Joint Universities Accelerator School

European Scientific Institute

Introduction to cryogenics

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Contents

- **κϱυος, ους** (το) — **1** deep cold [Arist. *Meteor.*]
  2 shiver of fear [Aeschyl. *Eumenid.*]

- **cryogenics,** that branch of physics which deals with the production of very low temperatures and their effects on matter

  Oxford English Dictionary
  2nd edition, Oxford University Press (1989)

- **cryogenics**, the science and technology of temperatures below 120 K

  New International Dictionary of Refrigeration
  4th edition, IIF-IIR Paris (2015)

Characteristic temperatures of cryogens

Cryogen	Triple point [K]	Normal boiling point [K]	Critical point [K]
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2 (*)	4.2	5.2

(*): λ Point

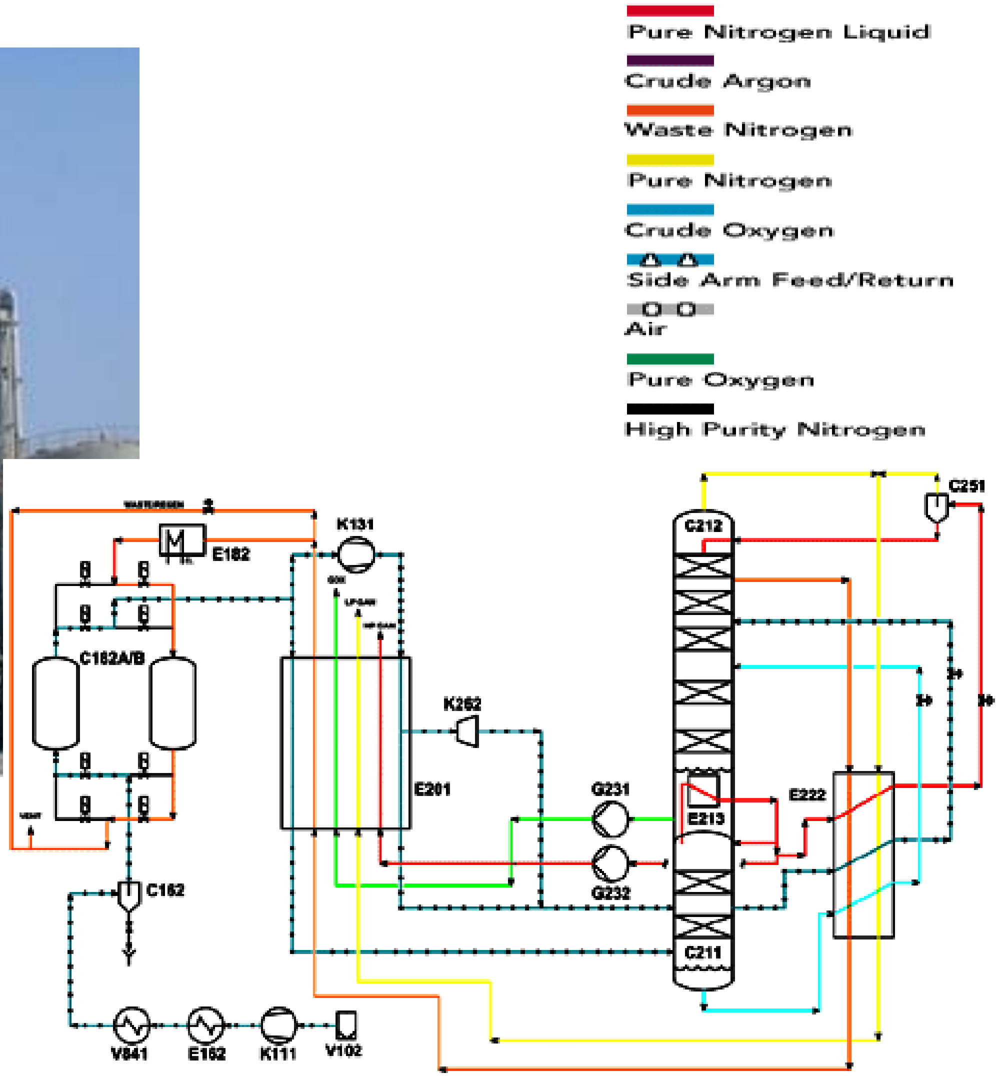
Cryogenic transport of natural gas: LNG

130 000 m^3 LNG carrier
with double hull

Invar® tanks hold LNG at ~110 K

Densification, liquefaction & separation of gases

LIN & LOX



Air separation by cryogenic distillation

Capacity up to 4500 t/day LOX

LIN as byproduct

Densification, liquefaction & separation of gases

Rocket fuels

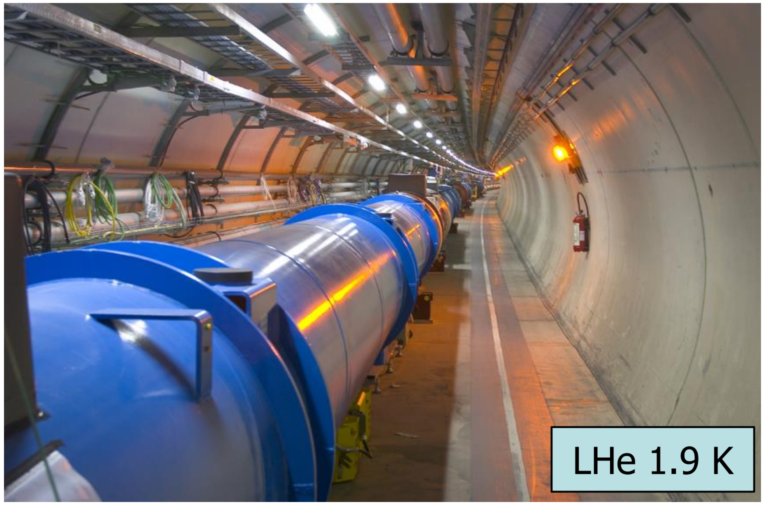
Ariane 5

25 t LHY, 130 t LOX

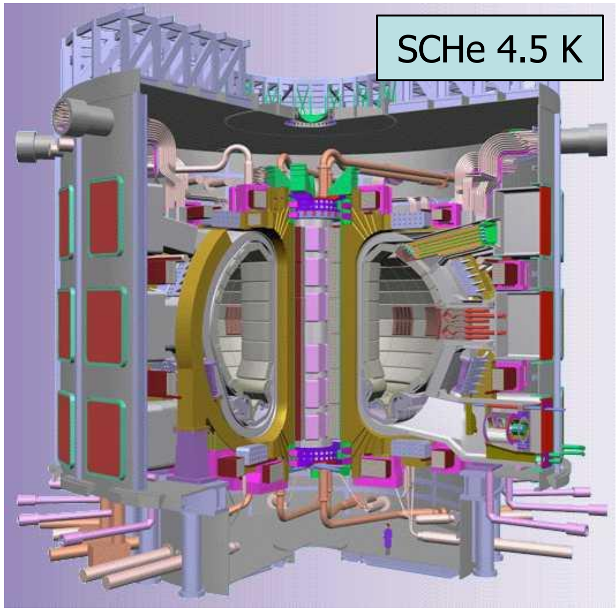
Space Shuttle

100 t LHY, 600 t LOX

Cooling of superconducting devices


LHe 1.9 K


LIN ~70 K


SCHe 4.5 K


LHe 4.2 K

What is a low temperature?

- The entropy of a thermodynamical system in a macrostate corresponding to a multiplicity W of microstates is

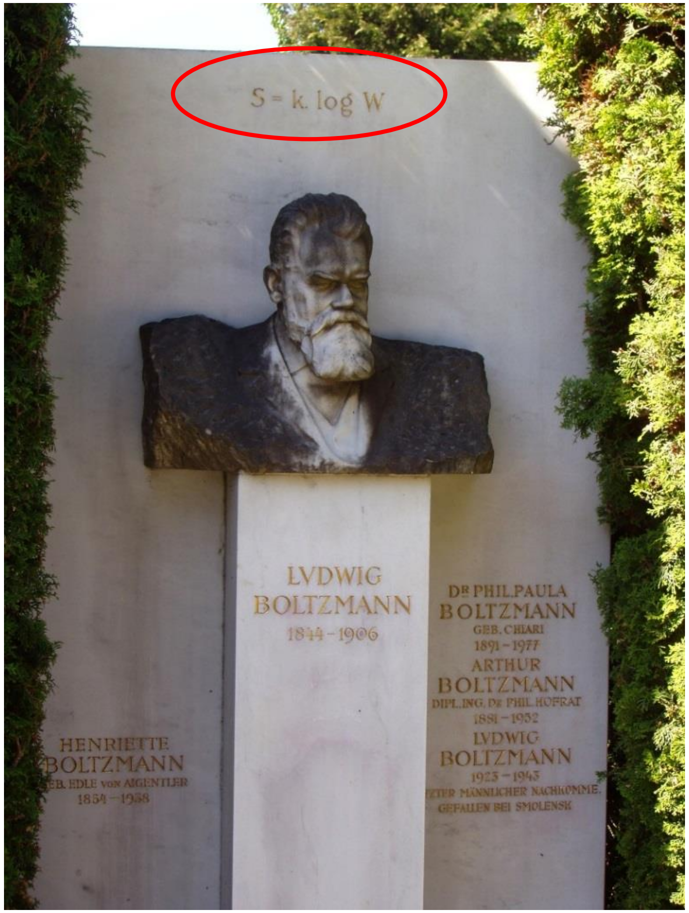
$$S = k_B \ln W$$

- Adding reversibly heat dQ to the system results in a change of its entropy dS with a proportionality factor T

$$T = dQ/dS$$

⇒ *high temperature: heating produces small entropy change*

⇒ *low temperature: heating produces large entropy change*



L. Boltzmann's grave in the Zentralfriedhof, Vienna, bearing the entropy formula

Temperature and energy

- The average thermal energy of a particle in a system in thermodynamic equilibrium at temperature T is

$$\boxed{\begin{array}{c} E \sim k_B\, T \\ k_B = 1.3806 \times 10^{-23}\ \mathrm{J.K^{-1}} \end{array}}$$

- 1 K is equivalent to $\sim 10^{-4}$ eV or $\sim 10^{-23}$ J thermal energy
  - a temperature is « low » for a given physical process when the corresponding average thermal energy k_BT is small compared with the characteristic energy E of the process considered
  - cryogenic temperatures reveal phenomena with low characteristic energy and enable their study and their application

Characteristic temperatures of low-energy phenomena

Phenomenon	Temperature
Debye temperature of metals	few 100 K
High-temperature superconductivity	~ 100 K
Low-temperature superconductivity	~ 10 K
Intrinsic transport properties of metals	< 10 K
Cryopumping	few K
Cosmic microwave background	2.7 K
Superfluid helium 4	2.2 K
Bolometers for cosmic radiation	< 1 K
Low-density atomic Bose-Einstein condensates	~ μK

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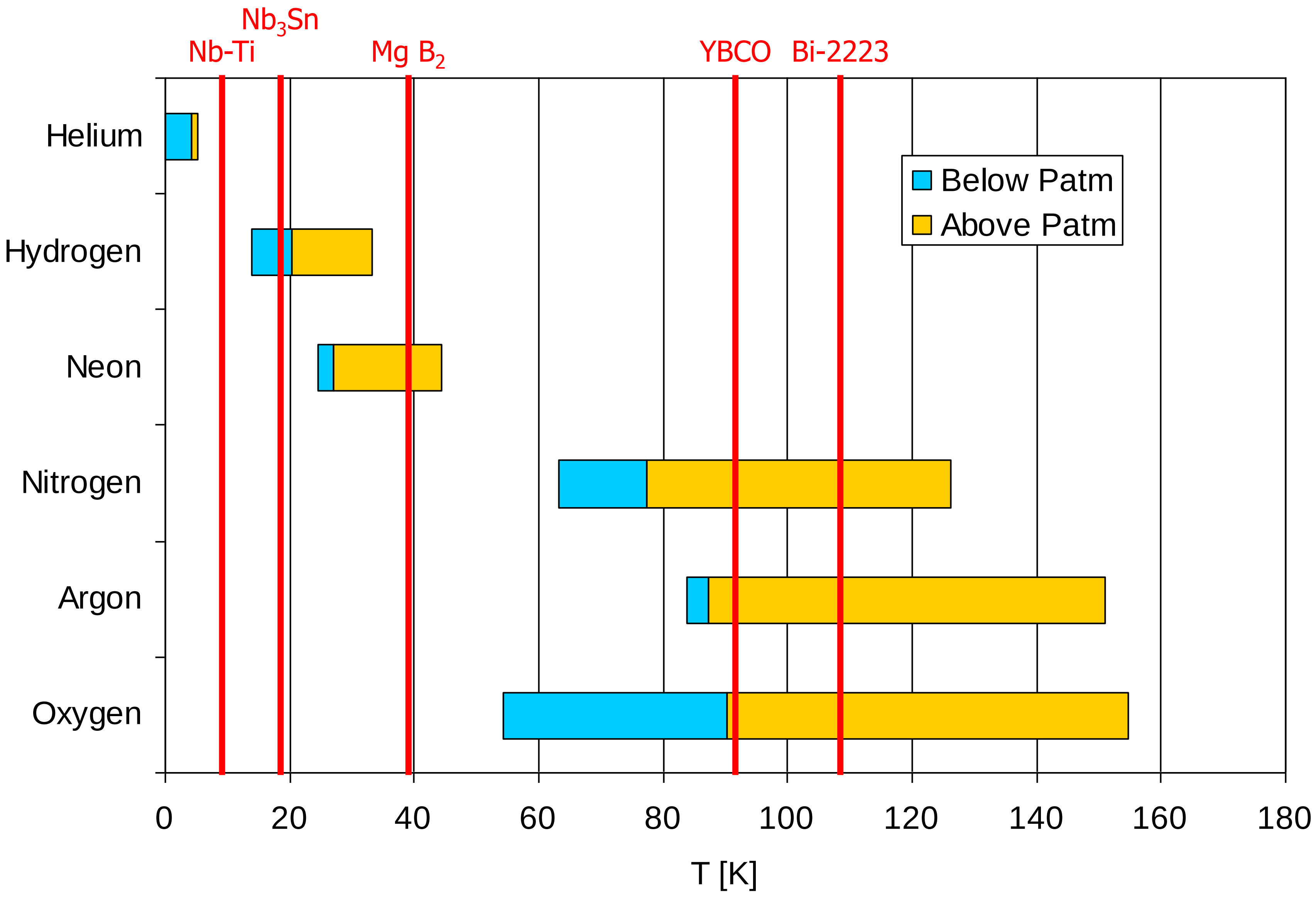
Useful range of liquid cryogens & critical temperature of superconductors



Properties of cryogens compared to water

Property		He	N_2	H_2O
Normal boiling point	[K]	4.2	77	373
Critical temperature	[K]	5.2	126	647
Critical pressure	[bar]	2.3	34	221
Liq./Vap. density (*)		7.4	175	1600
Heat of vaporization (*)	[J.g^{-1}]	20.4	199	2260
Liquid viscosity (*)	[μPl]	3.3	152	278

(*) at normal boiling point

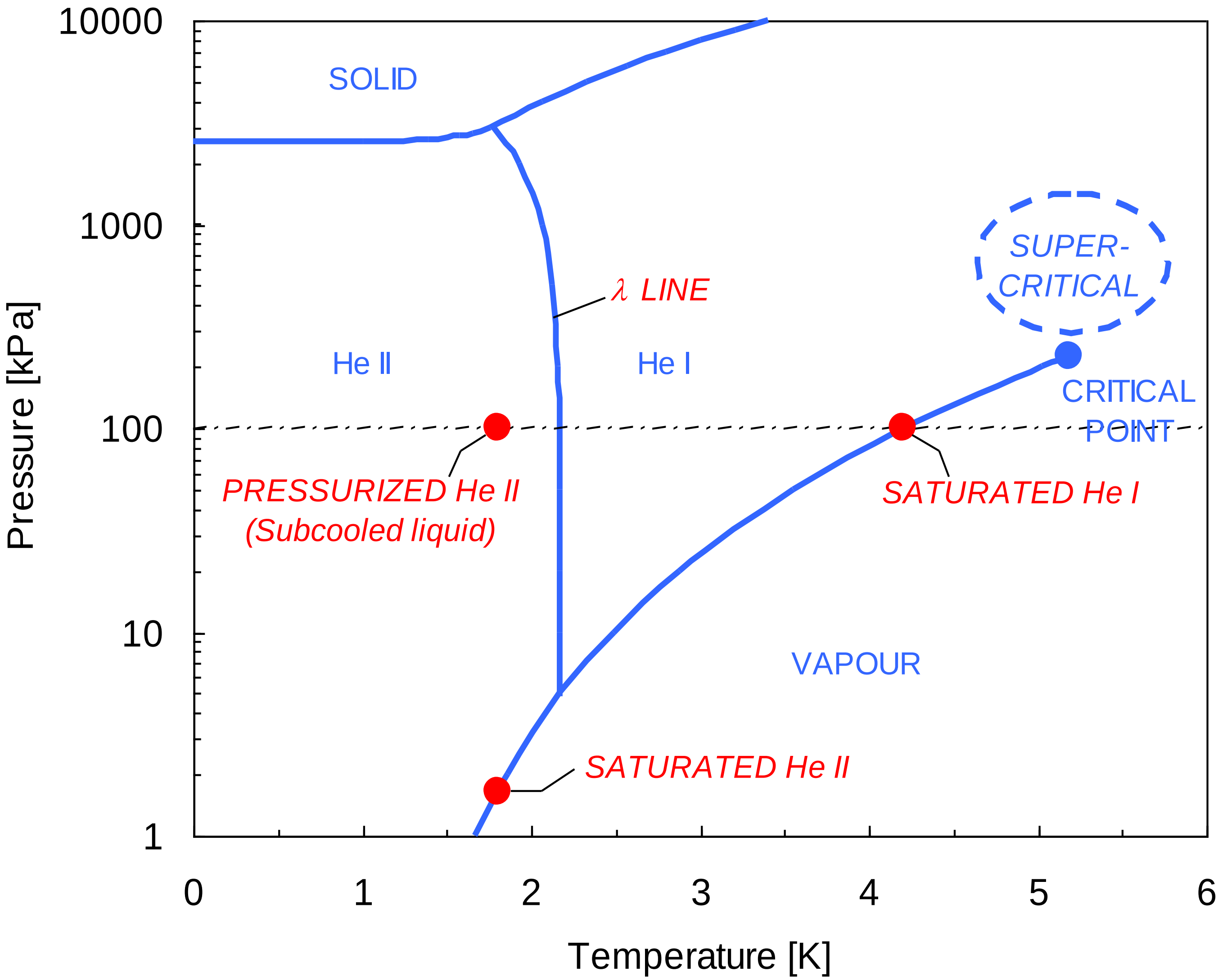
Vaporization of normal boiling cryogens under 1 W applied heat load

