-3}\cdot$K^{-1})
Q heat source (W$\cdot$m^{-3})



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

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

DIFFUSIVITY

$$\boldsymbol{\tau \approx \frac{4}{\pi^2}\frac{L^2}{D}}$$

τ characteristic diffusion time (95% T$_{\mathrm{fin}}$ = 3 τ)
L characteristic thermal length of the solid

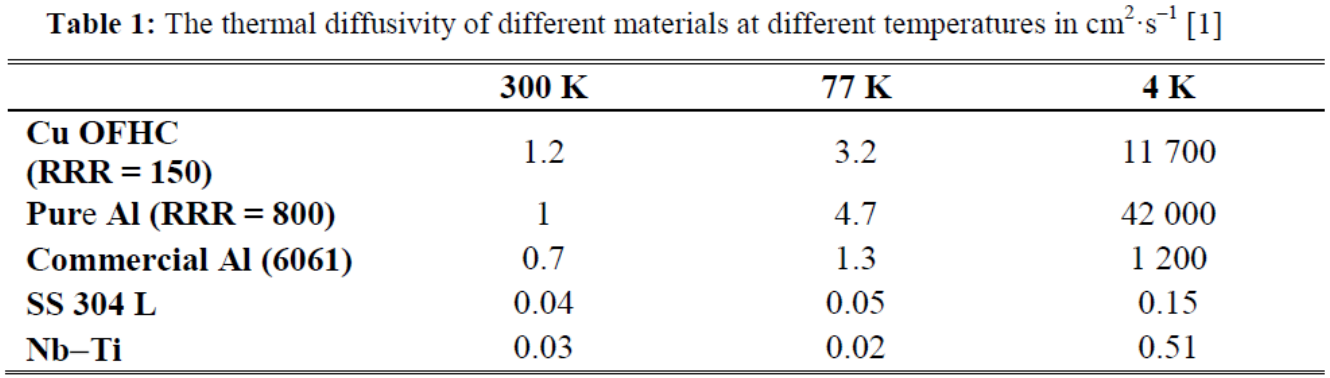
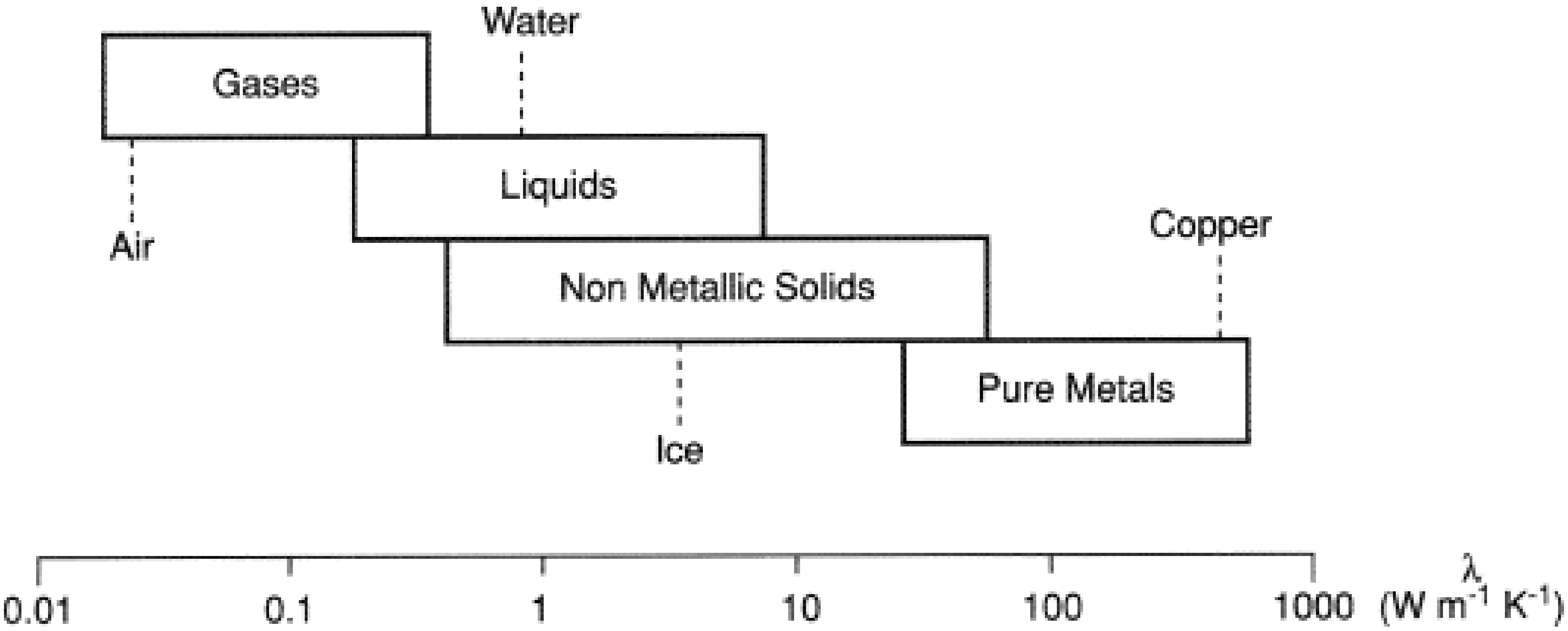


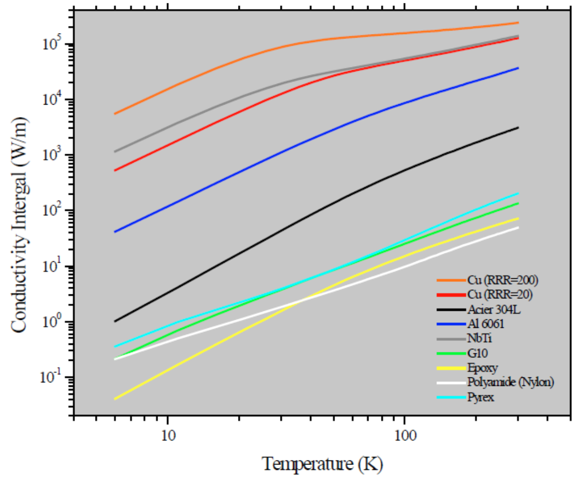
Table 1: The thermal diffusivity of different materials at different temperatures in cm$^2\cdot$s^{-1} [1]

	300 K	77 K	4 K
Cu OFHC (RRR = 150)	1.2	3.2	11 700
Pure Al (RRR = 800)	1	4.7	42 000
Commercial Al (6061)	0.7	1.3	1 200
SS 304 L	0.04	0.05	0.15
Nb–Ti	0.03	0.02	0.51

Thermal Conductivity (k) in different media



Thermal Conductivity (k) in different media



SOLIDS

O_2 (T = 90 K)	N_2 (T = 77 K)	H_2 (T = 20 K)	He (T = 4.2 K)
0.152	0.14	0.072	0.019

Thermal conductivity of some cryogens at atmospheric pressure ($W \cdot m^{-1} \cdot K^{-1}$)

LIQUIDS

bad thermal conductors

Except superfluid helium:

$k \approx 10^5\ W \cdot m^{-1} \cdot K^{-1}$

T (K)	^4He	H_2	N_2
300	150.7	176.9	25.8
75*	62.4	51.6	7.23
20	25.9	15.7	
5	9.7		

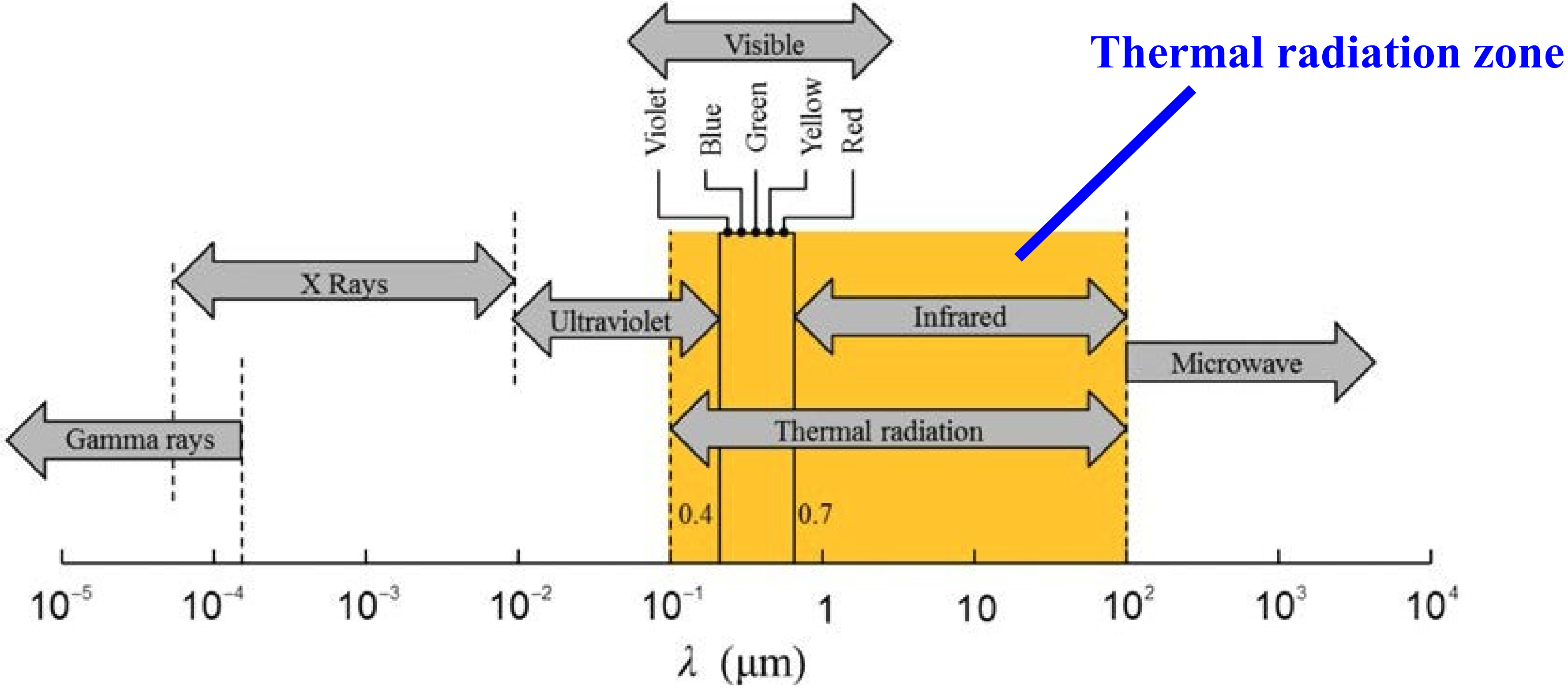
Thermal conductivity, k [$mW \cdot m^{-1} \cdot K^{-1}$] at 1 atm

GAS

Depends on mean free path λ 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**

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

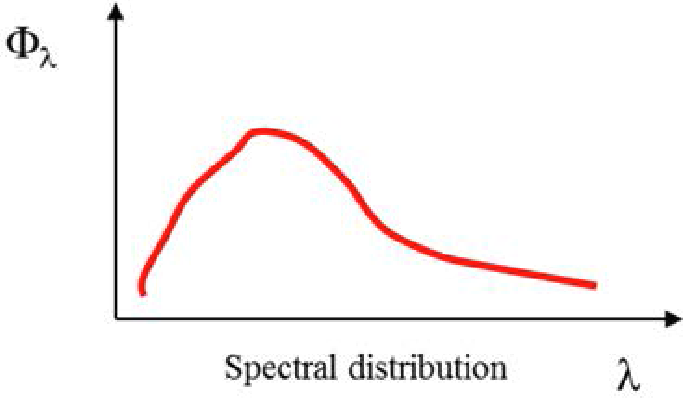
$$\sigma = 5.67 \cdot 10^{-8} W \cdot m^{-2} \cdot K^{-4}$$

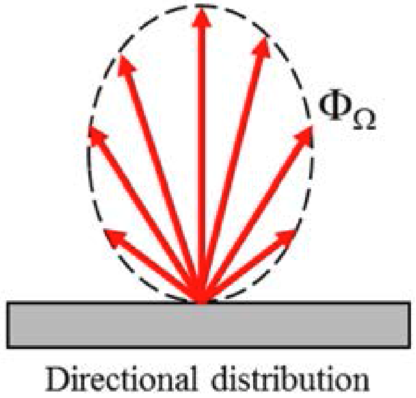
Stefan-Boltzmann constant

For real surface materials, emissive power is a fraction of the blackbody

Emissive power for real surface materials is defined as:

$$\boldsymbol{E^0} = \underbrace{\boldsymbol{\varepsilon}}_{\text{Emissivity}}\boldsymbol{\sigma T^4}$$

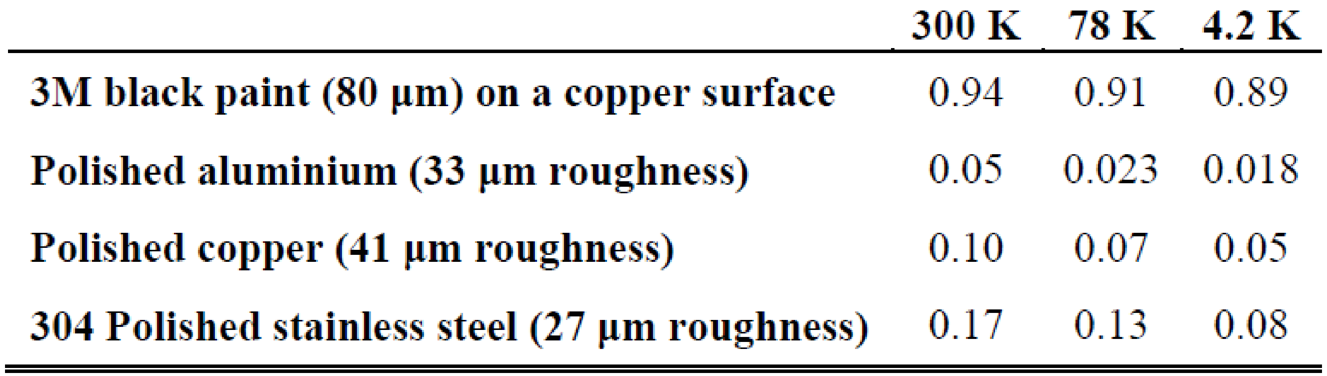




Emissivity

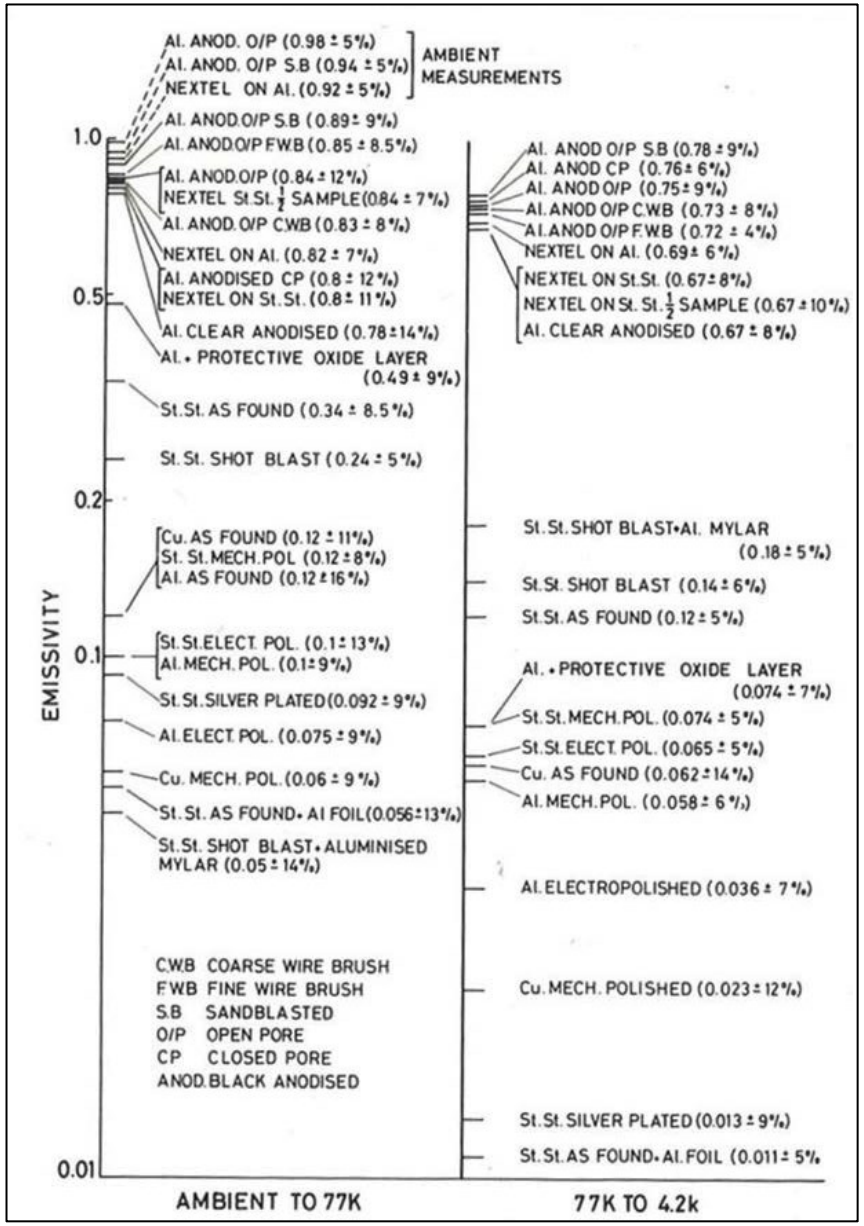
$$E^0 = \varepsilon \sigma T^4$$

- ε decreases with T
- ε increases with oxidation, impurities, dirt, …
- Highly polished and highly conductive clean surfaces allow to achieve the lowest emissivity values



	300 K	78 K	4.2 K
3M black paint (80 µm) on a copper surface	0.94	0.91	0.89
Polished aluminium (33 µm roughness)	0.05	0.023	0.018
Polished copper (41 µm roughness)	0.10	0.07	0.05
304 Polished stainless steel (27 µm roughness)	0.17	0.13	0.08