Cryogen	**[mg.s^{-1}]**	**[l.h^{-1}] (liquid)**	**[l.min^{-1}] (gas NTP)**
Helium	48	1.38	16.4
Nitrogen	5	0.02	0.24

Amount of cryogens required to cool down 1 kg iron

Using	Latent heat only	Latent heat and enthalpy of gas
LHe from 290 to 4.2 K	29.5 litre	0.75 liter
LHe from 77 to 4.2 K	1.46 litre	0.12 litre
LN2 from 290 to 77 K	0.45 litre	0.29 litre

Phase diagram of helium



Helium as a cooling fluid

Phase domain	Advantages	Drawbacks
Saturated He I	Fixed temperature High heat transfer	Two-phase flow Boiling crisis
Supercritical	Monophase Negative J-T effect	Non-isothermal Density wave instability
He II	Low temperature High conductivity Low viscosity	Second-law cost Subatmospheric

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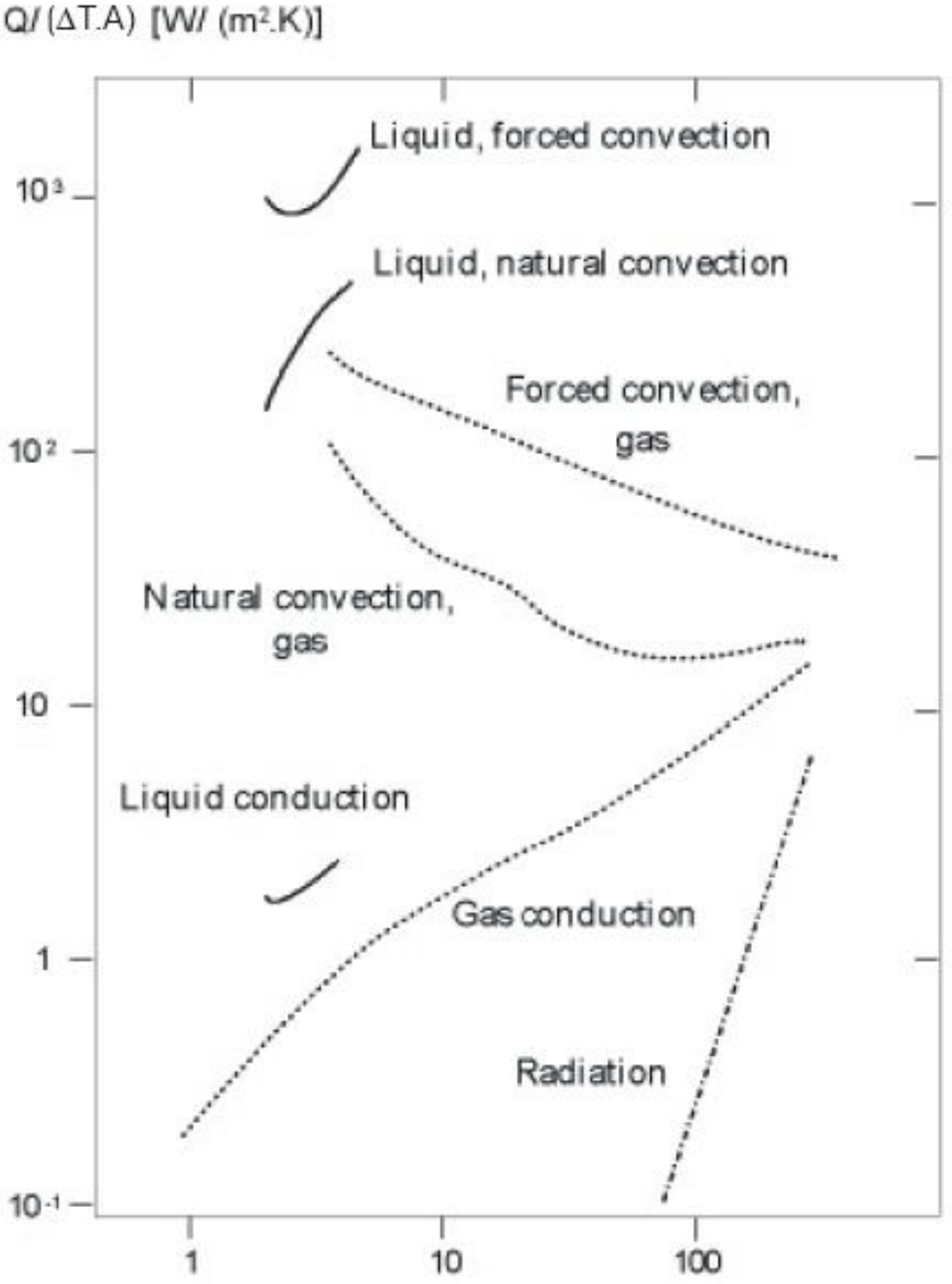
Typical heat transfer coefficients at cryogenic temperatures

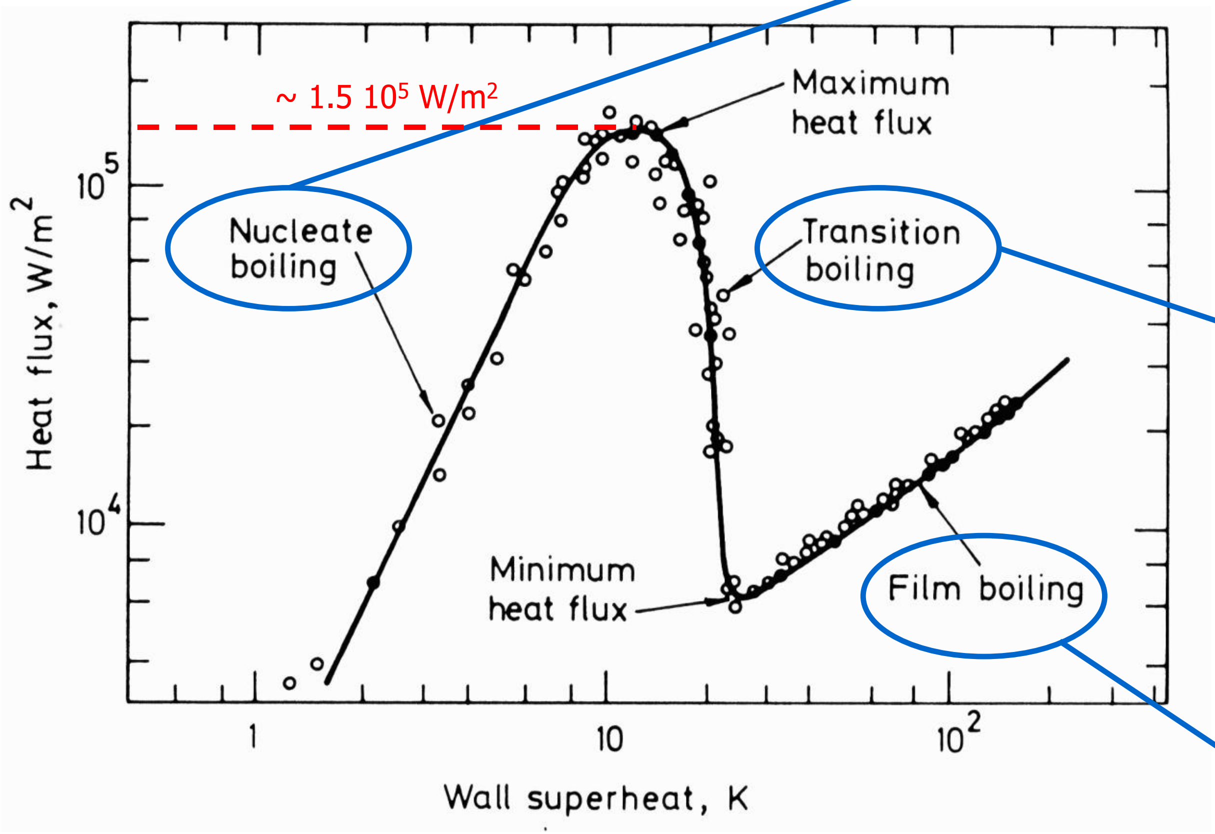
- Same basic heat transfer processes as at temperatures above ambiant, but large variations in orders of magnitude

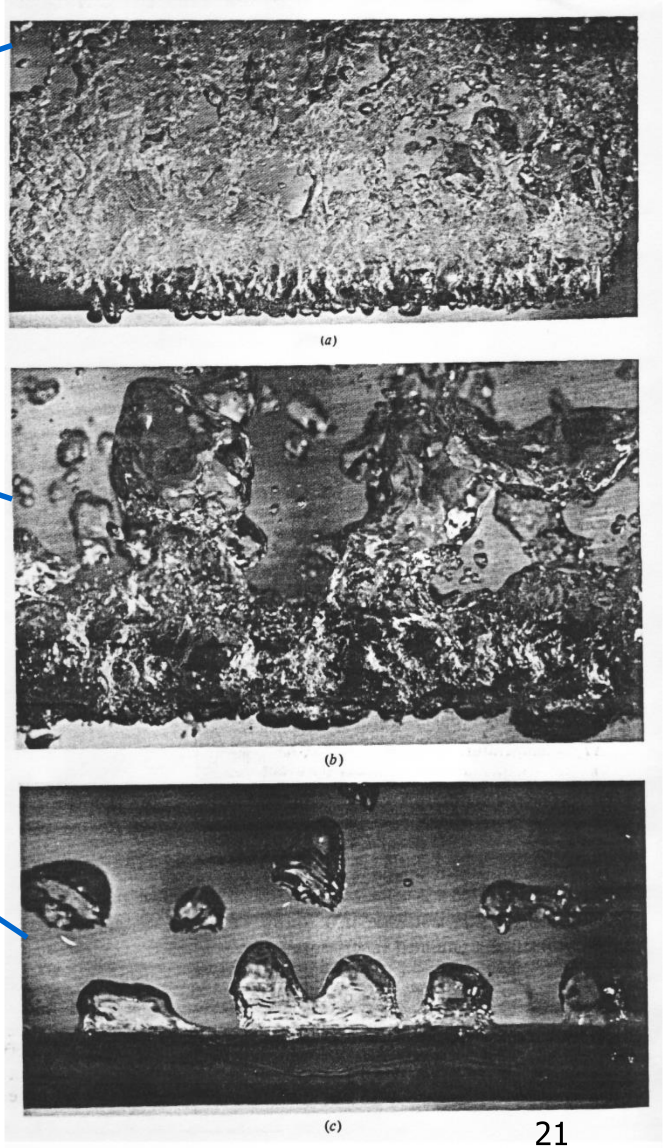
- Not on this diagram:
  - Importance of two-phase heat transfer (boiling)
  - At very low temperature, solid-to-liquid interface thermal resistance (Kapitza)



Non-linear heat transfer to liquid cryogens

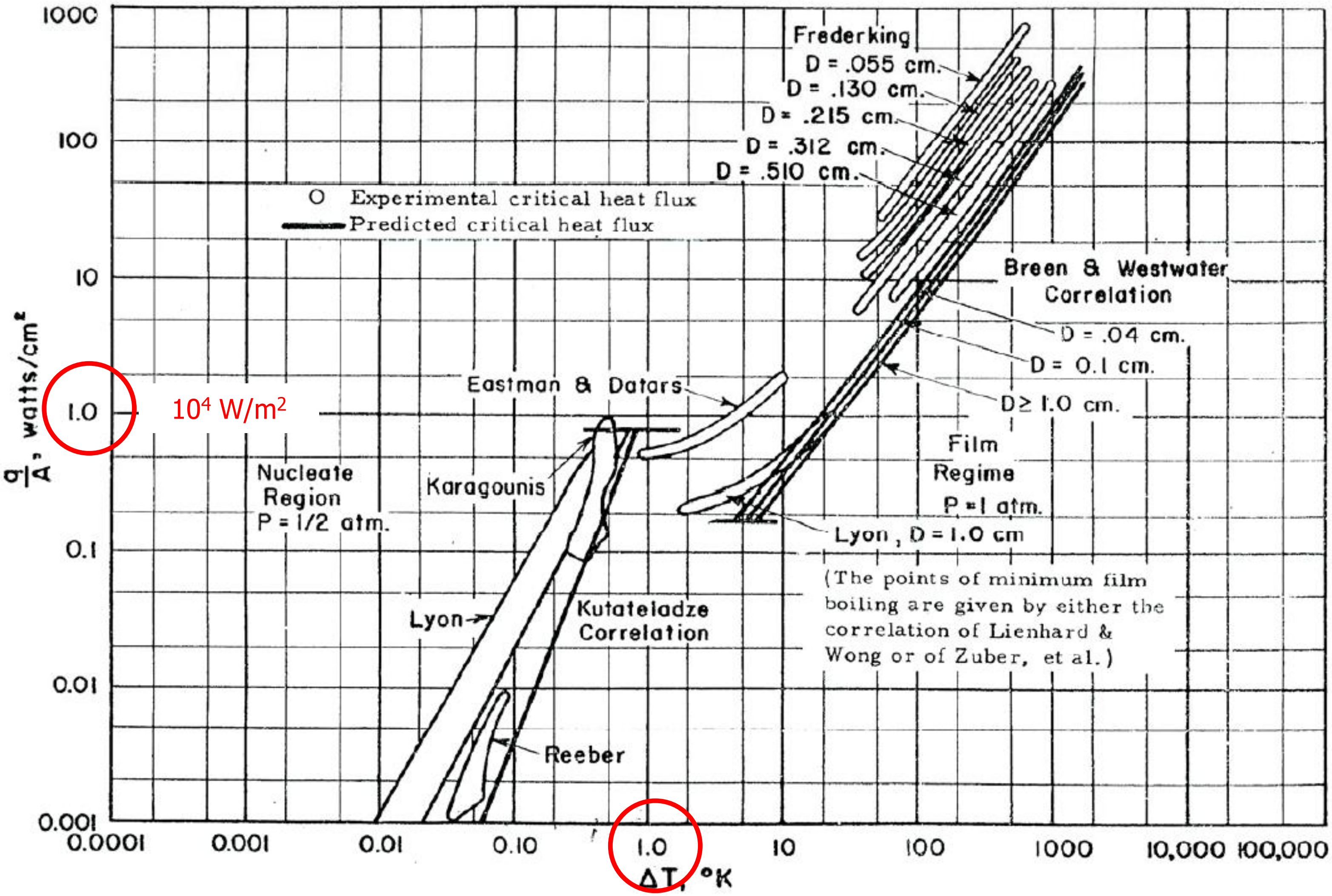
Pool boiling nitrogen



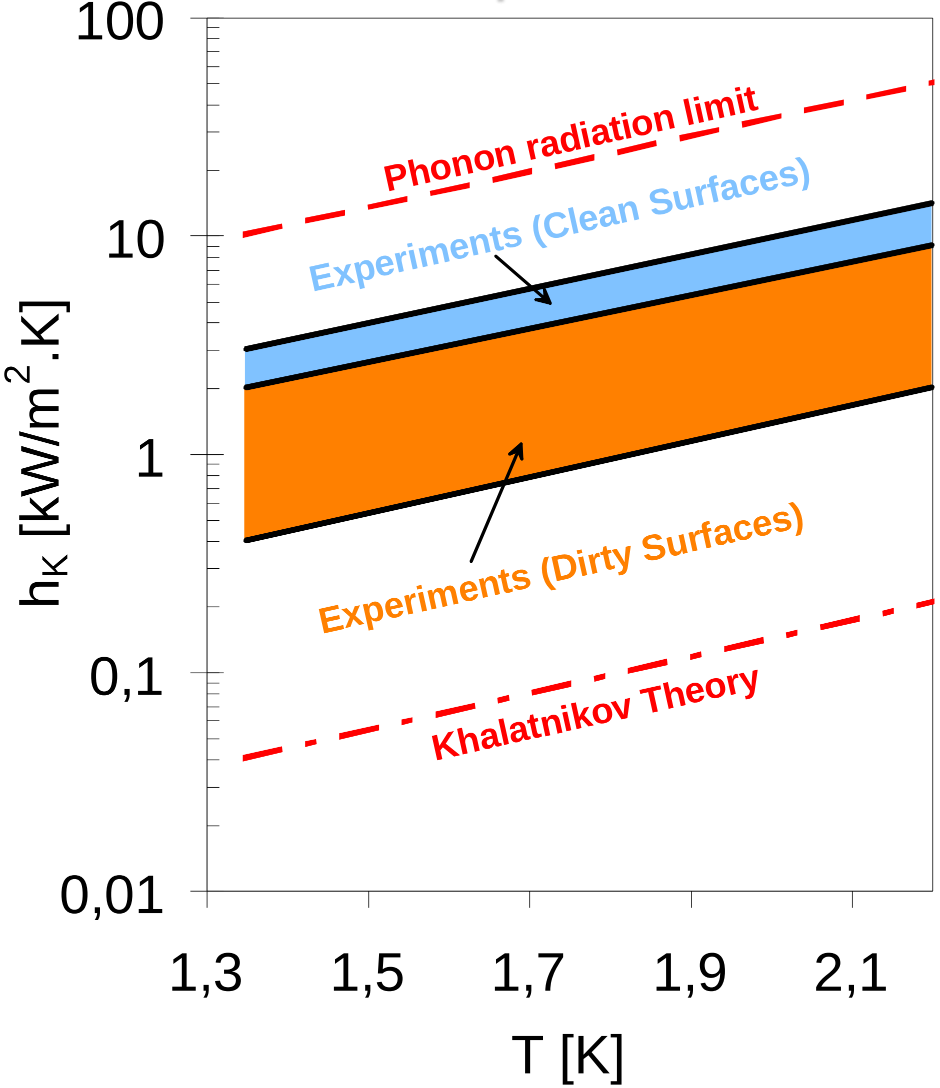


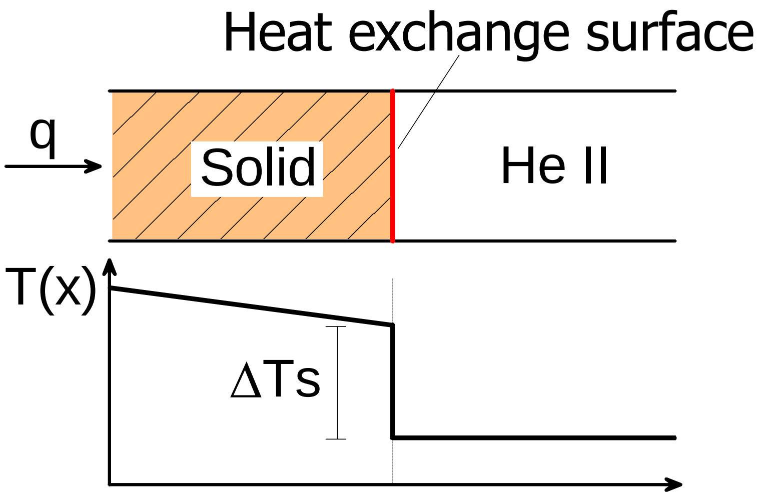
Non-linear heat transfer to liquid cryogens