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:

$$\boldsymbol{q = \sigma(T_{warm}^4 - T_{cold}^4)}$$

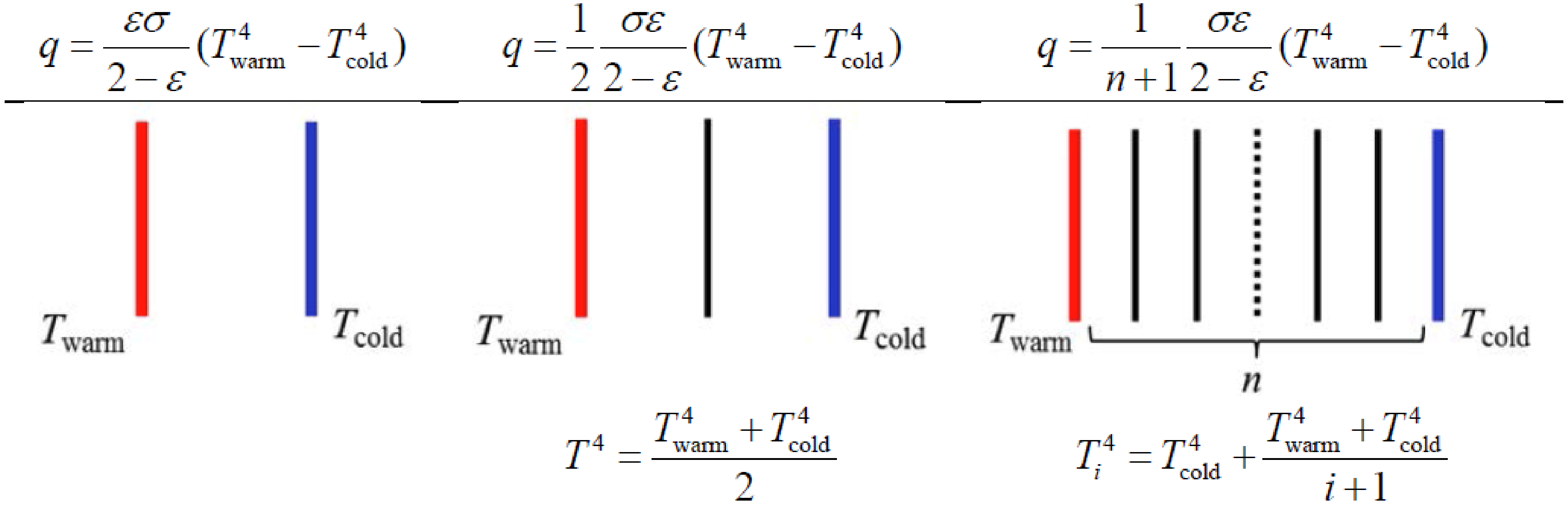
Heat transfer rate

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

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

$$\boldsymbol{q_{4.2\,K} = \sigma\left(T_{77}^4 - T_{4.2}^4\right) = 2W \cdot m^2}$$

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



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

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

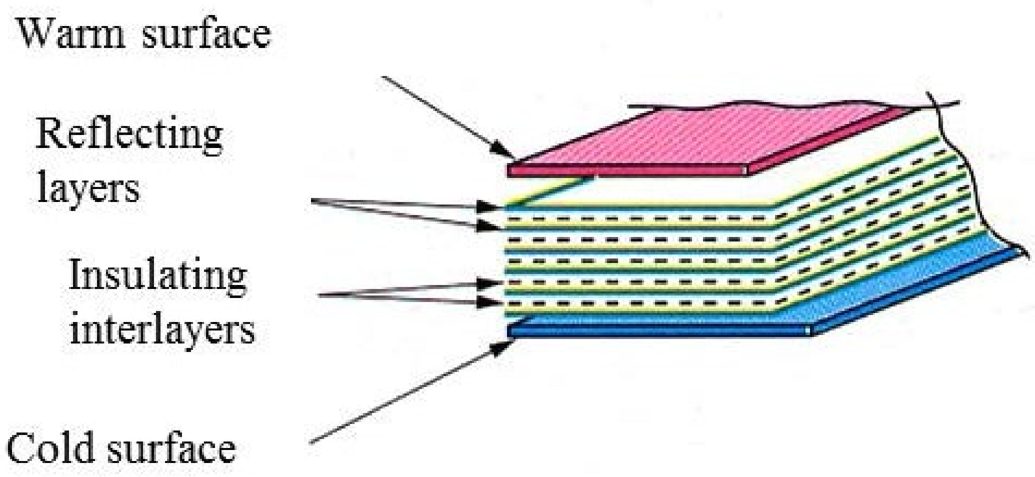
$$q = \frac{1}{n+1}\frac{\sigma\varepsilon}{2-\varepsilon}(T_{\text{warm}}^4 - T_{\text{cold}}^4)$$

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

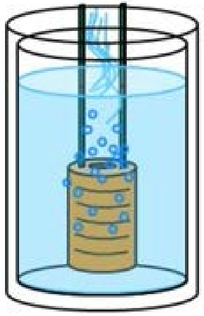
$$T_i^4 = T_{\text{cold}}^4 + \frac{T_{\text{warm}}^4 + T_{\text{cold}}^4}{i+1}$$

Multilayer insulation system (MLI)

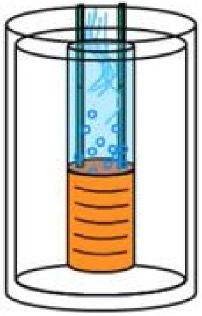
- Reflective films (usually aluminium or aluminized polyester film)
- Insulating interlayers (polyester, glass-fibre nets, or paper)
- Operated under vacuum



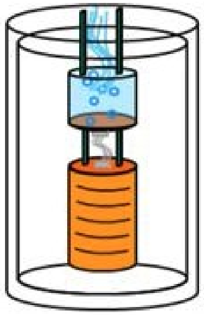
Cooling techniques at Low Temperature



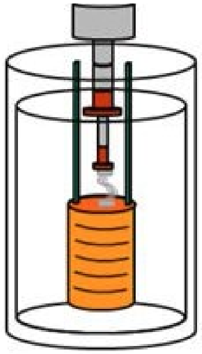
Direct cooling
Bath cooling



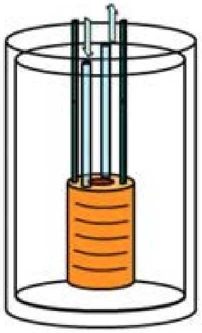
Indirect cooling
Bath cooling



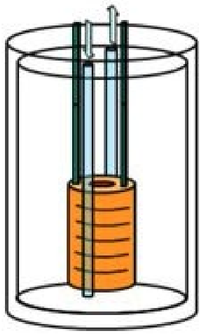
Indirect cooling
Bath as cold source



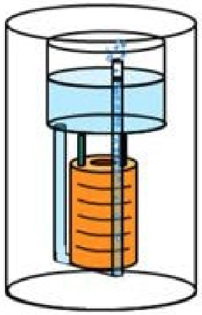
Indirect cooling
Cryocooler as cold source
Thermal link



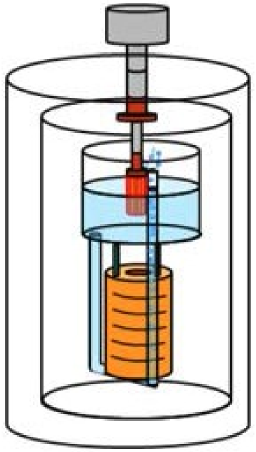
Direct cooling
Forced flow



Indirect cooling
Forced flow

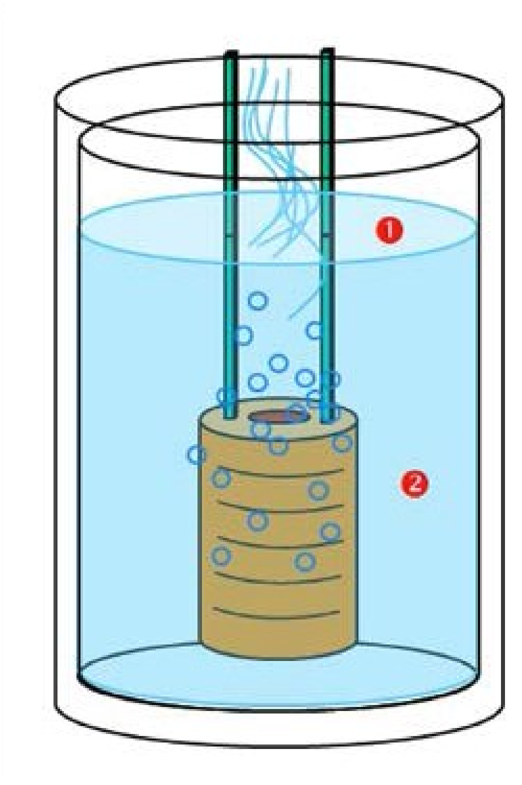


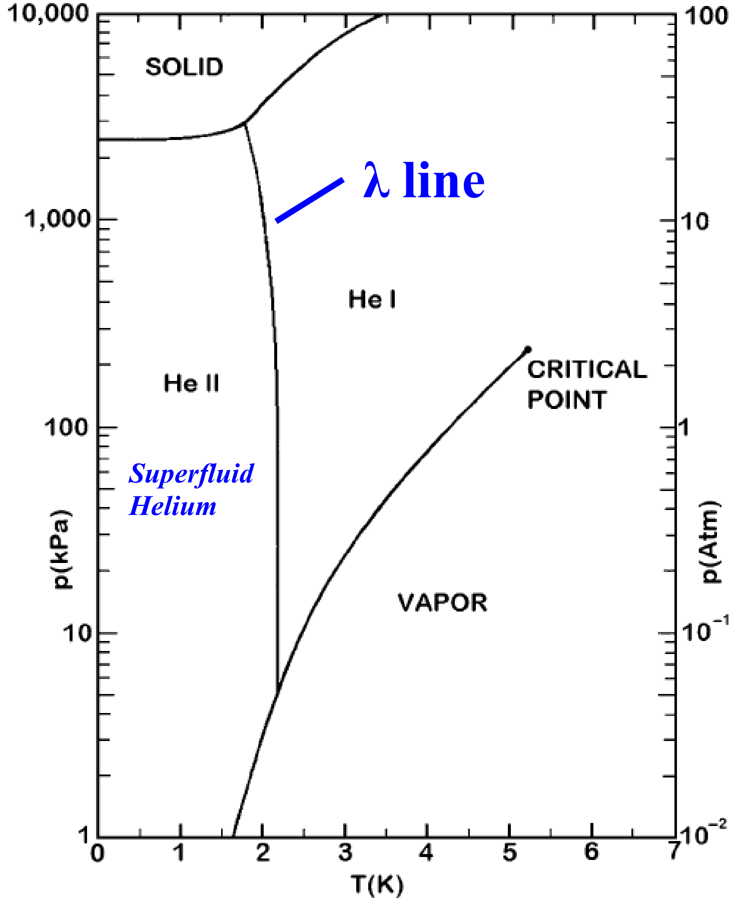
Indirect cooling
Two-phase thermosiphon

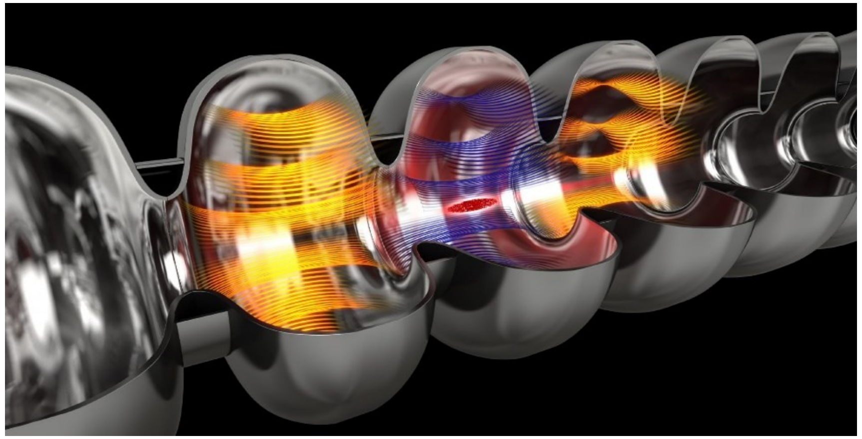


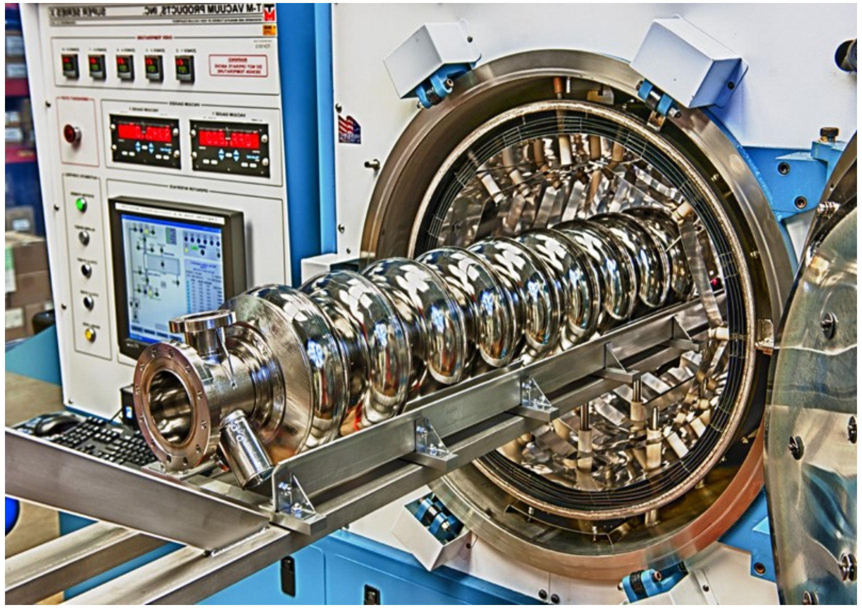
Indirect cooling
Two-phase thermosiphon
Coupled with a cryocooler