Pool boiling helium



Solid-liquid interface: Kapitza conductance





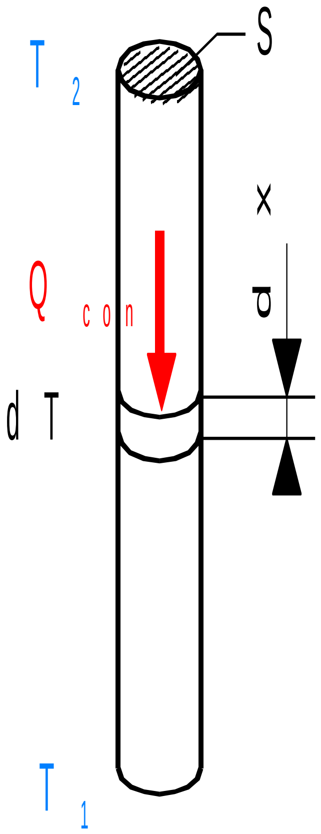
Experimental data for Copper

(S. Van Sciver, "Helium Cryogenics")

$h_K \sim T^3$

Valid for small heat flux (when $\Delta T << T$)

Heat conduction in solids



Fourier's law:

$$Q_{con} = k(T) \cdot S \cdot \frac{dT}{dx}$$

k(T): thermal conductivity [W/m.K]

Integral form:

$$Q_{con} = \frac{S}{L} \cdot \int_{T1}^{T2} k(T) \cdot dT$$

$\int k(T) \cdot dT$: thermal conductivity integral [W/m]

Thermal conductivity integrals for standard construction materials are tabulated

Thermal conductivity integrals of selected materials [W/m]

From vanishingly low temperature up to	20 K	80 K	290 K
OFHC copper	11000	60600	152000
DHP copper	395	5890	46100
1100 aluminium	2740	23300	72100
2024 aluminium alloy	160	2420	22900
AISI 304 stainless steel	16.3	349	3060
G-10 glass-epoxy composite	2	18	153

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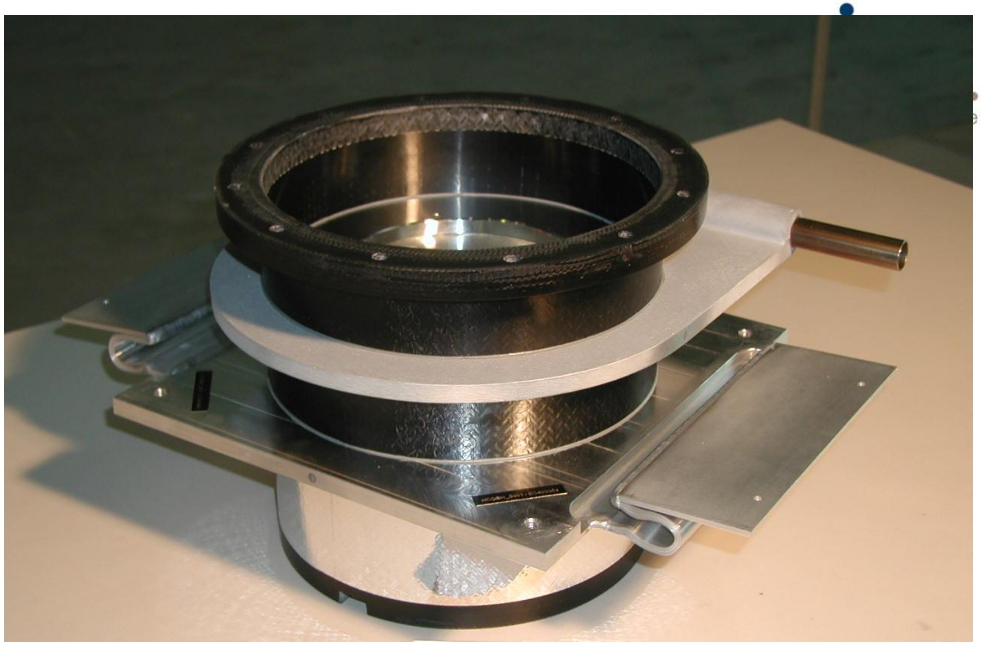
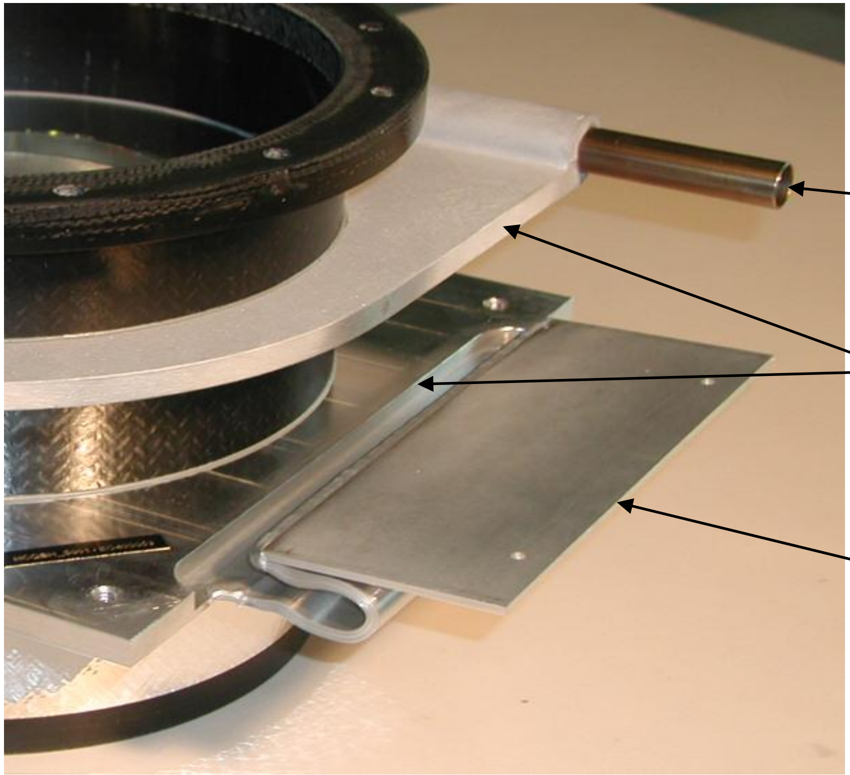
Non-metallic composite support post with heat intercepts



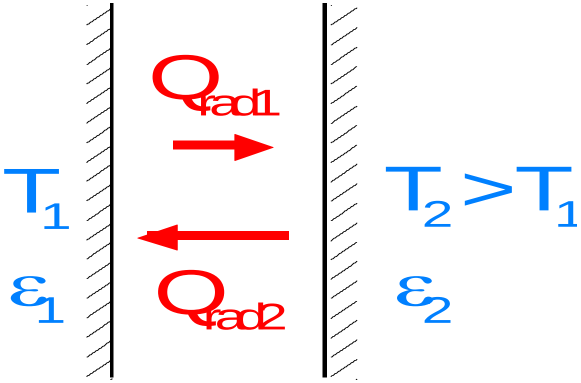


5 K cooling line (SC He)

Aluminium intercept plates glued to G-10 column

Aluminium strips to thermal shield at 50-75 K

Thermal radiation

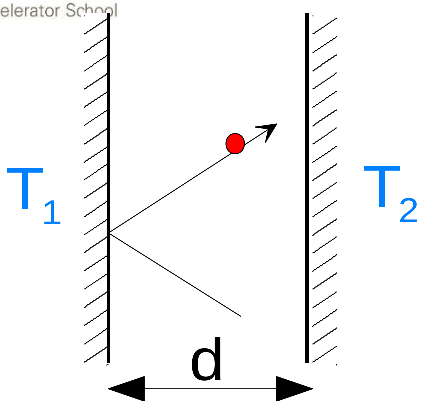


- Wien's law
  - Maximum of black body power spectrum
    $\lambda_{max} . T = 2898$ [µm.K]
- Stefan-Boltzmann's law
  - Black body — $Q_{rad} = \sigma A T^4$
    $\sigma = 5.67 \times 10^{-8}$ W/m².K⁴
    (Stefan Boltzmann's constant)
  - "Gray"body — $Q_{rad} = \varepsilon \sigma A T^4$
    ε emissivity of surface
  - "Gray" surfaces at T_1 and T_2 — $Q_{rad} = E \sigma A (T_1^4 - T_2^4)$
    E function of ε_1, ε_2, geometry

Emissivity of technical materials at low temperatures

	Radiation from 290 K Surface at 77 K	**Radiation from 77 K Surface at 4.2 K**
Stainless steel, as found	0.34	0.12
Stainless steel, mech. polished	0.12	0.07
Stainless steel, electropolished	0.10	0.07
Stainless steel + Al foil	0.05	0.01
Aluminium, as found	0.12	0.07
Aluminium, mech. polished	0.10	0.06
Aluminium, electropolished	0.08	0.04
Copper, as found	0.12	0.06
Copper, mech. Polished	0.06	0.02

Residual gas conduction



$\lambda_{molecule}$: mean free path of gas molecules

- Viscous regime
  - At high gas pressure $\lambda_{molecule} << d$
  - Classical conduction $Q_{res} = k(T)\,A\,dT/dx$
  - Thermal conductivity *k(T)* independant of pressure
- Molecular regime
  - At low gas pressure $\lambda_{molecule} >> d$
  - Kennard's law $Q_{res} = A\,\alpha(T)\,\Omega\,P\,(T_2 - T_1)$
  - Conduction heat transfer proportional to pressure, independant of spacing between surfaces

    Ω depends on gas species
  - Accommodation coefficient $\alpha(T)$ depends on gas species, T_1, T_2, and geometry of facing surfaces

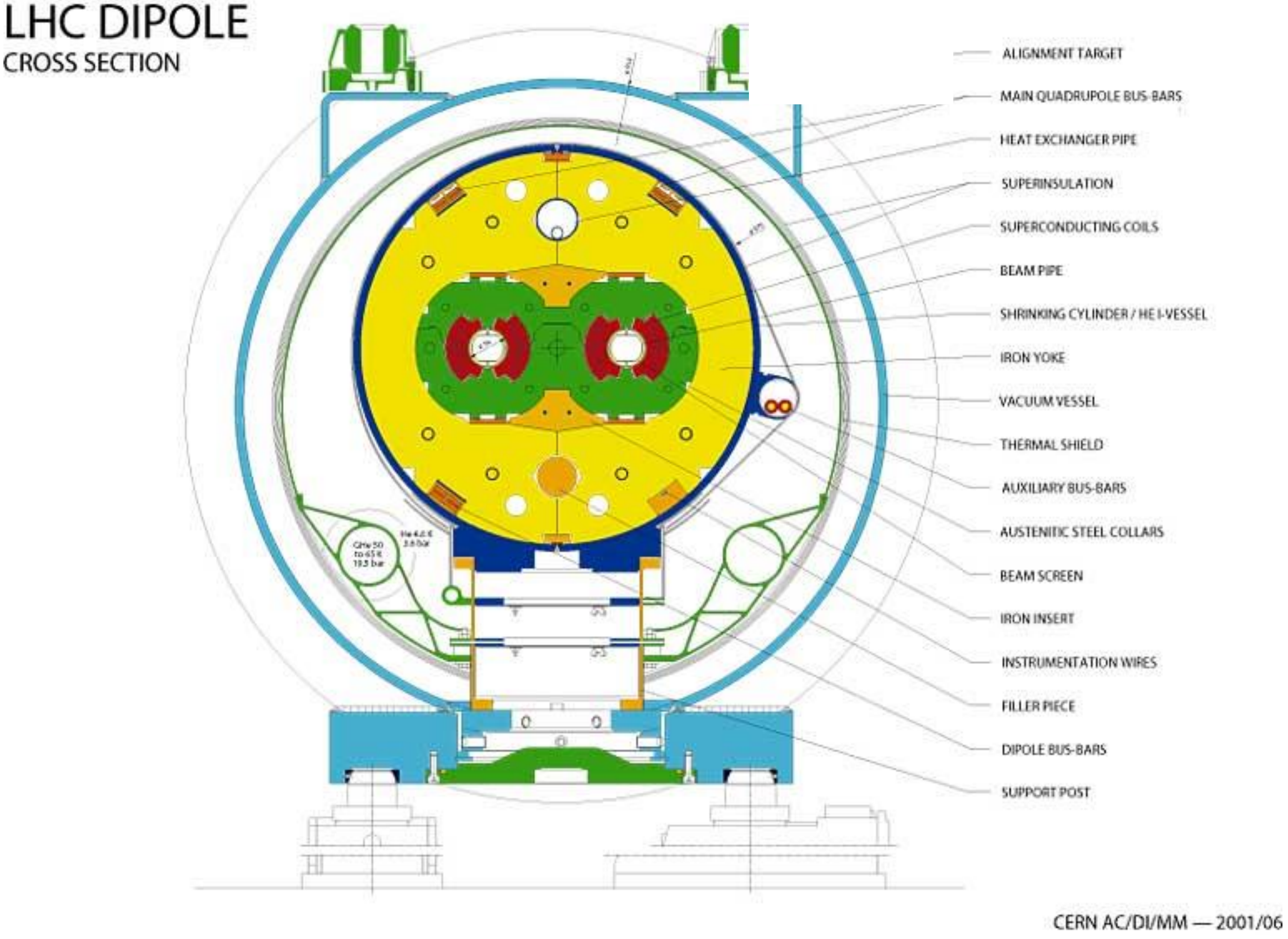
Multi-layer insulation (MLI)

- Complex system involving three heat transfer processes
  - $Q_{MLI} = Q_{rad} + Q_{sol} + Q_{res}$
  - With n reflective layers of equal emissivity, $Q_{rad} \sim 1/(n+1)$
  - Due to parasitic contacts between layers, Q_{sol} increases with layer density
  - Q_{res} due to residual gas trapped between layers, scales as 1/n in molecular regime
  - Non-linear behaviour requires layer-to-layer modeling
- In practice
  - Typical data available from (abundant) literature
  - Measure performance on test samples

Typical heat fluxes at vanishingly low temperature between flat plates [W/m^2]

Black-body radiation from 290 K	401
Black-body radiation from 80 K	2.3
Gas conduction (100 mPa He) from 290 K	19
Gas conduction (1 mPa He) from 290 K	0.19
Gas conduction (100 mPa He) from 80 K	6.8
Gas conduction (1 mPa He) from 80 K	0.07
MLI (30 layers) from 290 K, pressure below 1 mPa	1-1.5
MLI (10 layers) from 80 K, pressure below 1 mPa	0.05
MLI (10 layers) from 80 K, pressure 100 mPa	1-2

Cross-section of LHC dipole cryostat



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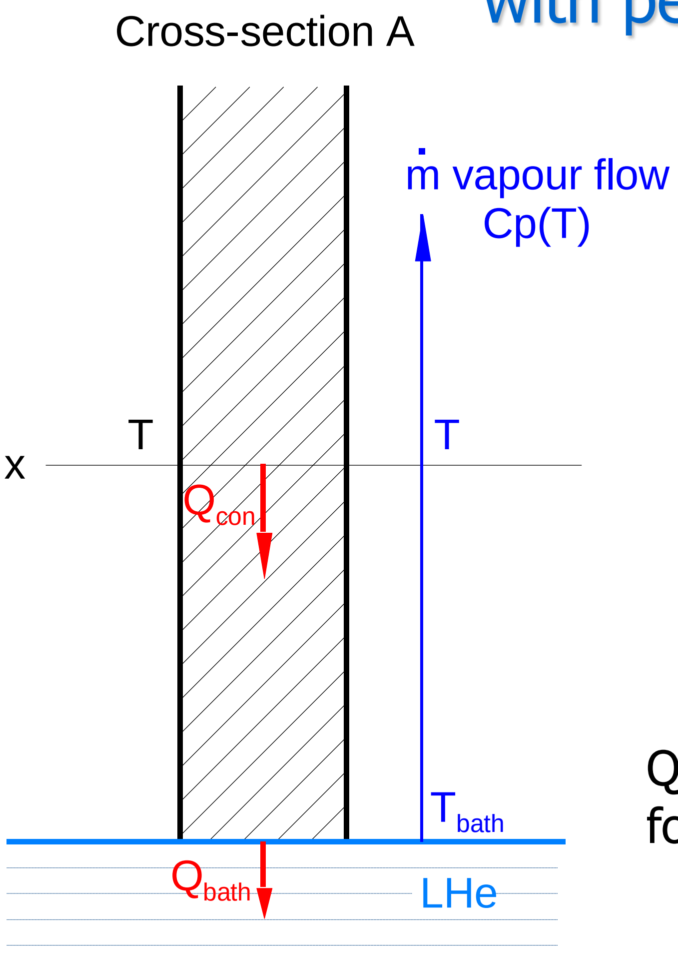
Vapour cooling of necks and supports with perfect heat exchange