Helium direct cooling bath method



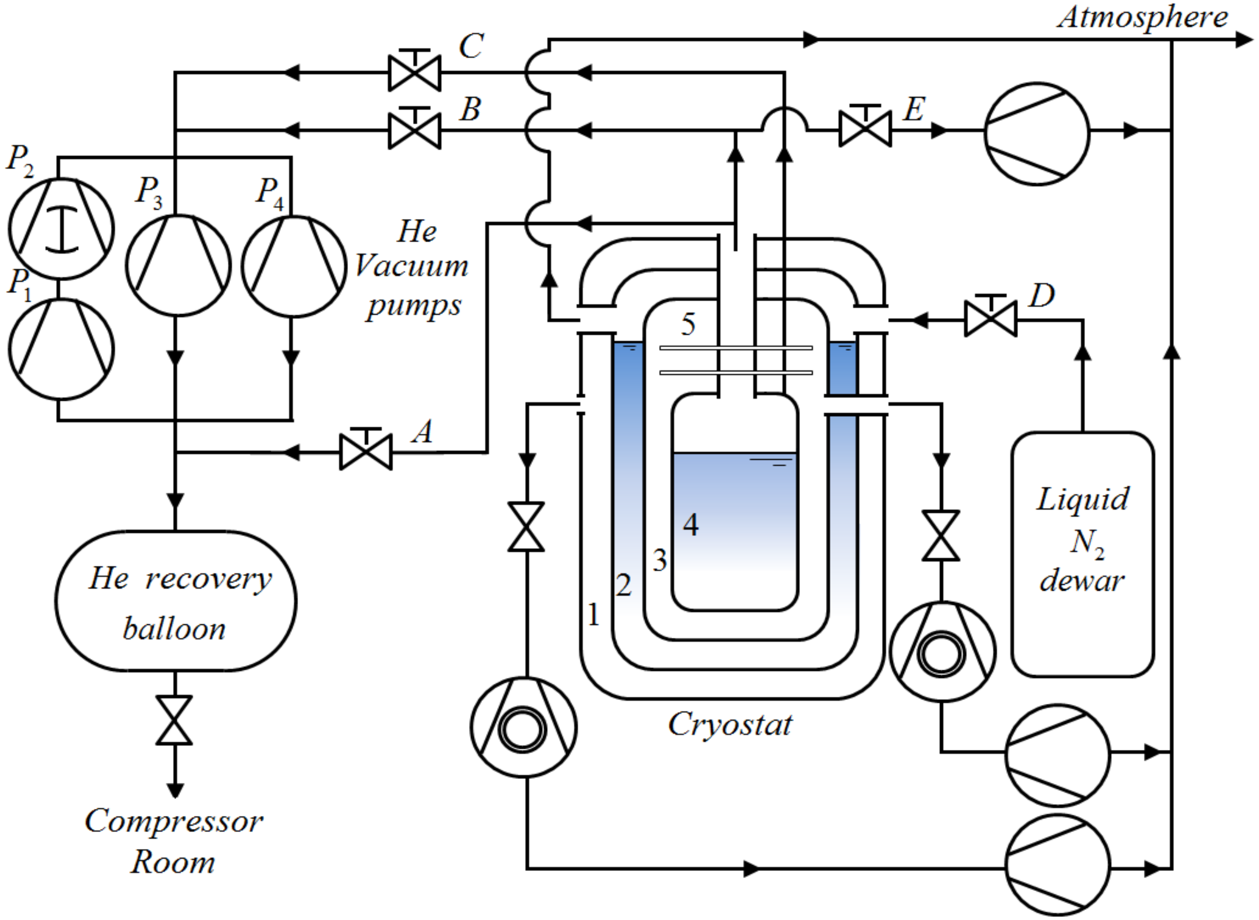




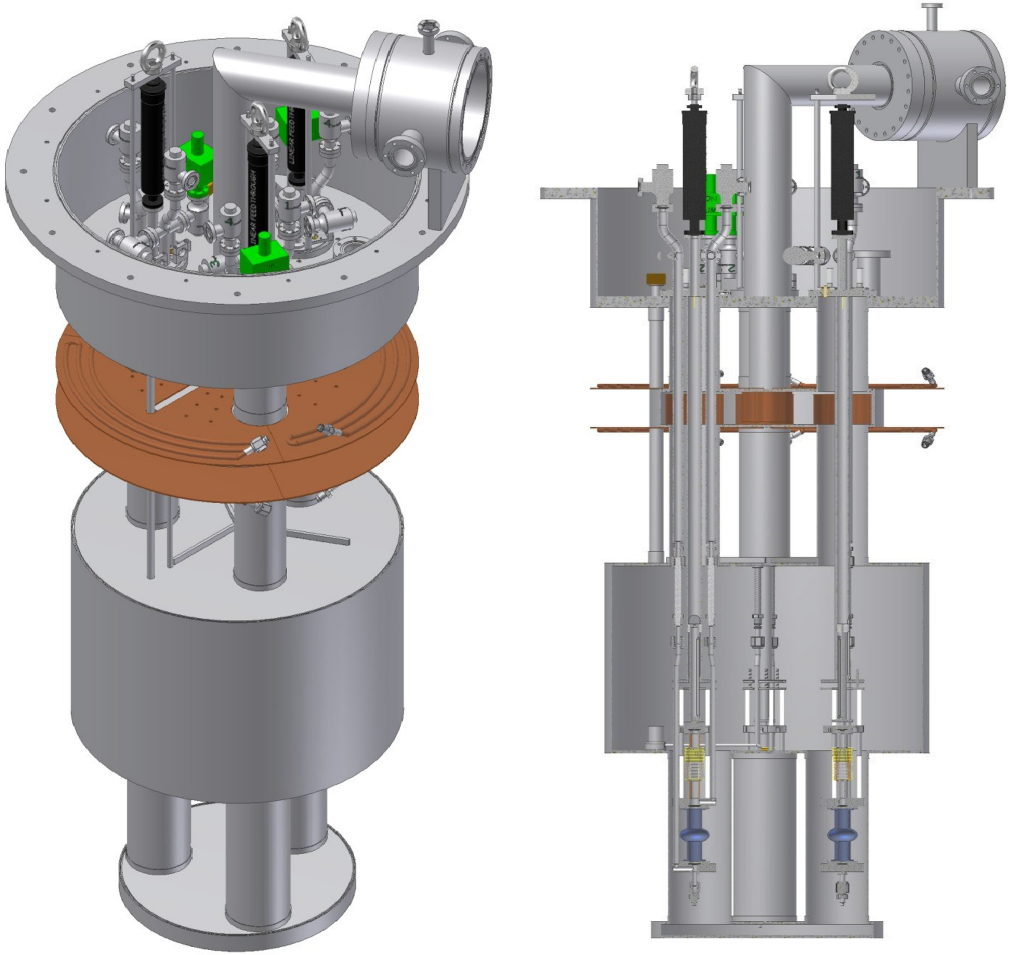


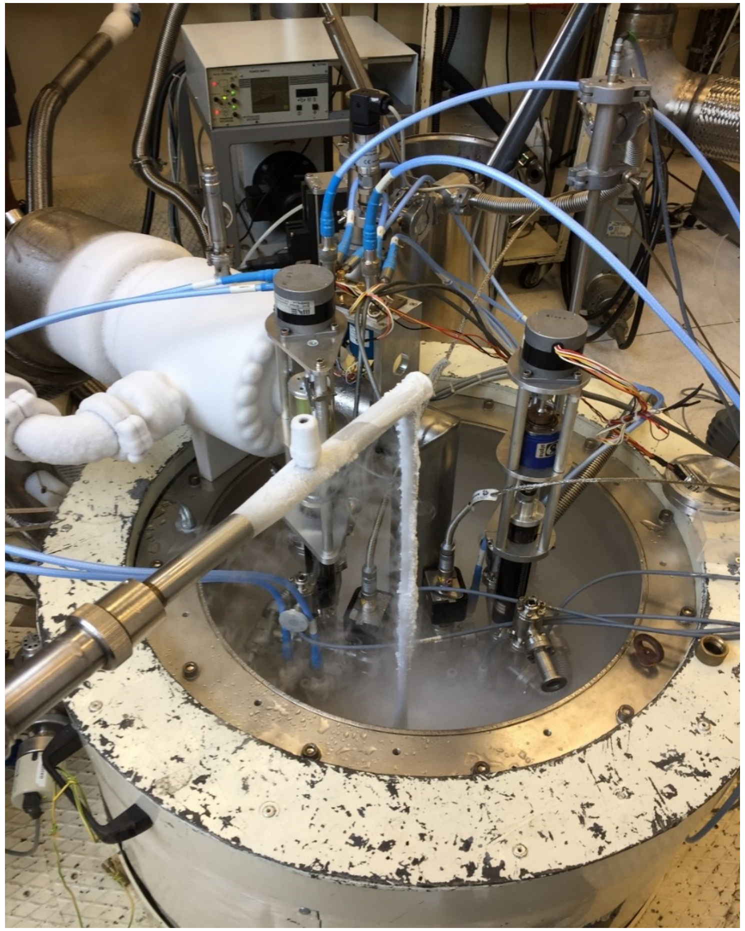
Elliptical cavities

He Cryostat @ LNL



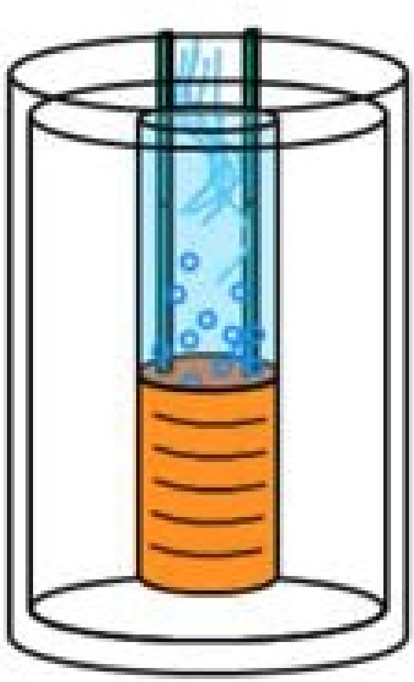
He Cryostat @ LNL



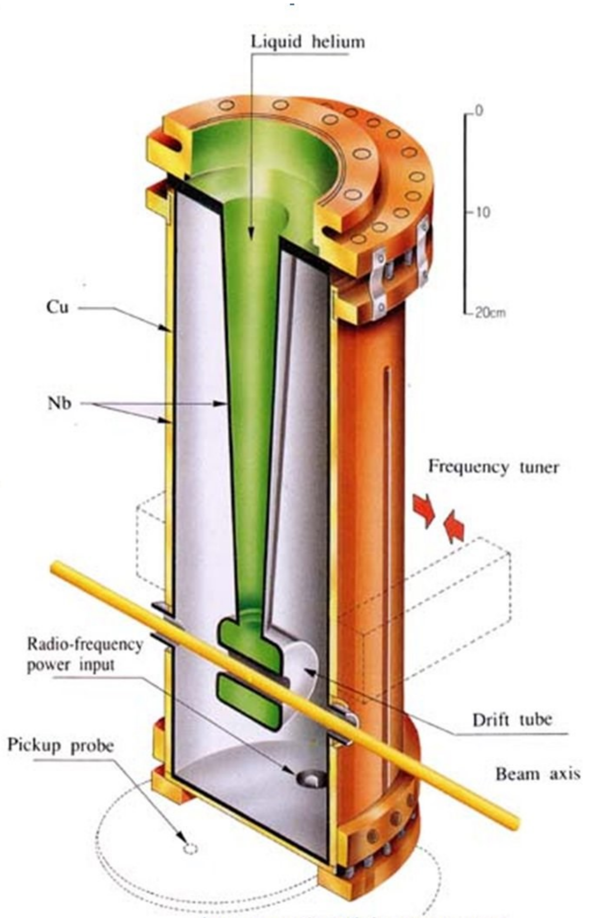


Helium indirect cooling bath method

Quarter Wave Resonators (QWR)