Assuming perfect heat exchange between solid and gas, i.e. $T_{sol}(x)=T_{gas}(x)=T(x)$:

$$Q_{con} = Q_{bath} + \dot{m} \cdot Cp(T) \cdot (T - T_{bath})$$

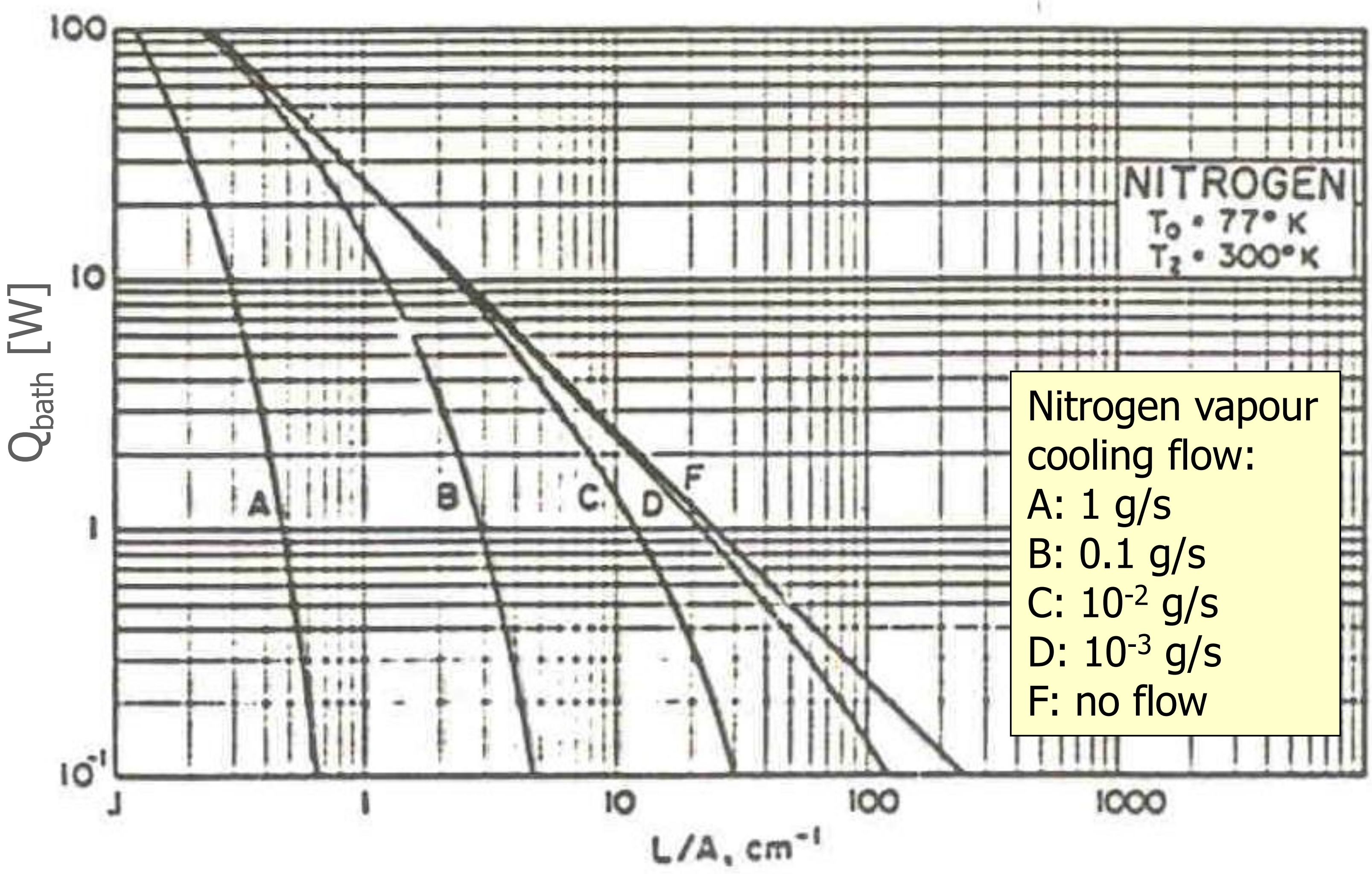
$$k(T) \cdot A \cdot \frac{dT}{dx} = Q_{bath} + \dot{m} \cdot Cp(T) \cdot (T - T_{bath})$$

Cp(T): Specific heat of vapour
k(T) : Thermal conductivity of the support

Q_{bath} can then be calculated by numerical integration for :

- different cryogens,
- different values of aspect ratio L/A
- different values of vapour flow

Heat reaching the cold end of a stainless steel neck



Nitrogen vapour cooling flow:
A: 1 g/s
B: 0.1 g/s
C: 10^{-2} g/s
D: 10^{-3} g/s
F: no flow

Vapour cooling of necks and supports with perfect heat exchange in self-sustained mode

A particular case of gas cooling is the self-sustained mode, i.e. the vapour flow is generated only by the residual heat Q_{bath} reaching the bath. Then:

$$Q_{bath} = L_v \cdot \dot{m}$$

(Lv: latent heat of vaporization)

Given the general equation

$$k(T) \cdot A \cdot \frac{dT}{dx} = Q_{bath} + \dot{m} \cdot Cp(T) \cdot \left(T - T_{bath}\right)$$

After integration, we finally have:

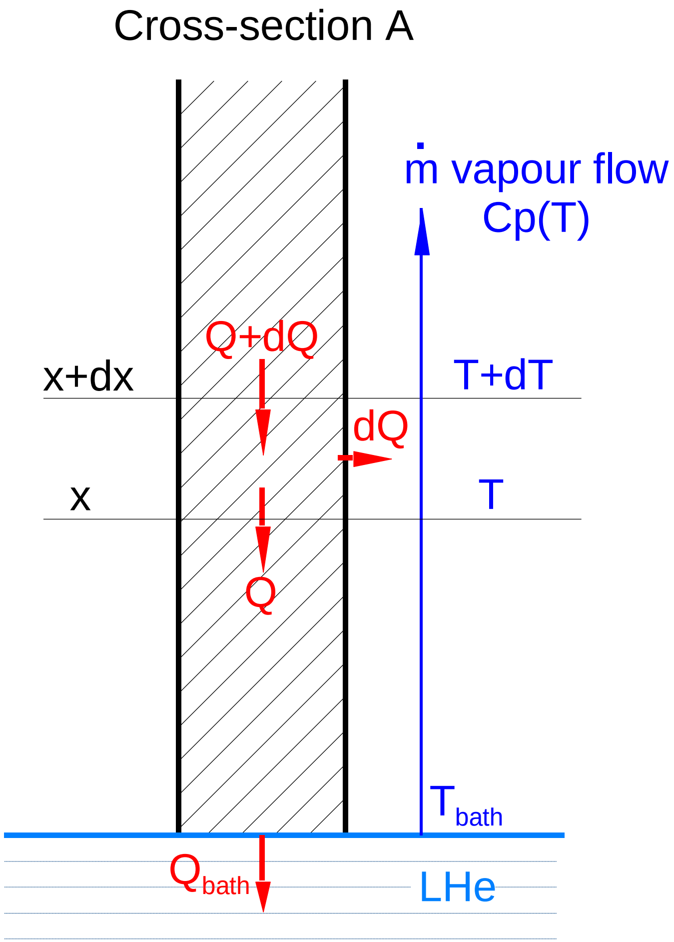
$$Q_{bath} = \frac{A}{L} \cdot \int_{T_{bath}}^{T_{ambient}} \frac{K(T)}{1 + \left(T - T_{bath}\right) \cdot \frac{Cp(T)}{Lv}} \cdot dT$$

Attenuation factor w.r. to pure conduction

Reduction of heat conduction by self-sustained helium vapour cooling

Effective thermal conductivity integral from 4 to 300 K	Purely conductive regime [$W.cm^{-1}$]	Self-sustained vapour-cooling [$W.cm^{-1}$]
ETP copper	1620	128
OFHC copper	1520	110
Aluminium 1100	728	39.9
Nickel 99% pure	213	8.65
Constantan	51.6	1.94
AISI 300 stainless steel	30.6	0.92

Vapour cooling of necks and supports with imperfect heat exchange



$$dQ = f \cdot \dot{m} \cdot Cp(T) \cdot dT$$

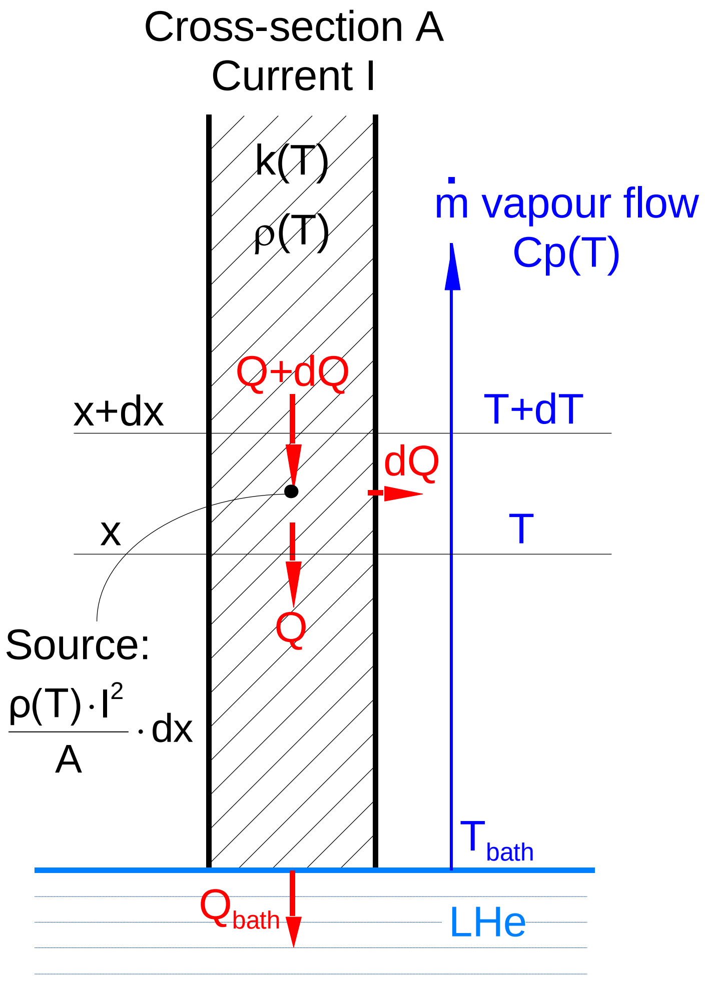
With f, the efficiency of the heat transfer

In steady state, the heat balance equation becomes:

$$\frac{d}{dx}\left[k(T) \cdot A \cdot \frac{dT}{dx}\right] = f \cdot \dot{m} \cdot Cp(T) \cdot \frac{dT}{dx}$$

→ Numerical integration for solving this equation

Vapor-cooled current leads



ρ(T): electrical resistivity

$$dQ = f\cdot\dot{m}\cdot Cp(T)\cdot dT$$

In steady-state, heat balance equation:

$$\frac{d}{dx}\left[k(T)\cdot A\cdot\frac{dT}{dx}\right] - f\cdot\dot{m}\cdot Cp(T)\cdot\frac{dT}{dx} + \frac{\rho(T)\cdot I^2}{A} = 0$$

Solid conduction

Vapour cooling

Joule heating

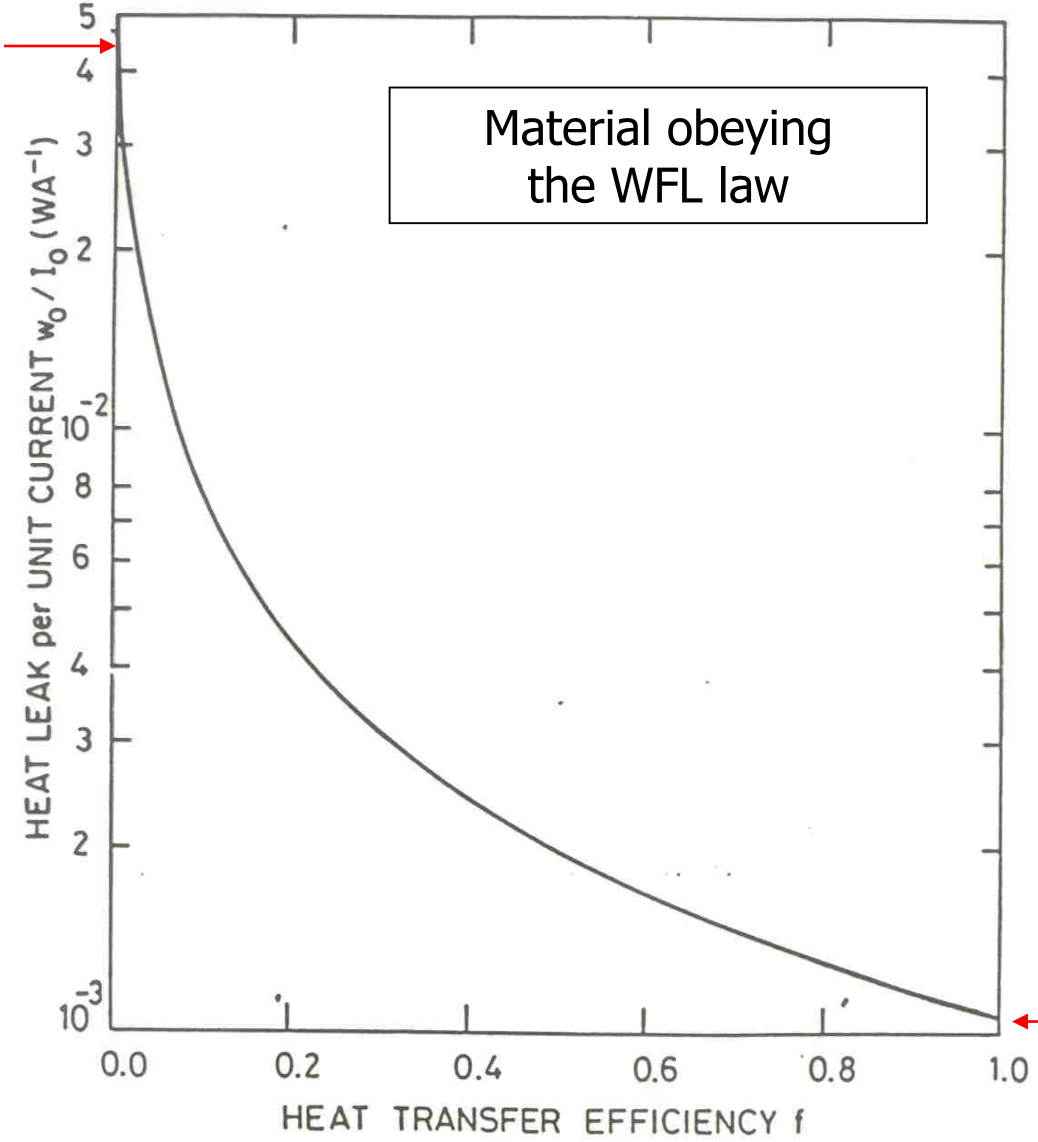
Assuming the material of the lead follows the Wiedemann-Franz-Lorenz (WFL) law:

$$k(T)\cdot\rho(T) = L_0\cdot T$$

L_0: Lorenz number (2.45 10^{-8} W.Ω.K^{-2})

→ Then numerical integration

Heat load of optimized current lead



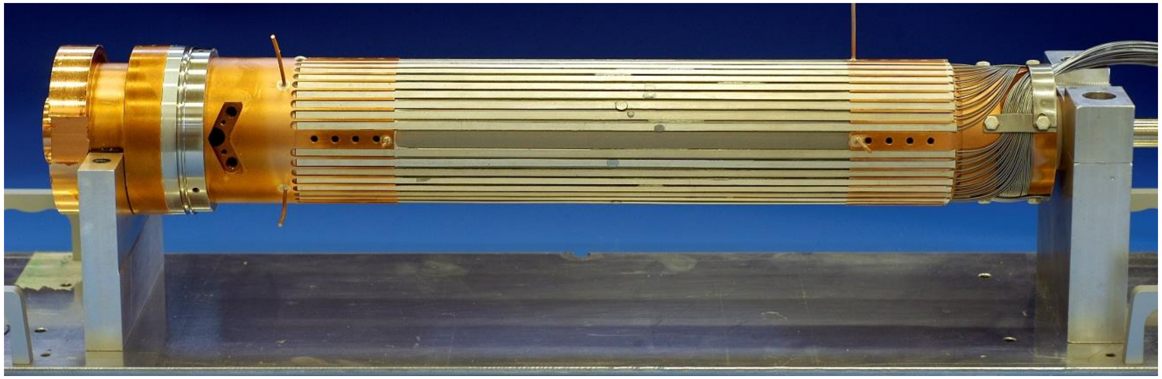
Uncooled
47 W/kA

Material obeying
the WFL law

Minimum residual
heat load
1.04 W/kA

Beating the WFL law: HTS current leads

- The WFL law essentially states that good electrical conductors are also good thermal conductors
- Current leads need good electrical conductors with low thermal conductivity
- Superconductors are bad thermal conductors with zero resisitivity
- Build current lead with superconductor up to temperature as high as possible, i.e. HTS



HTS vs. normal conducting current leads

Type		**Resistive**	**HTS (4 to 50 K)** **Resistive (above)**
Heat into LHe	[W/kA]	1.1	0.1
Total exergy consumption	[W/kA]	430	150
Electrical power from grid	[W/kA]	1430	500

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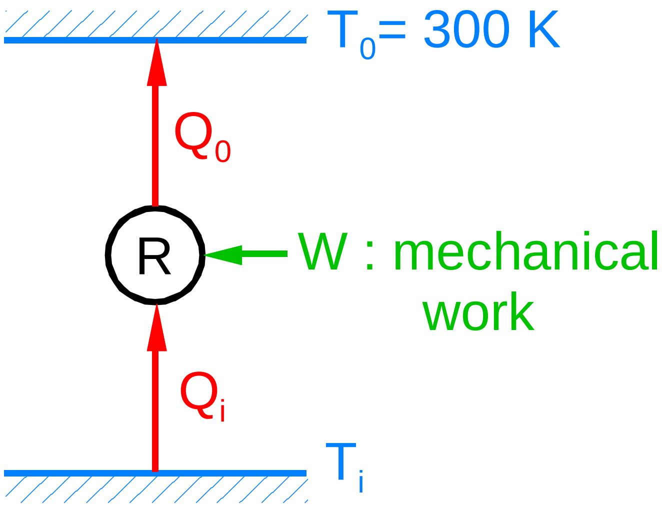
Thermodynamics of cryogenic refrigeration



First principle [Joule] $$Q_0 = Q_i + W$$

Second principle [Clausius] $$\frac{Q_0}{T_0} \ge \frac{Q_i}{T_i}$$

(= for reversible process)

Hence, $$W \ge T_0 \cdot \frac{Q_i}{T_i} - Q_i$$ which can be written in three different ways:

① $$W \ge T_0 \cdot \Delta S_i - Q_i$$ introducing entropy S as $$\Delta S_i = \frac{Q_i}{T_i}$$

② $$W \ge Q_i \cdot \boxed{\left(\frac{T_0}{T_i} - 1\right)}$$ Carnot factor

③ $$W \ge \Delta E_i$$ introducing exergy E as $$\Delta E_i = Q_i \cdot \left(\frac{T_0}{T_i} - 1\right)$$

Minimum refrigeration work

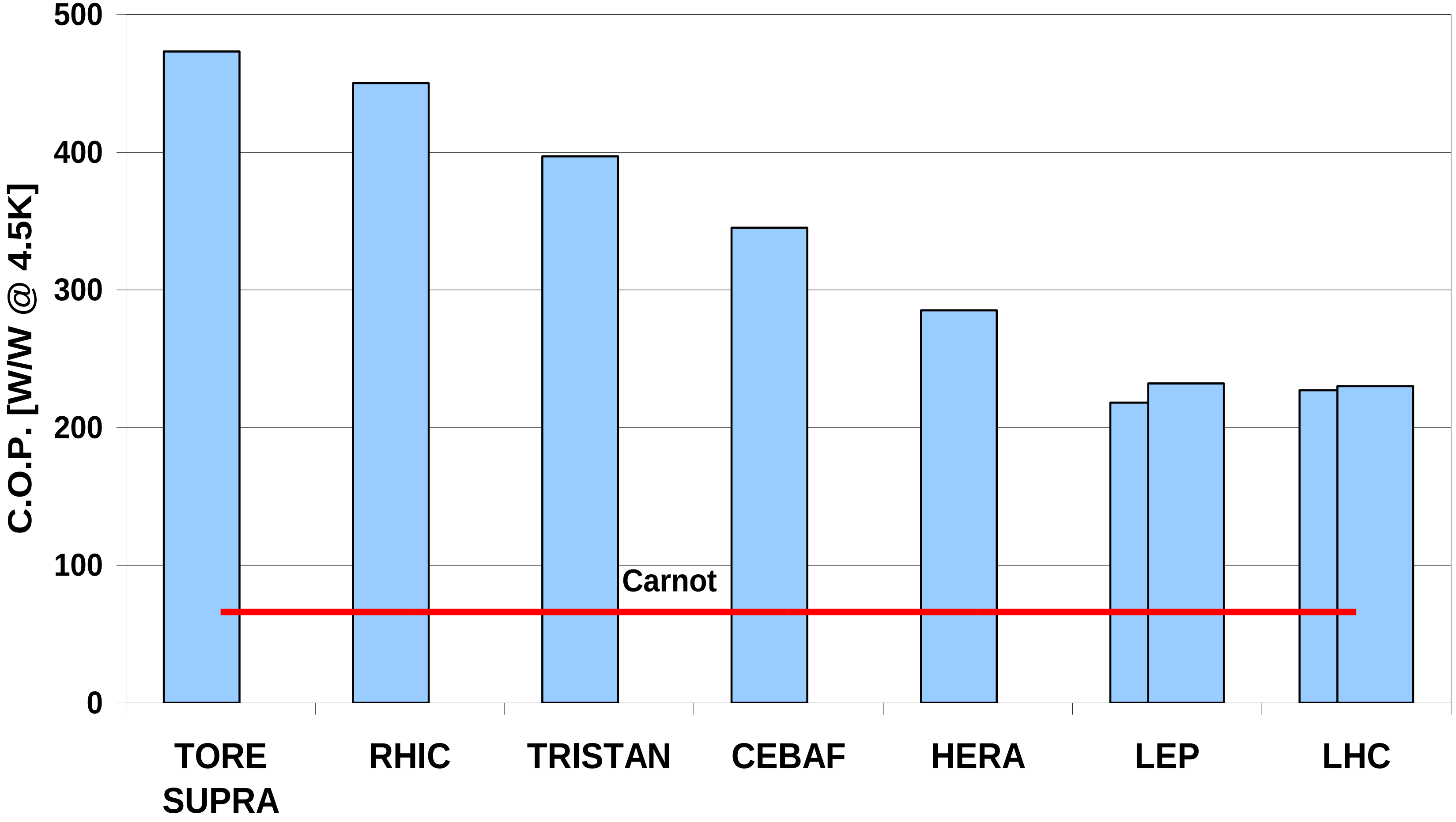
Consider the extraction of 1 W at 4.5 K, rejected at 300 K
The minimum refrigeration work (equation 2) is:

$$W_{min} = Q_i \cdot \left(\frac{T_0}{T_i} - 1 \right) = 1 \cdot \left(\frac{300}{4.5} - 1 \right) = 65.7 \text{ W}$$

In practice, the most efficient helium refrigerators have an efficiency of about 30% w.r. to the Carnot limit

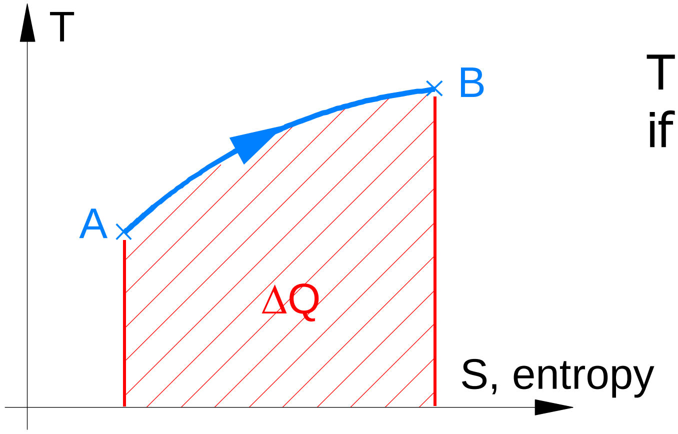
$$\Rightarrow W_{real} = \frac{W_{min}}{\eta} = \frac{65.7}{0.3} = 220 \text{ W}$$

C.O.P. of large cryogenic helium refrigerators



Refrigeration cycles and duties

Introduction to the T-S diagram

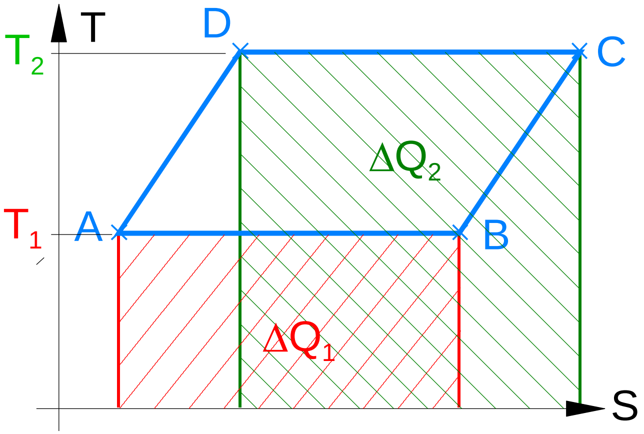


Thermodynamic transformation from A to B, if reversible:

$$\Delta Q = \int_A^B T \cdot dS$$

To make a refrigeration cycle, need a substance, the entropy of which depends on some other variable than temperature

Pressure of gas: Compression/expansion cycle
Magnetization of solid: magnetic refr. cycle

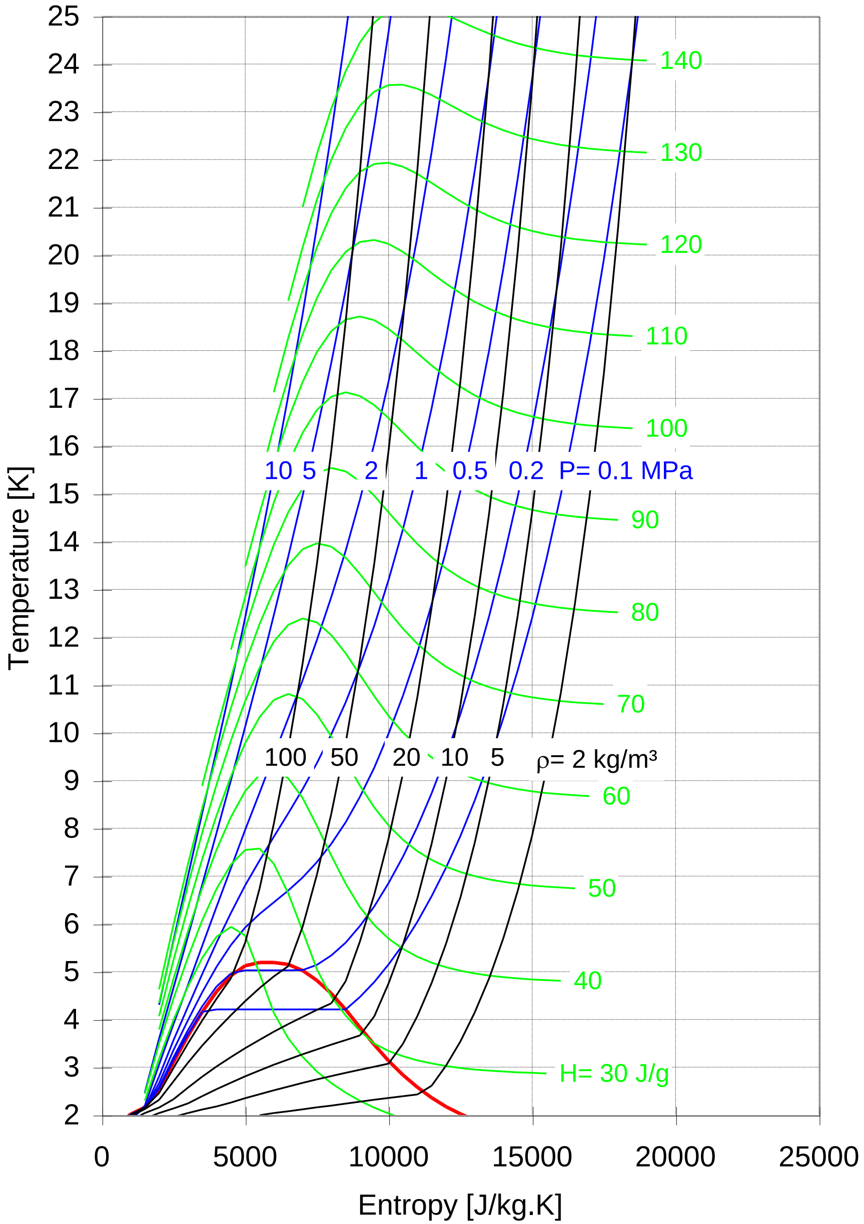


ΔQ_1: heat absorbed at T_1

ΔQ_2: heat rejected at T_2

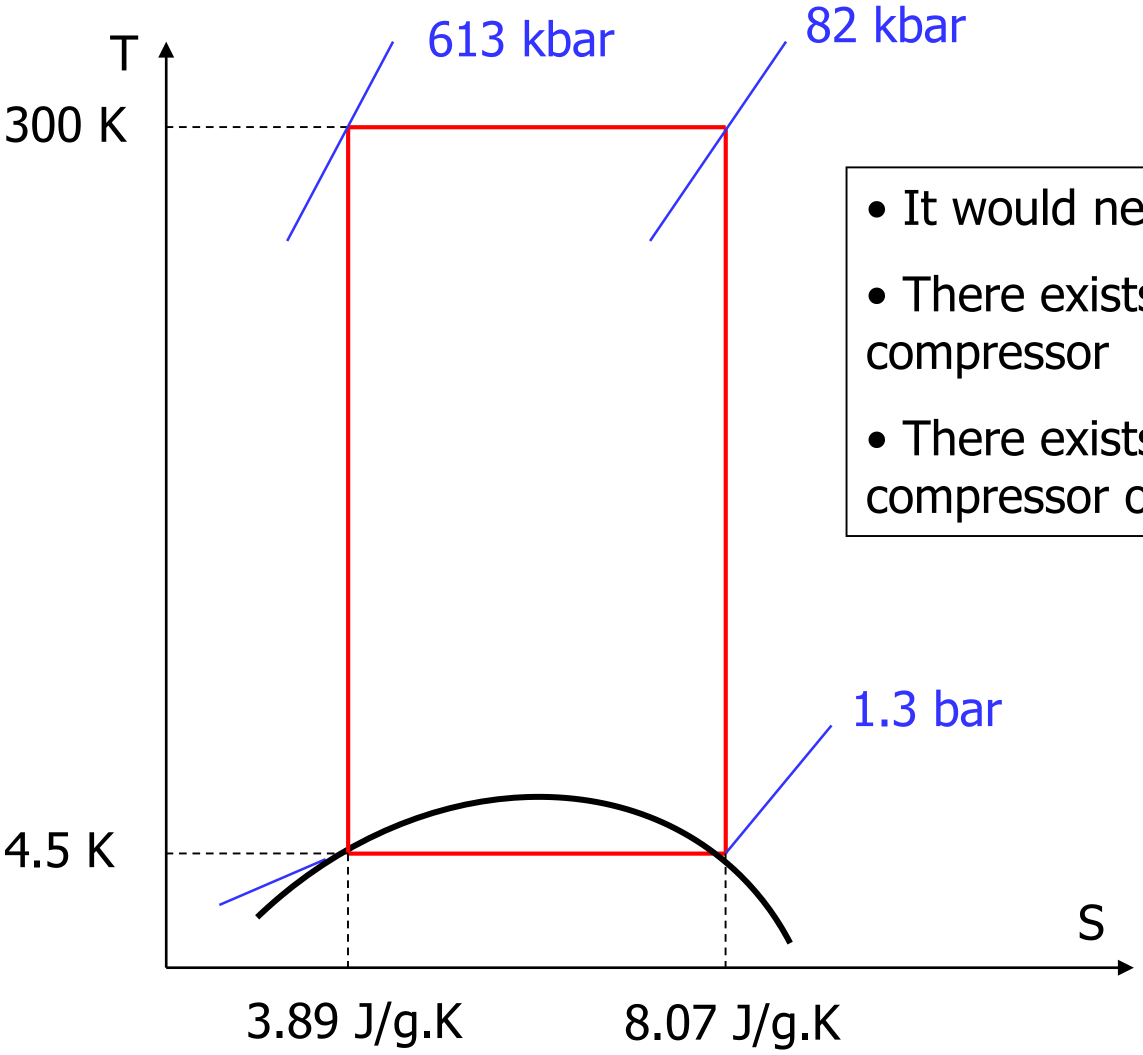
→ Refrigeration cycle A B C D

T-S diagram for helium



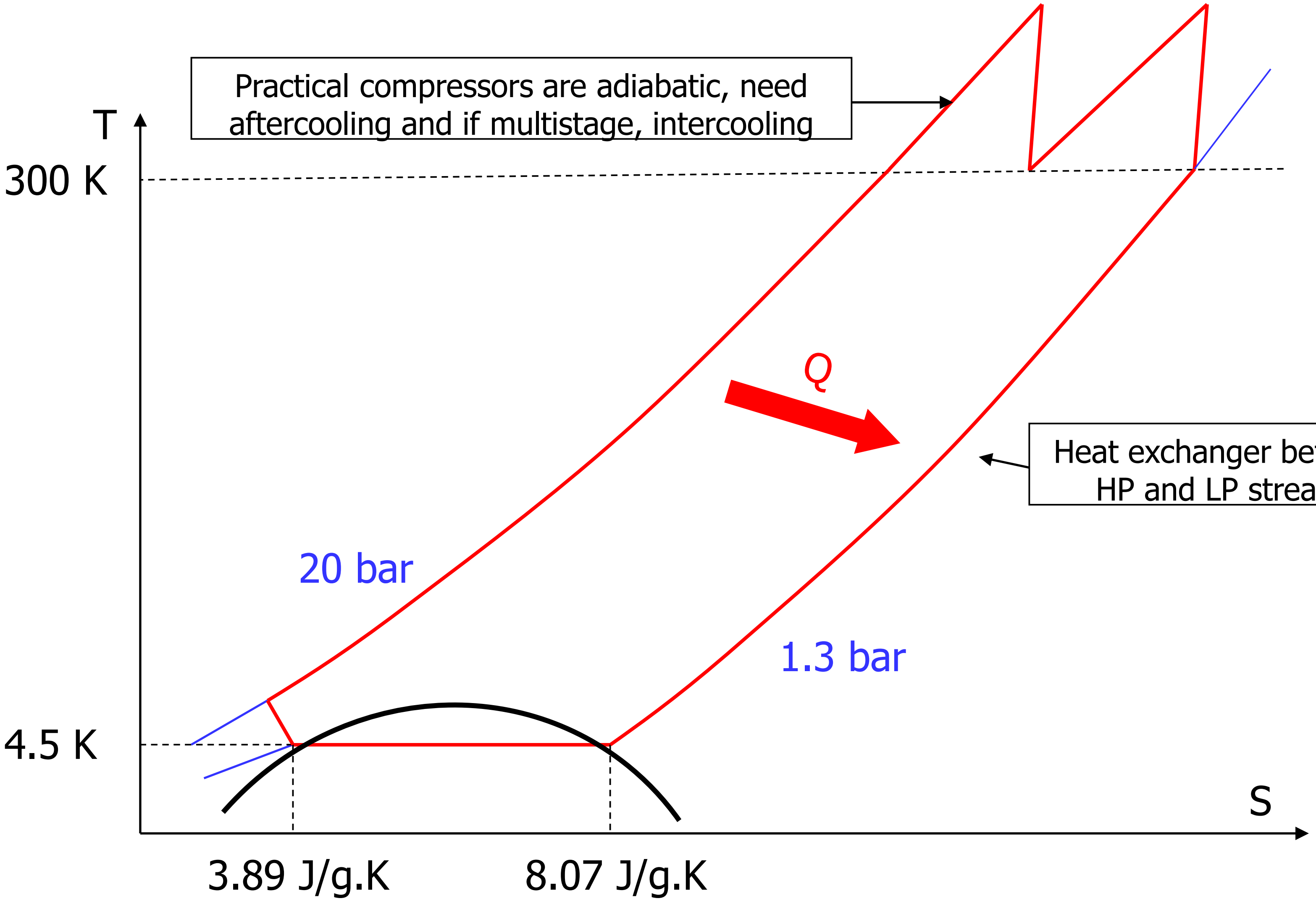
Ph. Lebrun

A Carnot cycle is not feasible for helium liquefaction

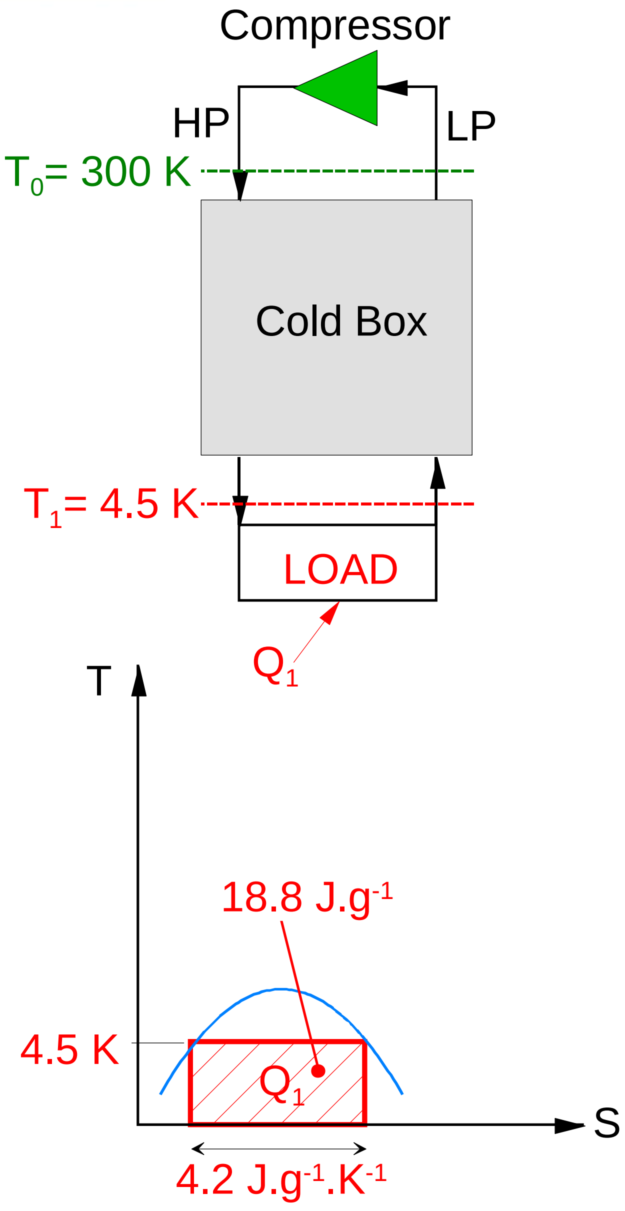


- It would need a HP of 613 kbar!
- There exists no true isothermal compressor
- There exists no true isentropic compressor or expander