Indirect cooling
Bath cooling

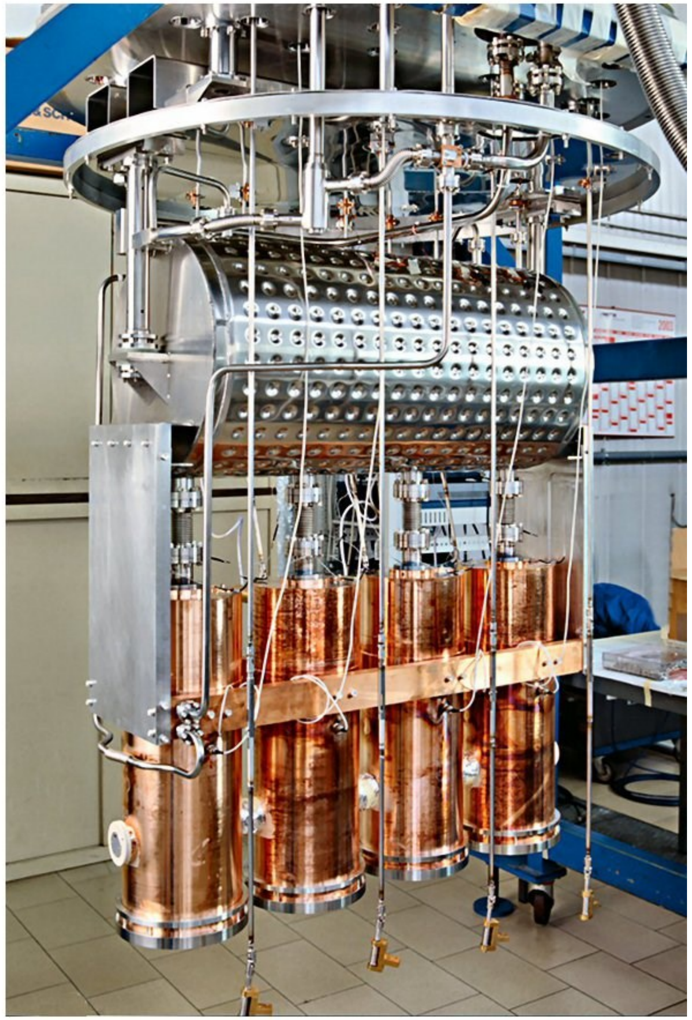


▲ Cross section of the quarter wave superconducting resonator

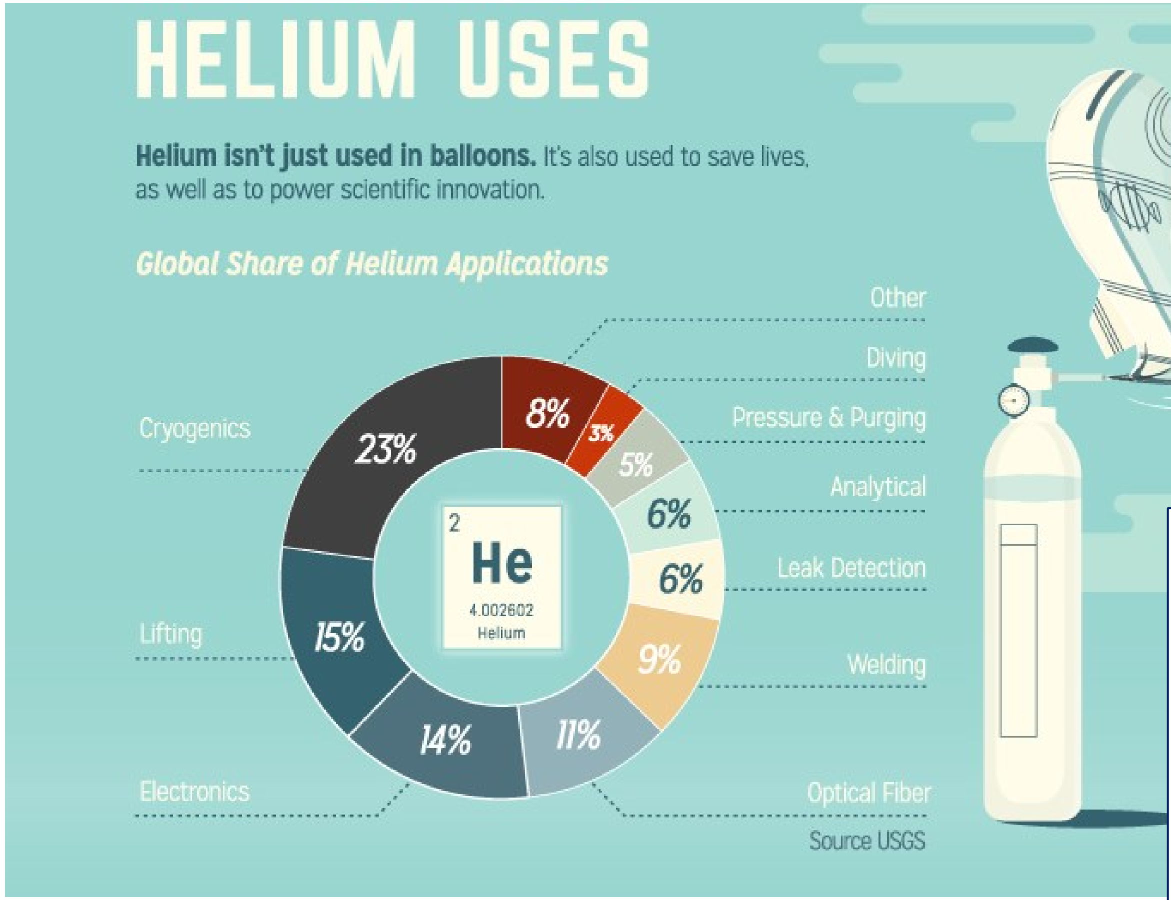
(http://rrsys.tokaisc.jaea.go.jp/rrsys/html/tandem/english/koumoku-03/booster.html)

ALPI Cryostat @ LNL

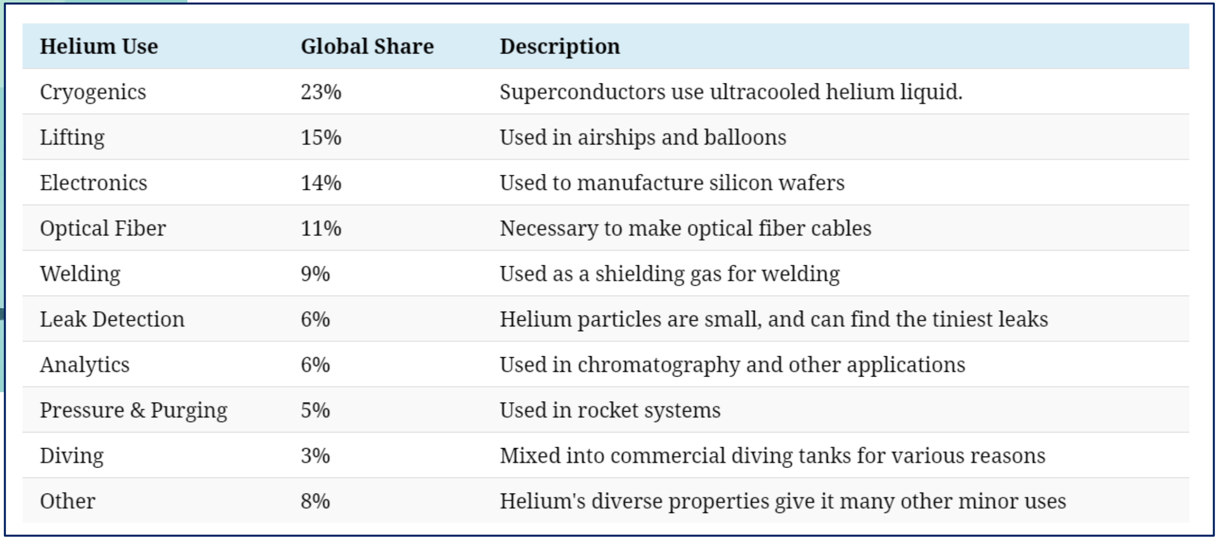
ALPI Cryostat



Helium uses



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

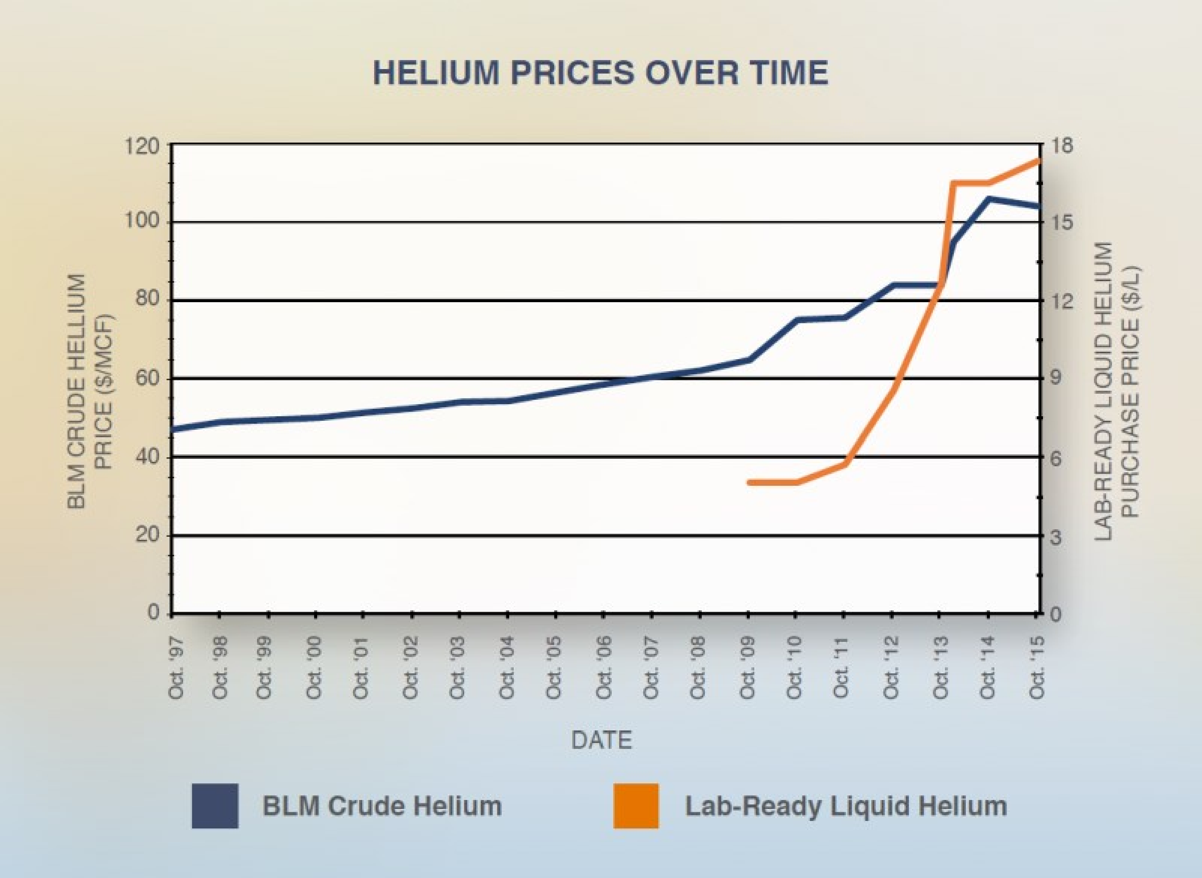


Helium Use	Global Share	Description
Cryogenics	23%	Superconductors use ultracooled helium liquid.
Lifting	15%	Used in airships and balloons
Electronics	14%	Used to manufacture silicon wafers
Optical Fiber	11%	Necessary to make optical fiber cables
Welding	9%	Used as a shielding gas for welding
Leak Detection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