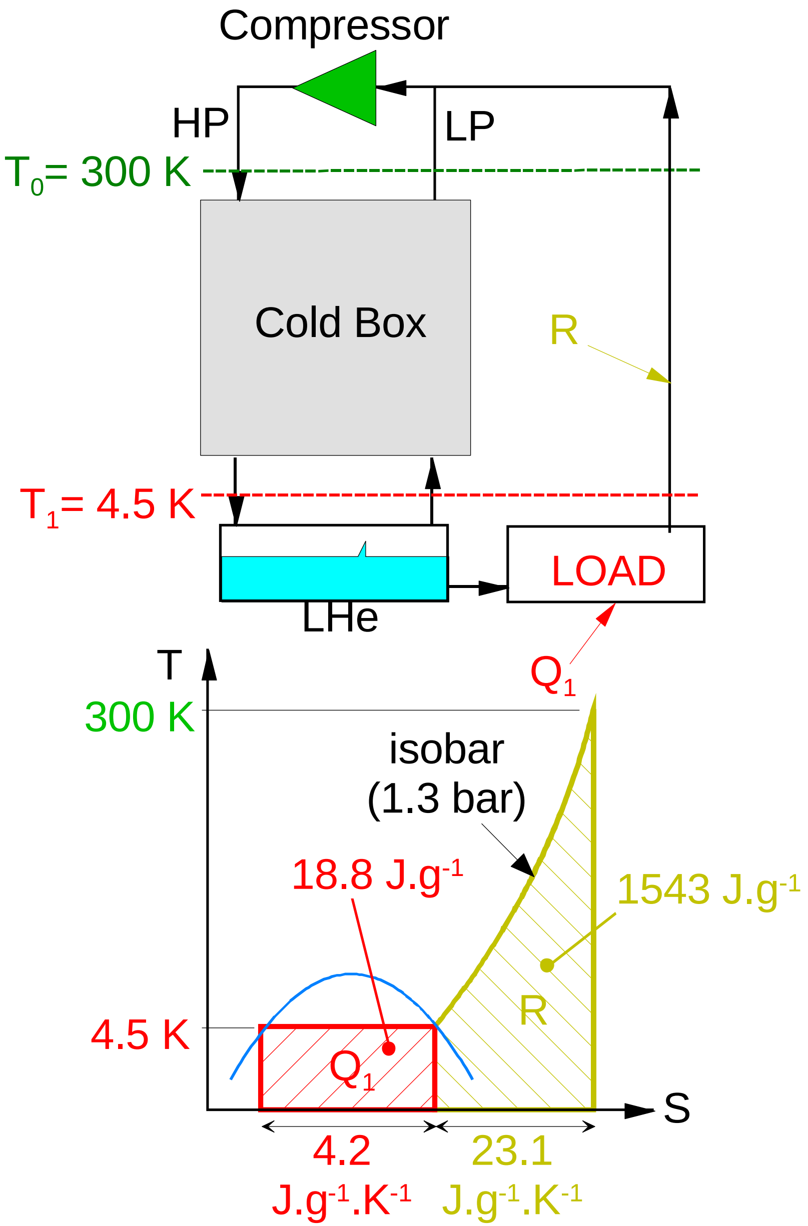
A real cycle needs heat exchange and para-isothermal compression



Refrigerator



Liquefier



Thermodynamic equivalence between refrigeration and liquefaction

What is the isothermal 4.5 K (T_1) refrigeration equivalent to 1 g.s^{-1} He liquefaction?

$$\dot{W}_{\text{min.lique}} = \dot{m}_{\text{lique}} \cdot (T_0 \cdot \Delta S - Q_1 - R)$$

$$\dot{m}_{\text{lique}} = 1 \text{ g.s}^{-1},\ T_0 = 300 \text{ K},\ \Delta S = 27.3 \text{ J.g}^{-1}.\text{K}^{-1},\ Q_1 = 18.8 \text{ J.g}^{-1},\ R = 1543 \text{ J.g}^{-1}$$

$$\boxed{\dot{W}_{\text{min.lique}} = 6628 \text{ W}}$$

Write that the same work is used to produce isothermal refrigeration at 4.5 K:

$$\dot{W}_{\text{min.refrig}} = \dot{Q}_1 \cdot \left(\frac{T_0}{T_1} - 1 \right)$$

$$\dot{W}_{\text{min.refrig}} = \dot{W}_{\text{min.lique}} = 6628 \text{ W}$$

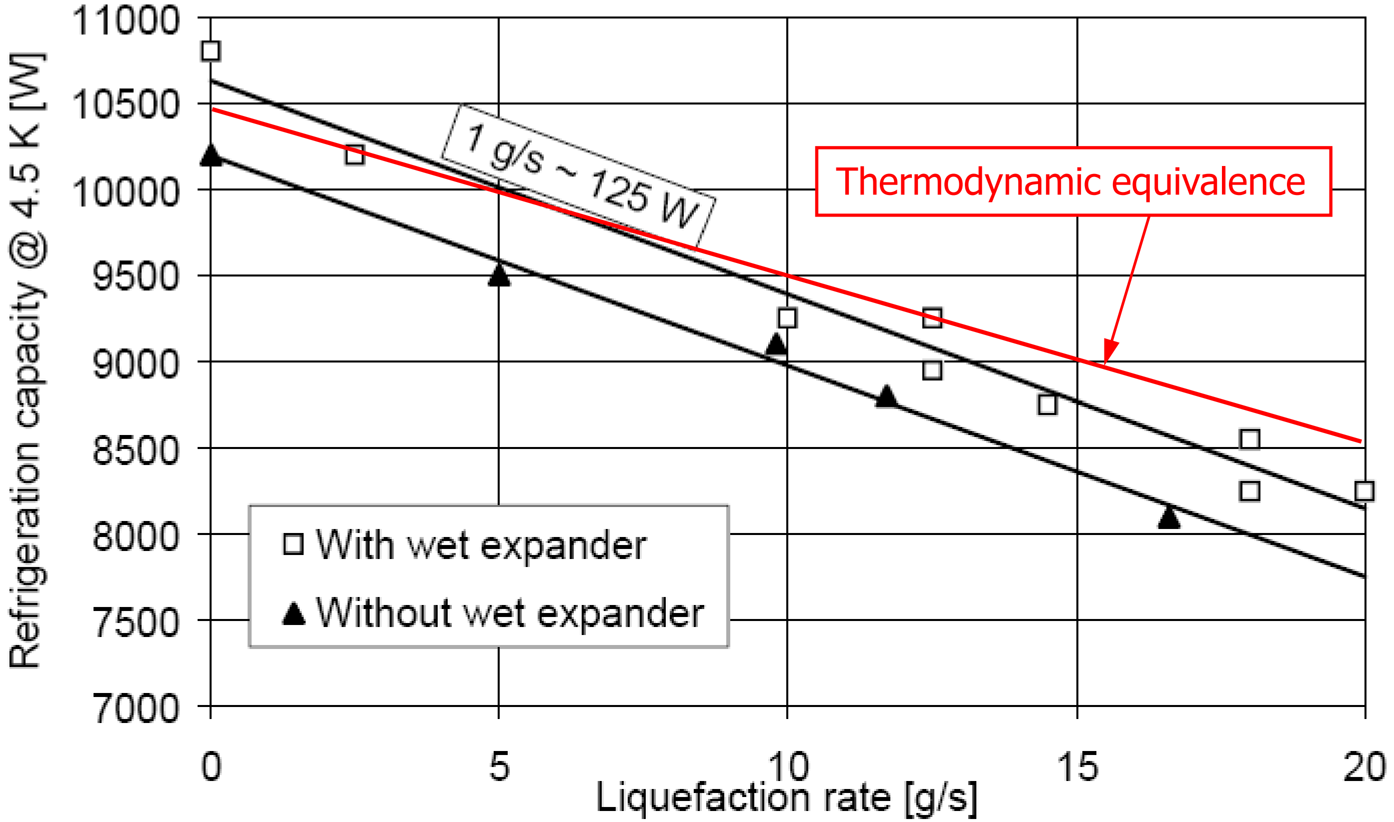
$$\Rightarrow \boxed{\dot{Q}_1 = 100 \text{ W}}$$

For refrigerators/liquefiers with the same efficiency:

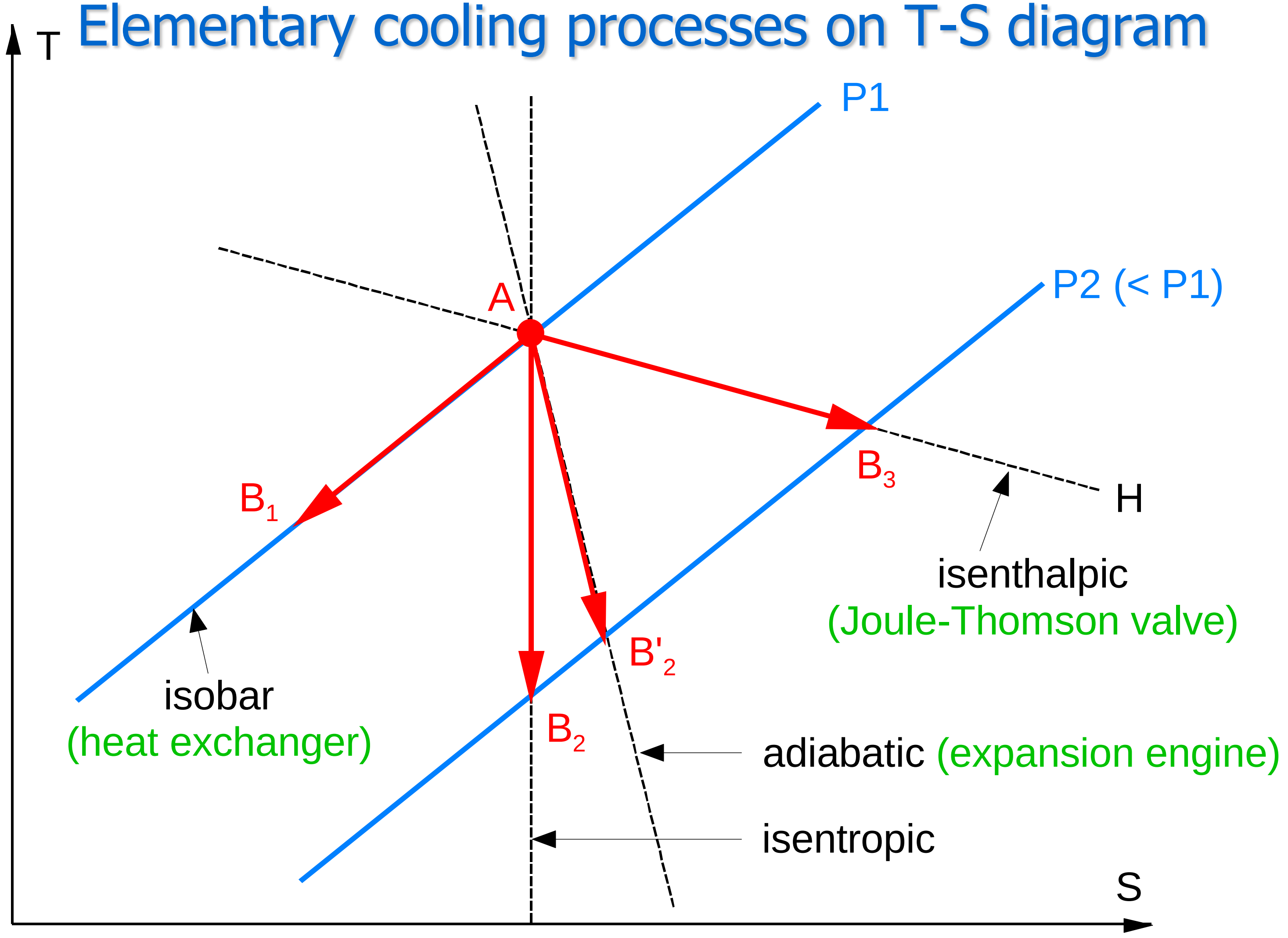
$$\boxed{1 \text{ g.s}^{-1} \text{ LHe} \equiv 100 \text{ W @ } 4.5 \text{ K}}$$

Measured refrigeration/liquefaction equivalence

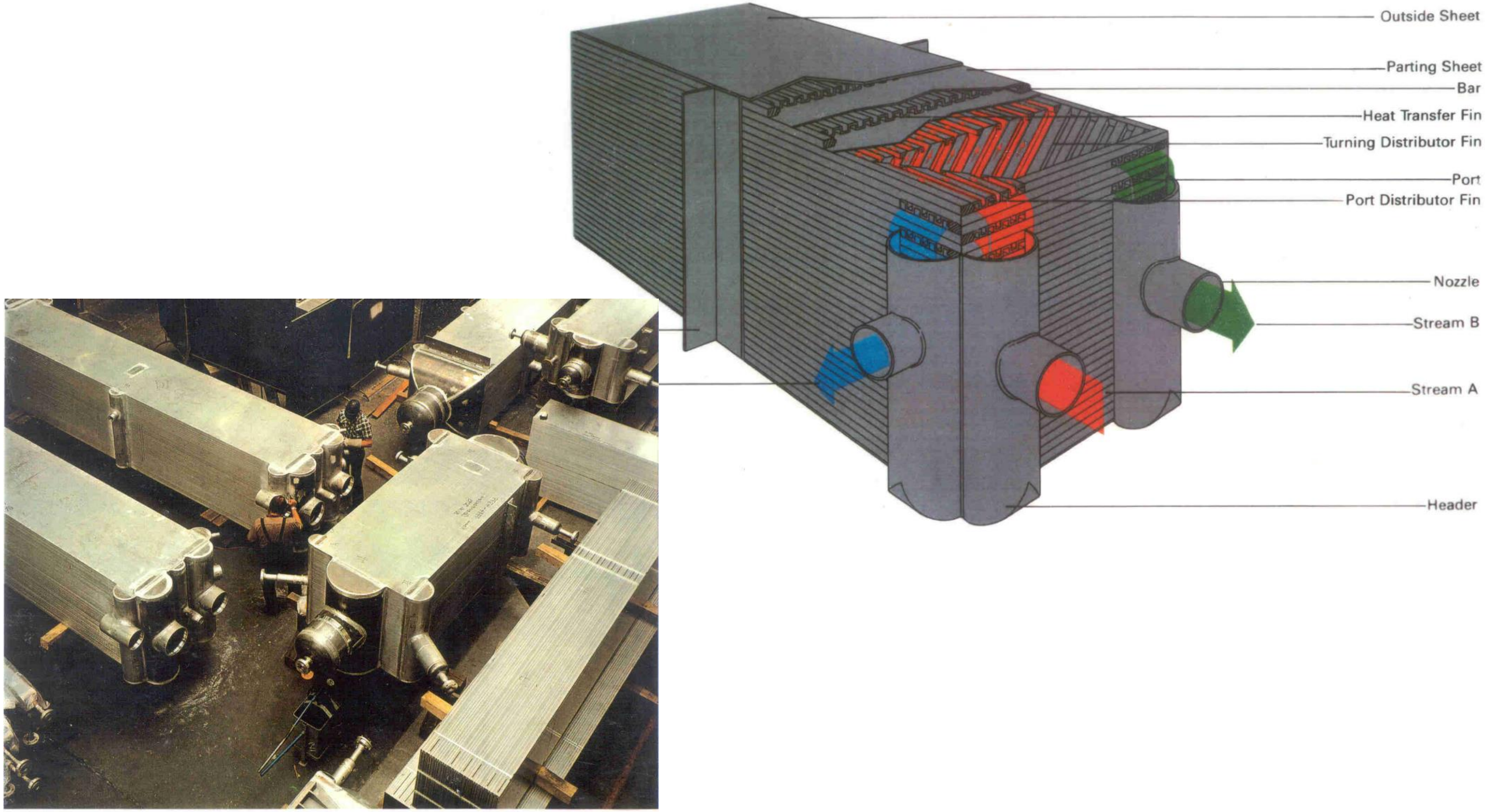
12 kW @ 4.5 K helium refrigerators for LEP 2



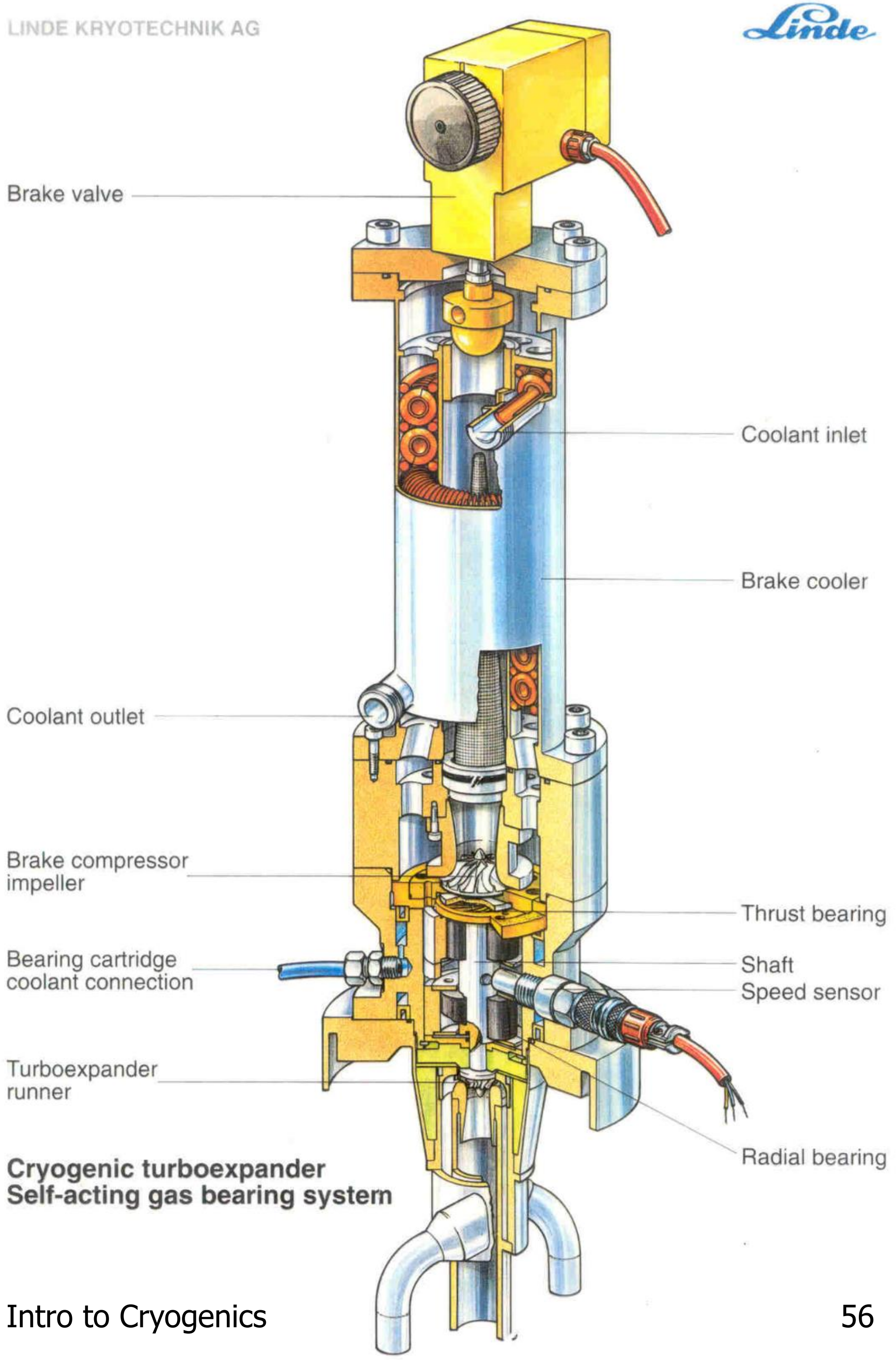
Elementary cooling processes on T-S diagram



Brazed aluminium plate heat exchanger



Cryogenic turbo-expander

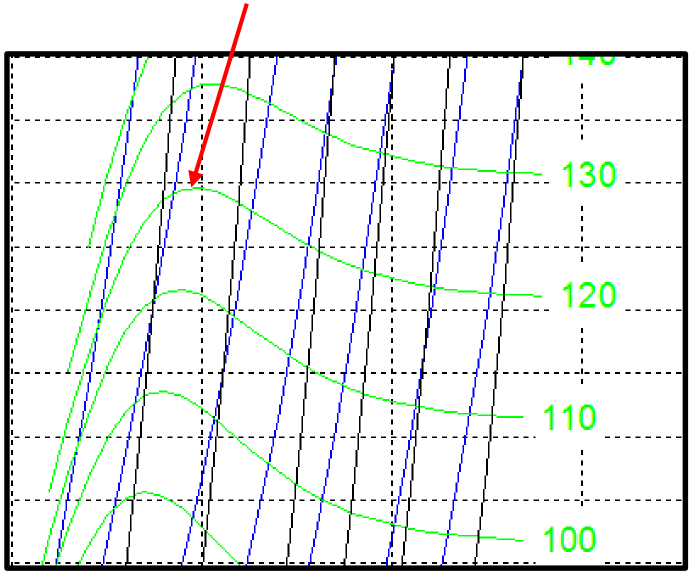


Cryogenic turboexpander
Self-acting gas bearing system

Joule-Thomson inversion temperatures

Isenthalps in T-S diagram can have positive or negative slope, i.e. isenthalpic expansion can produce warming or cooling

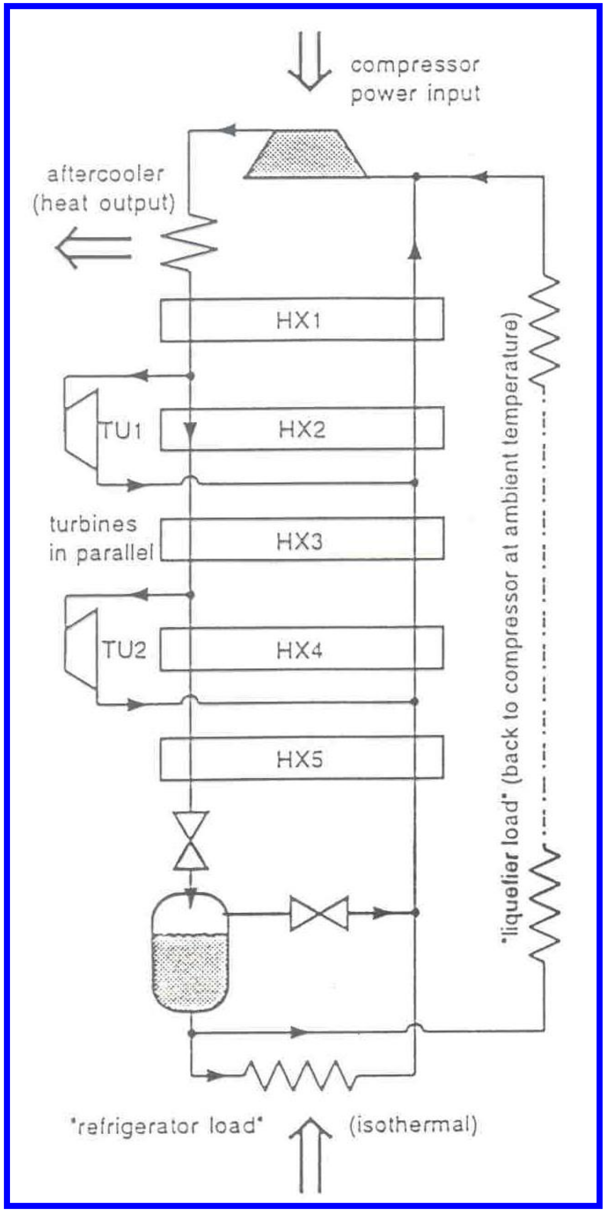
⇒ **inversion temperature**

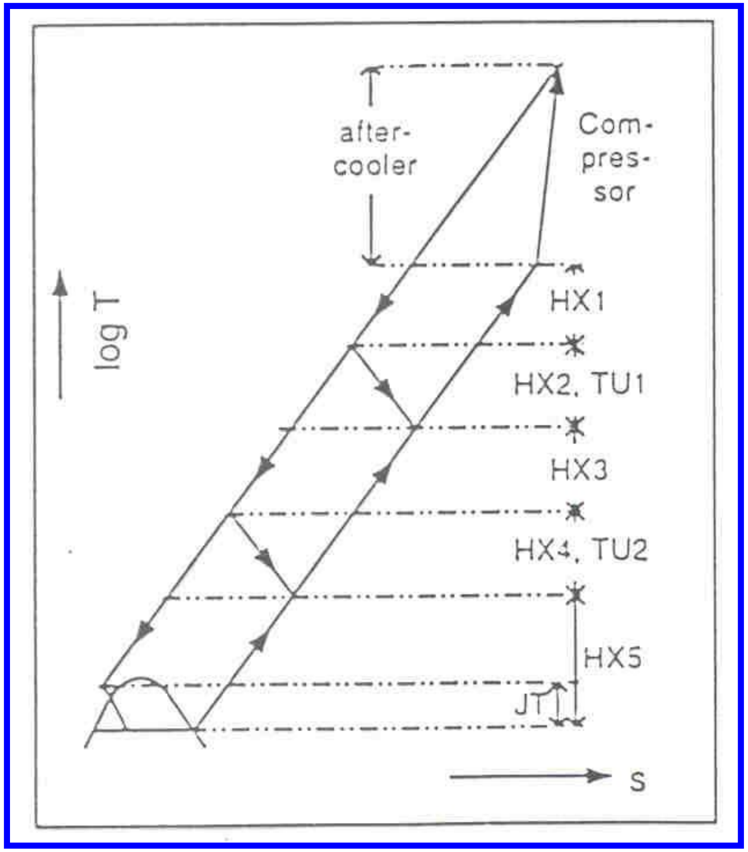


Cryogen	Maximum inversion temperature [K]
Helium	43
Hydrogen	202
Neon	260
Air	603
Nitrogen	623
Oxygen	761

While air can be cooled down and liquefied by JT expansion from room temperature, helium and hydrogen need precooling down to below inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)

Two-stage Claude cycle

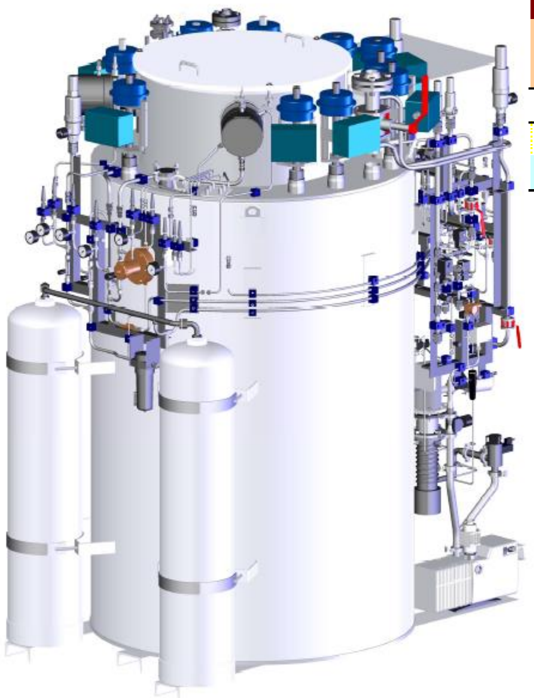


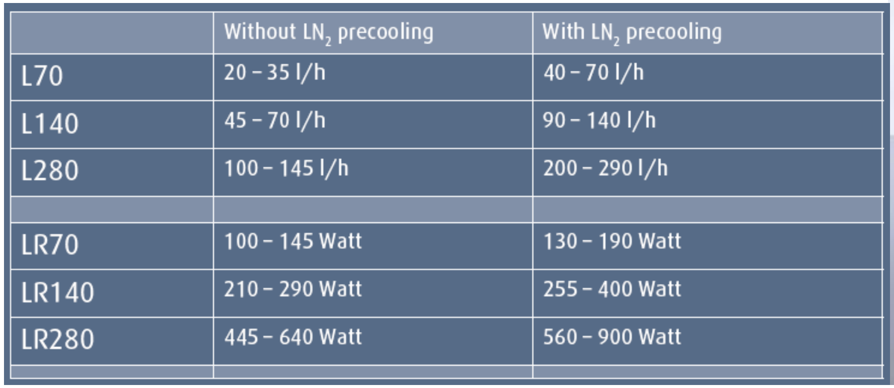


Claude-cycle helium refrigerators/liquefiers

Air Liquide & Linde

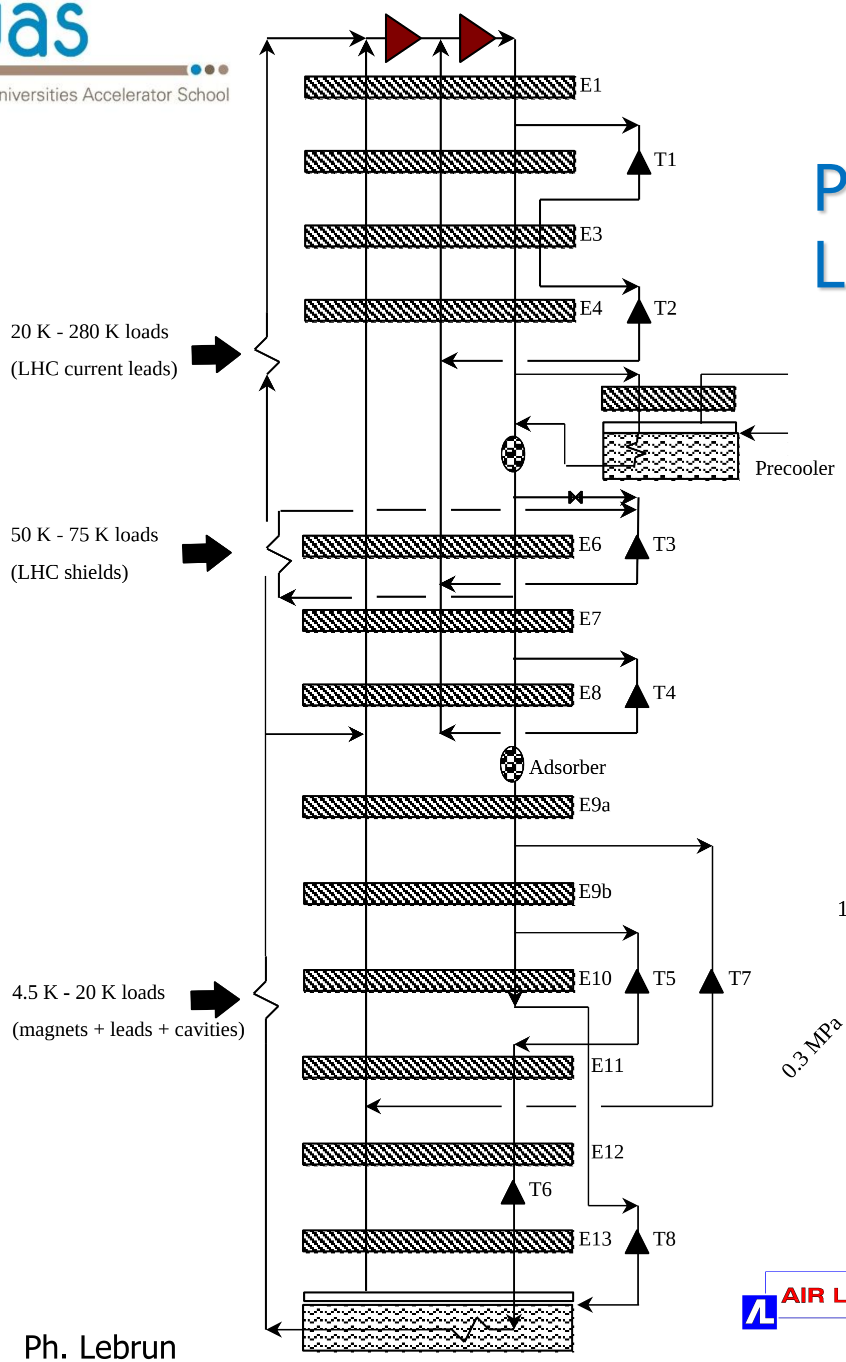
	HELIAL SL	**HELIAL ML**	**HELIAL LL**
Max. Liquefaction capacity without LN2	25 L/h	70 L/h	145 L/h
Max. Liquefaction capacity with LN2	50 L/h	150 L/h	330 L/h
Compressor electrical motor	55 kW	132 kW	250 kW
Specific consumption for liquefaction w/o LN2	645 W/W	552 W/W	505 W/W
% Carnot	**10%**	**12%**	**13%**

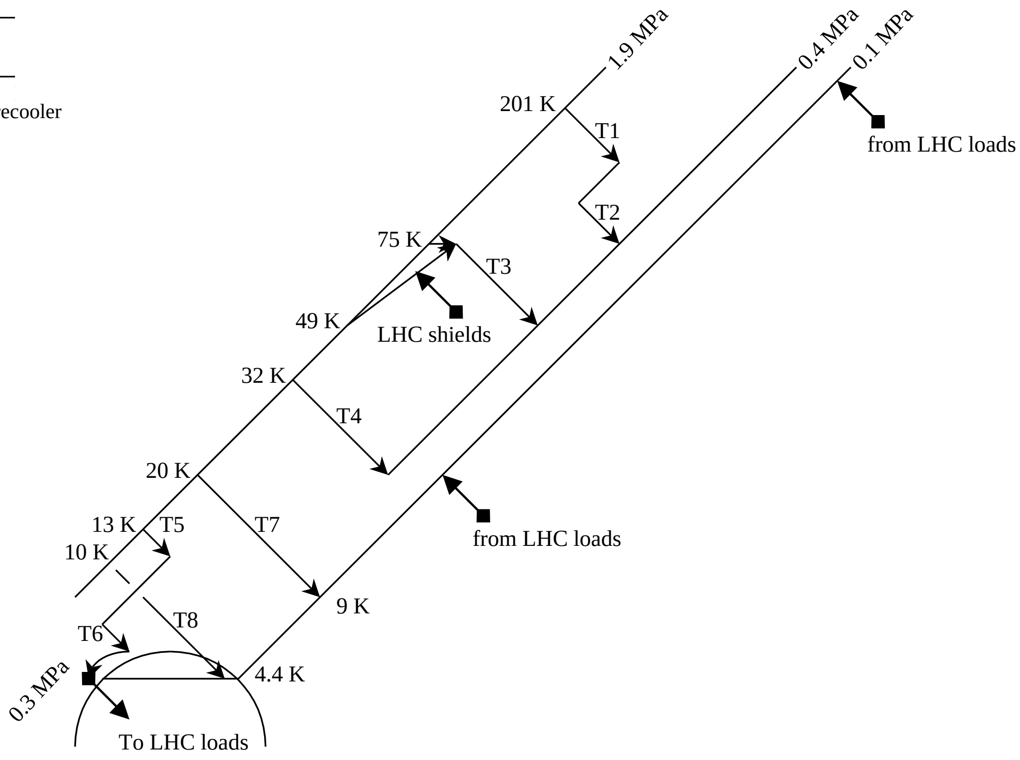




	Without LN_2 precooling	With LN_2 precooling
L70	20 – 35 l/h	40 – 70 l/h
L140	45 – 70 l/h	90 – 140 l/h
L280	100 – 145 l/h	200 – 290 l/h
LR70	100 – 145 Watt	130 – 190 Watt
LR140	210 – 290 Watt	255 – 400 Watt
LR280	445 – 640 Watt	560 – 900 Watt