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

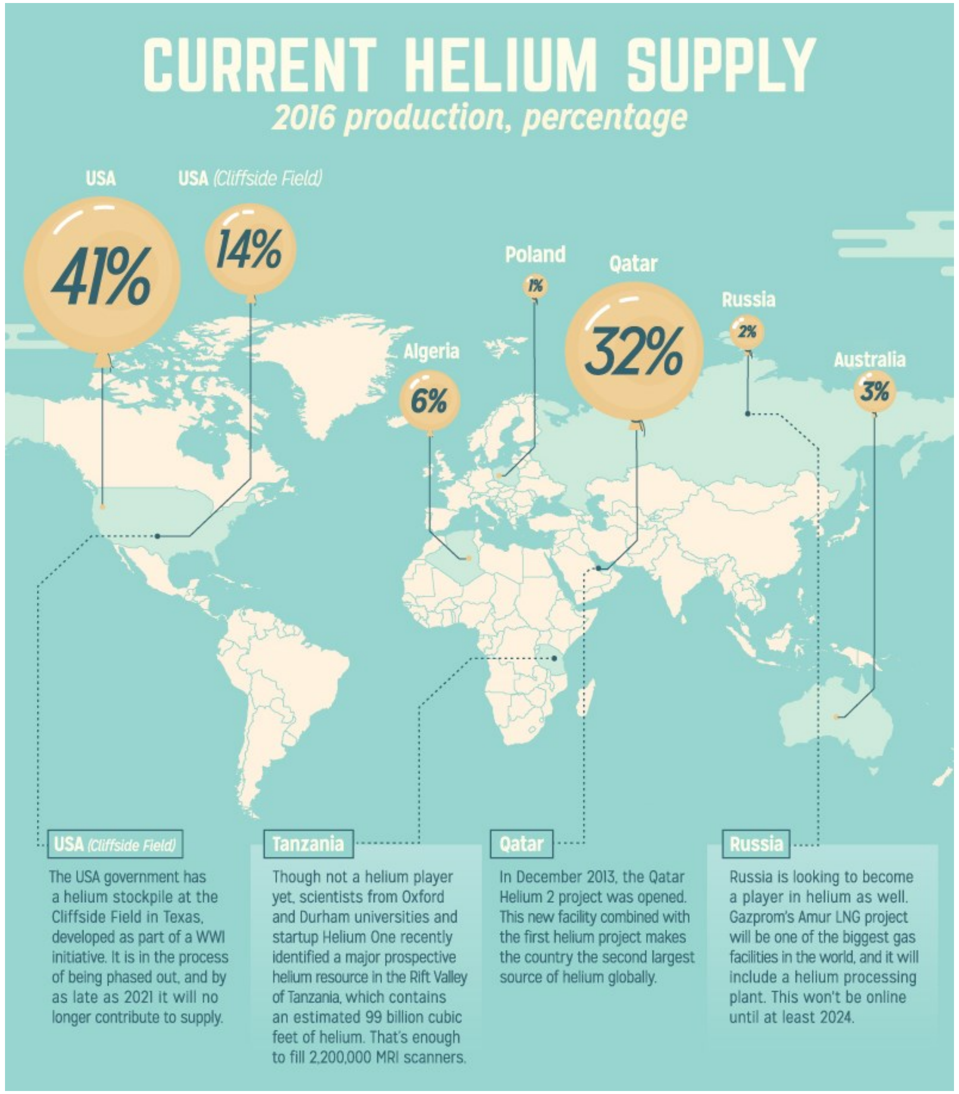
https://business.financialpost.com/



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

https://physicstoday.scitation.org/do/10.1063/PT.6.2.20200605a/full/

Helium shortage reasons



CURRENT HELIUM SUPPLY

2016 production, percentage

USA *(Cliffside Field)*

The USA government has a helium stockpile at the Cliffside Field in Texas, developed as part of a WWI initiative. It is in the process of being phased out, and by as late as 2021 it will no longer contribute to supply.

Tanzania

Though not a helium player yet, scientists from Oxford and Durham universities and startup Helium One recently identified a major prospective helium resource in the Rift Valley of Tanzania, which contains an estimated 99 billion cubic feet of helium. That's enough to fill 2,200,000 MRI scanners.

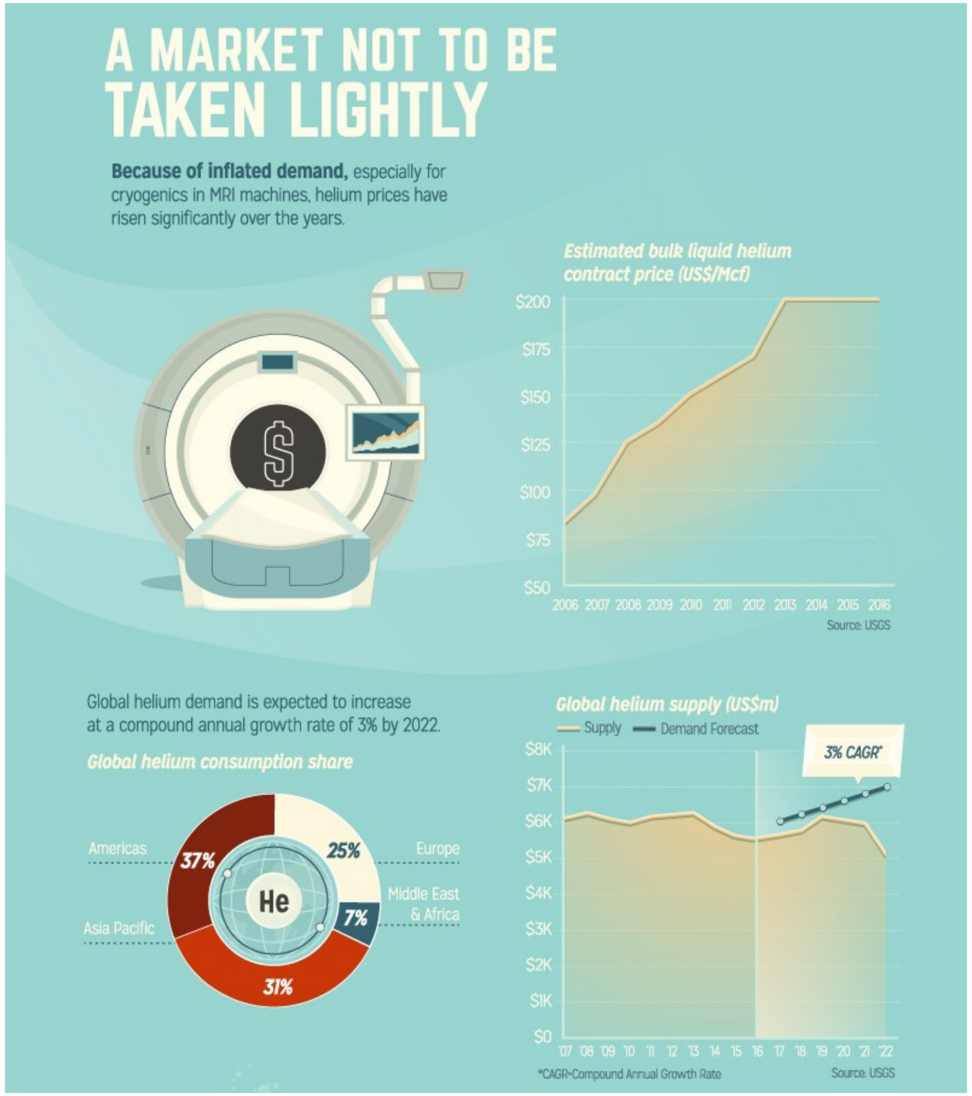
Qatar

In December 2013, the Qatar Helium 2 project was opened. This new facility combined with the first helium project makes the country the second largest source of helium globally.

Russia

Russia is looking to become a player in helium as well. Gazprom's Amur LNG project will be one of the biggest gas facilities in the world, and it will include a helium processing plant. This won't be online until at least 2024.

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



A MARKET NOT TO BE TAKEN LIGHTLY

Because of inflated demand, especially for cryogenics in MRI machines, helium prices have risen significantly over the years.

Global helium demand is expected to increase at a compound annual growth rate of 3% by 2022.

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**

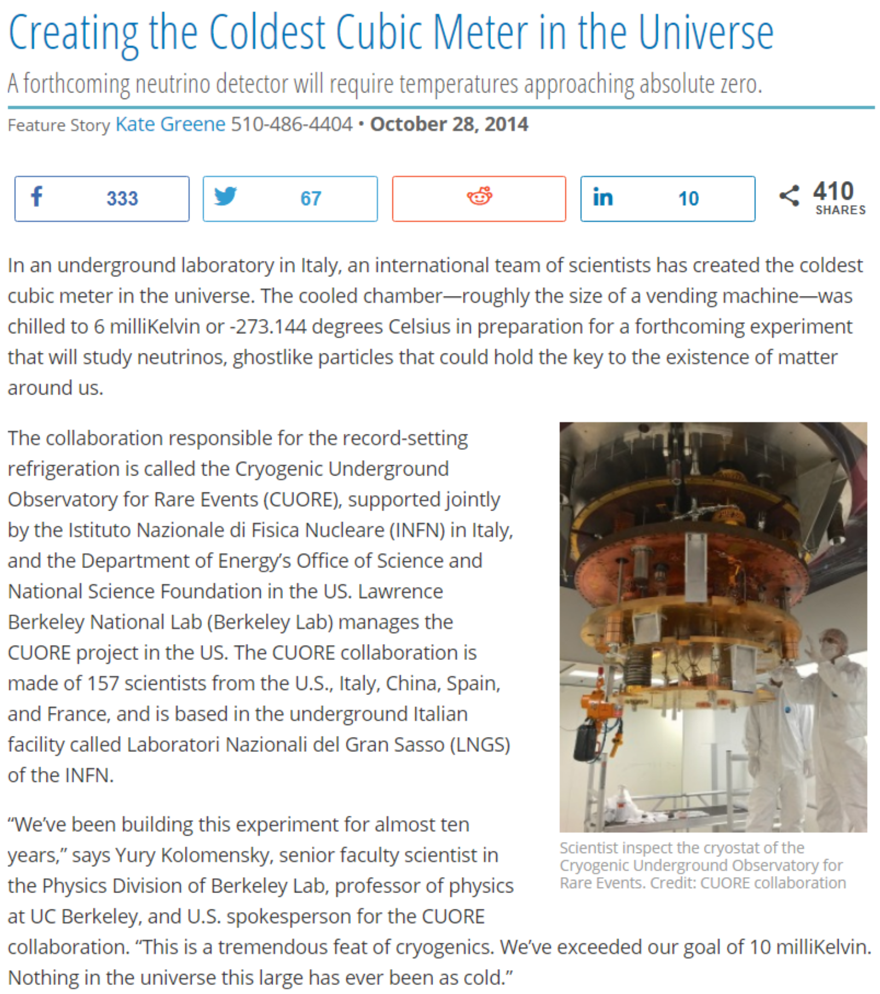
Just to have an idea: when I test a single Accelerating cavity, I use 200-400 liters of Helium, for a theoretical cost of more than 10000 €!!!

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 m^3, 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



Creating the Coldest Cubic Meter in the Universe

A forthcoming neutrino detector will require temperatures approaching absolute zero.

Feature Story Kate Greene 510-486-4404 • **October 28, 2014**

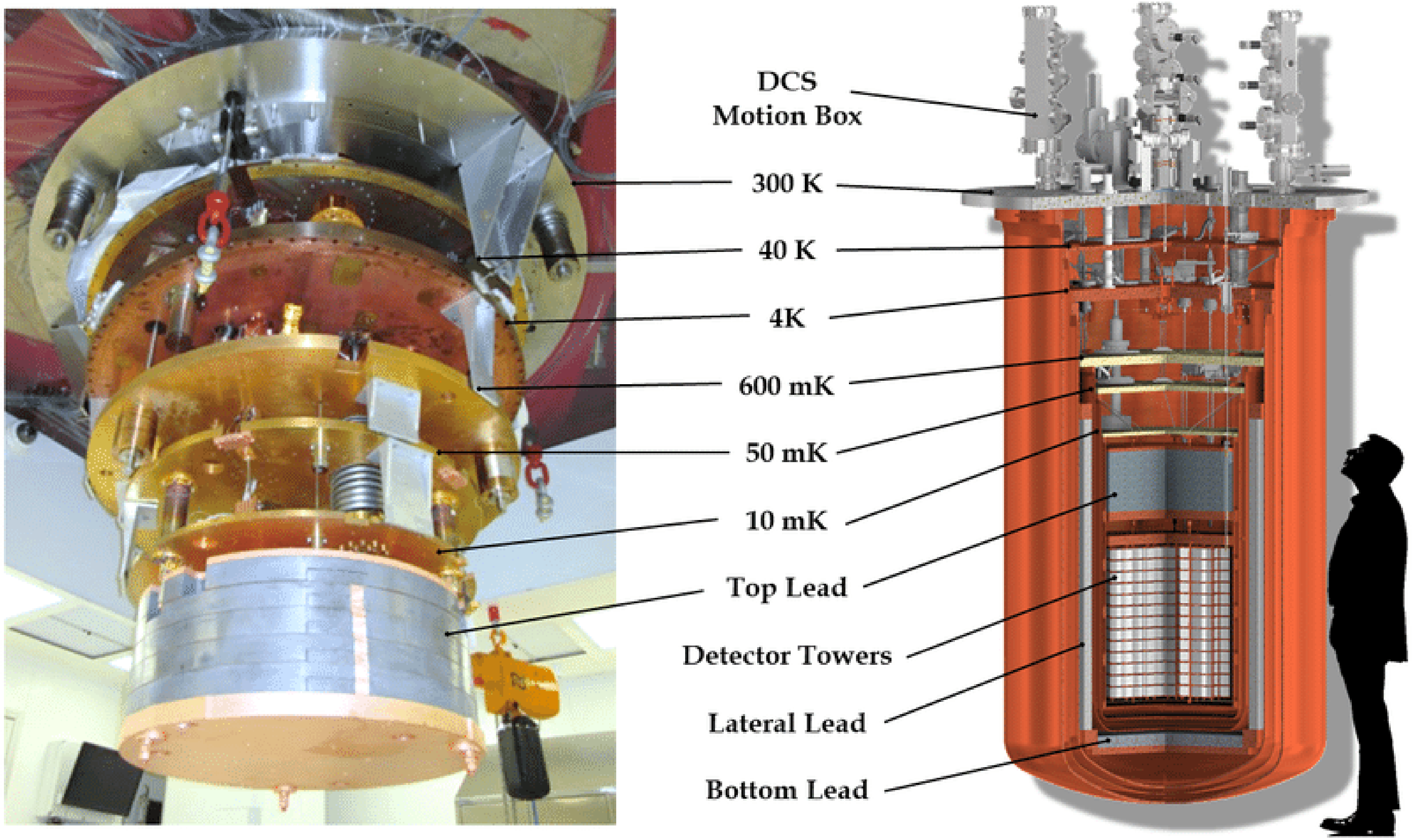
In an underground laboratory in Italy, an international team of scientists has created the coldest cubic meter in the universe. The cooled chamber—roughly the size of a vending machine—was chilled to 6 milliKelvin or -273.144 degrees Celsius in preparation for a forthcoming experiment that will study neutrinos, ghostlike particles that could hold the key to the existence of matter around us.

The collaboration responsible for the record-setting refrigeration is called the Cryogenic Underground Observatory for Rare Events (CUORE), supported jointly by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and the Department of Energy's Office of Science and National Science Foundation in the US. Lawrence Berkeley National Lab (Berkeley Lab) manages the CUORE project in the US. The CUORE collaboration is made of 157 scientists from the U.S., Italy, China, Spain, and France, and is based in the underground Italian facility called Laboratori Nazionali del Gran Sasso (LNGS) of the INFN.

Scientist inspect the cryostat of the Cryogenic Underground Observatory for Rare Events. Credit: CUORE collaboration

"We've been building this experiment for almost ten years," says Yury Kolomensky, senior faculty scientist in the Physics Division of Berkeley Lab, professor of physics at UC Berkeley, and U.S. spokesperson for the CUORE collaboration. "This is a tremendous feat of cryogenics. We've exceeded our goal of 10 milliKelvin. Nothing in the universe this large has ever been as cold."

Nowadays: CUORE Experiment @ LNGS INFN



Nowadays: CUORE Experiment @ LNGS INFN

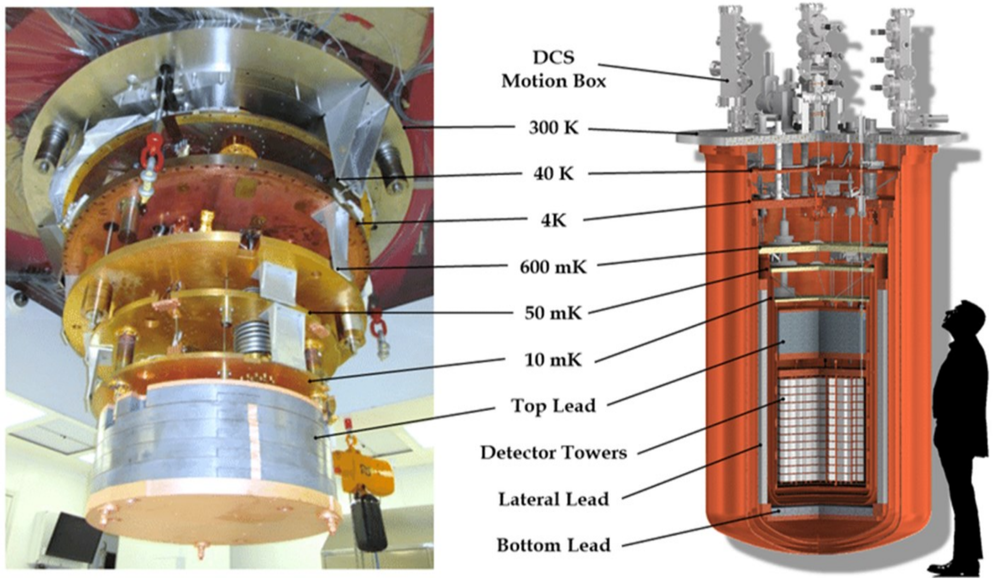
The CUORE detectors and their shielding must be cooled to approximately 10 mK before they can take data. We cool them using one of the largest and most powerful helium dilution refrigerators ever constructed. Our cryostat produces the coldest cubic meter in the known universe.

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 3He 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.



https://cuore.lngs.infn.it/en/about/cryostat

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