Process cycle & T-S diagram of LHC 18 kW @ 4.5 K cryoplant





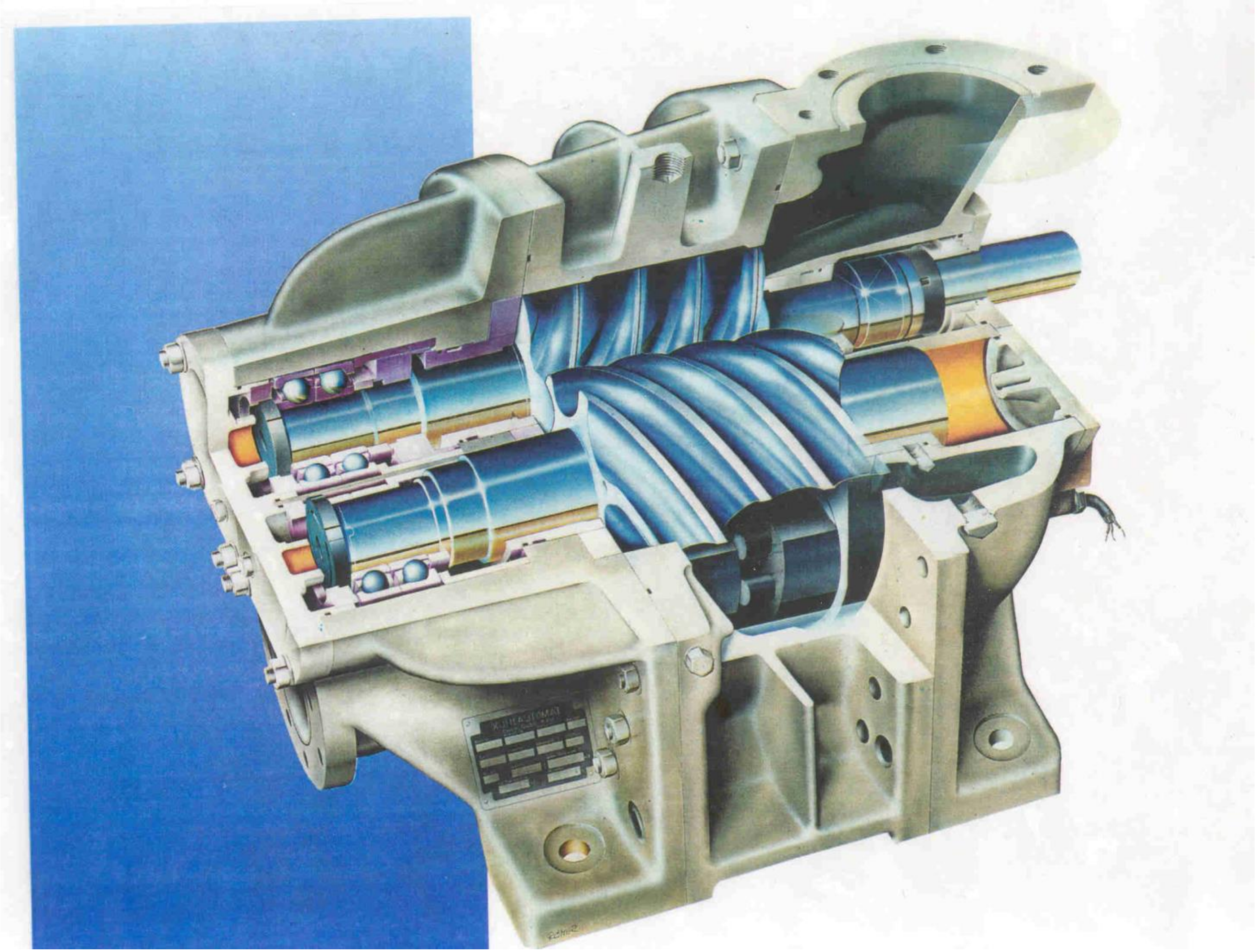
LHC 18 kW @ 4.5 K helium cryoplants

33 kW @ 50 K to 75 K
23 kW @ 4.6 K to 20 K
41 g/s liquefaction
4 MW compressor power
C.O.P. 220-230 W/W @ 4.5 K

Air Liquide

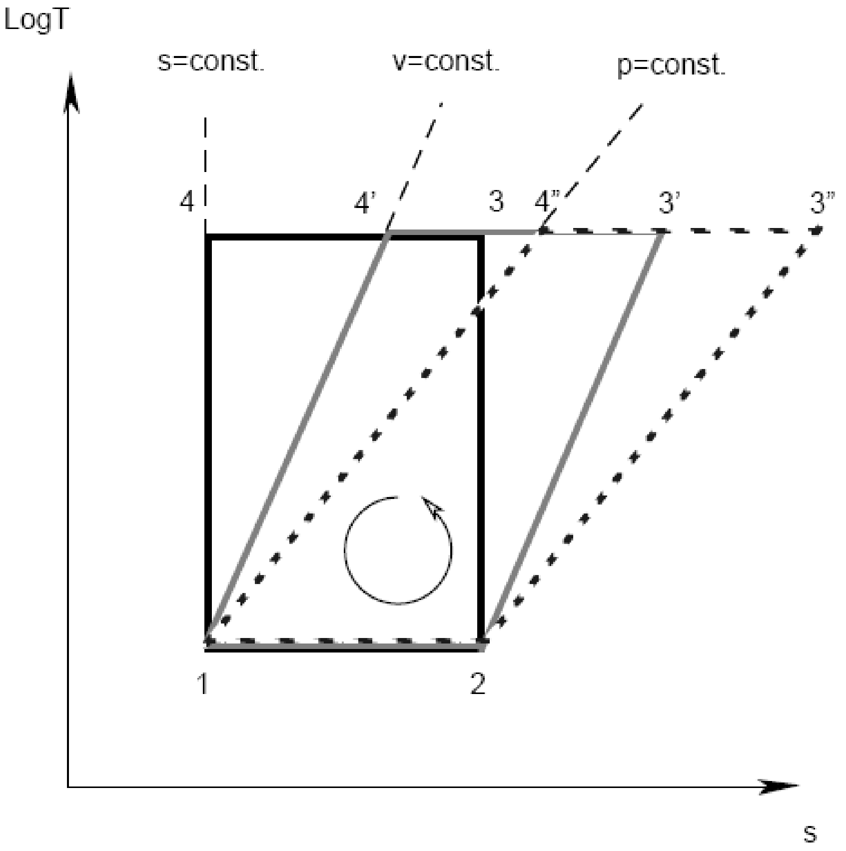
Linde

Oil-injected screw compressor



Compressor station of LHC 18 kW@ 4.5 K helium refrigerator

Carnot, Stirling and Ericsson cycles



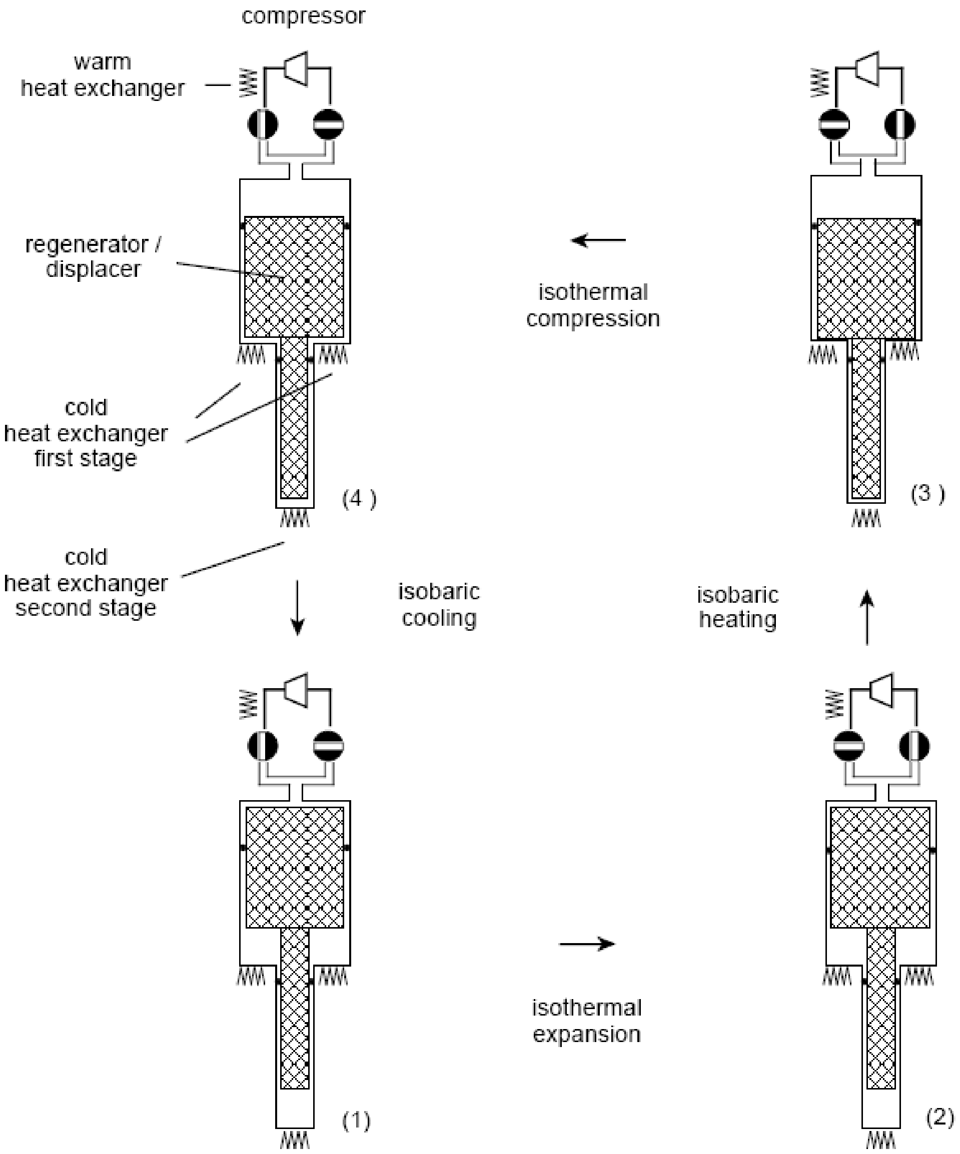
Carnot cycle (1,2,3,4), Stirling cycle (1,2,3',4') and Ericsson cycle (1,2,3",4")

All «sloping» cycles need internal heat exchange

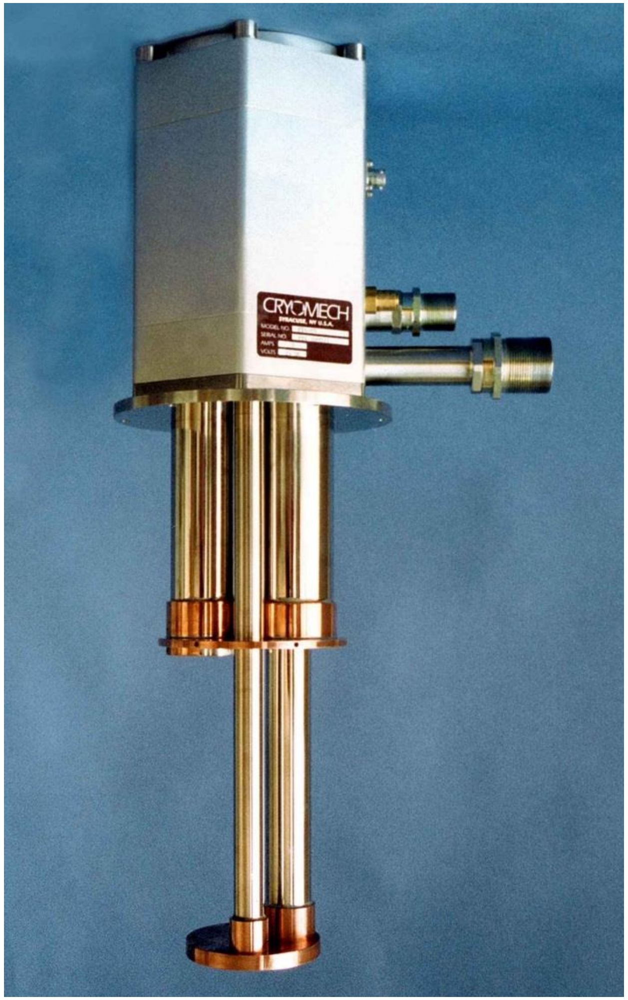
For small machines, this is done by regenerative, rather than recuperative heat exchangers

⇒ alternating rather than continuous operation

Operation of a Gifford-McMahon cryocooler (Ericsson cycle)



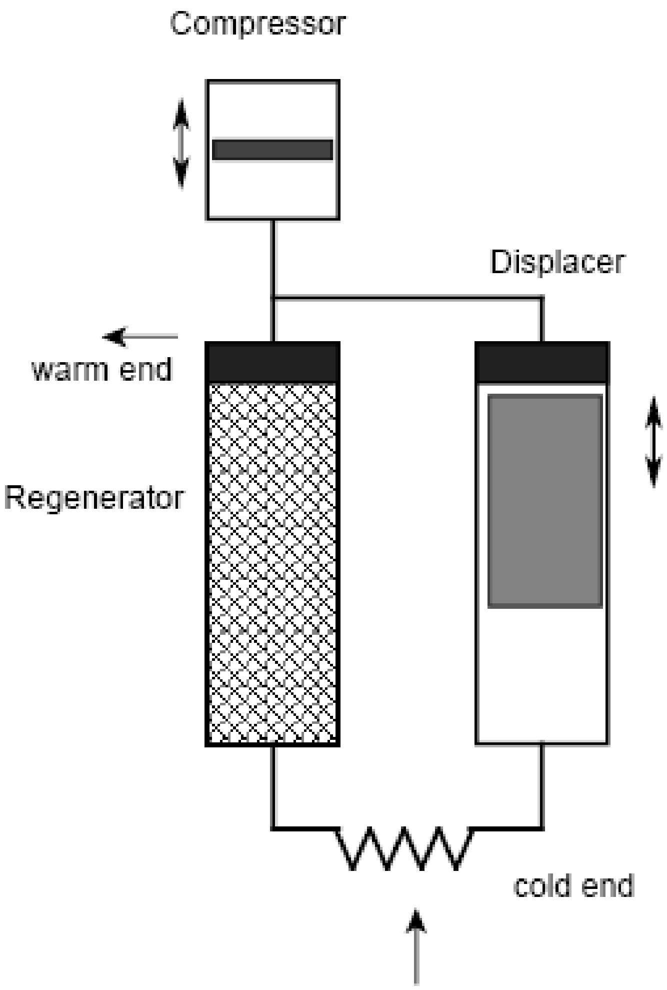
Two-stage Gifford-McMahon cryocooler



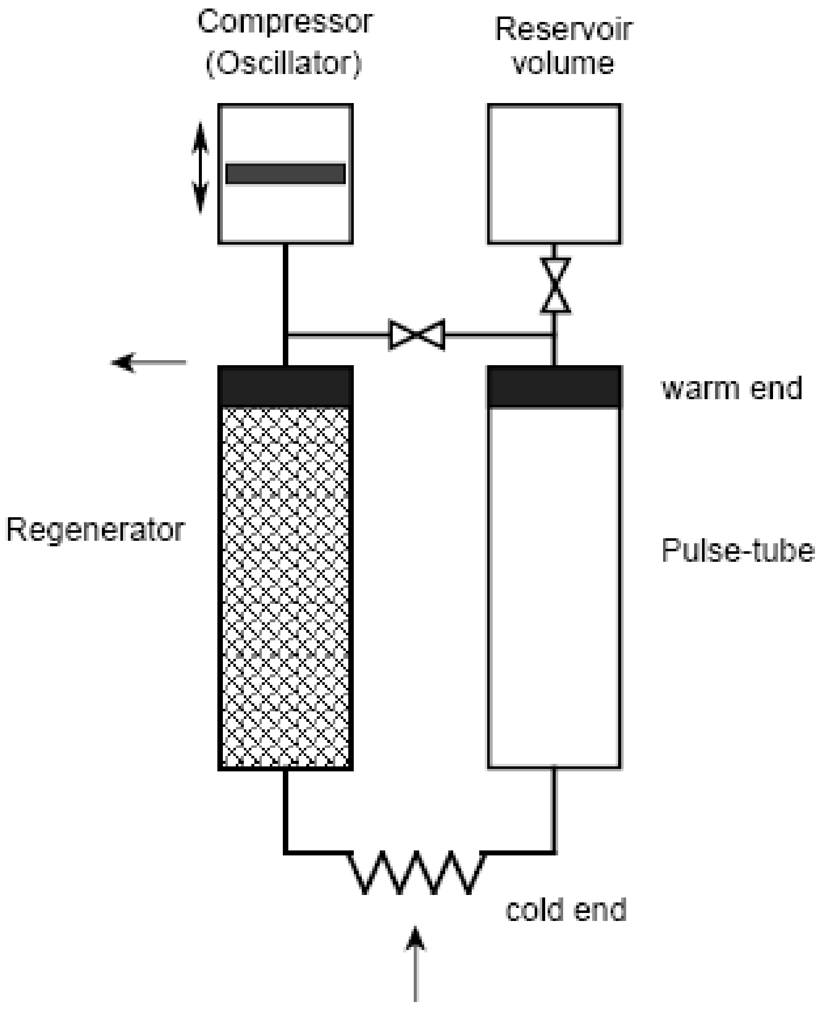
CRYOMECH PT407 & CP970 compressor

~ 0.7 W @ 4.2 K & 25 W @ 55 K

Stirling and pulse-tube cryocoolers

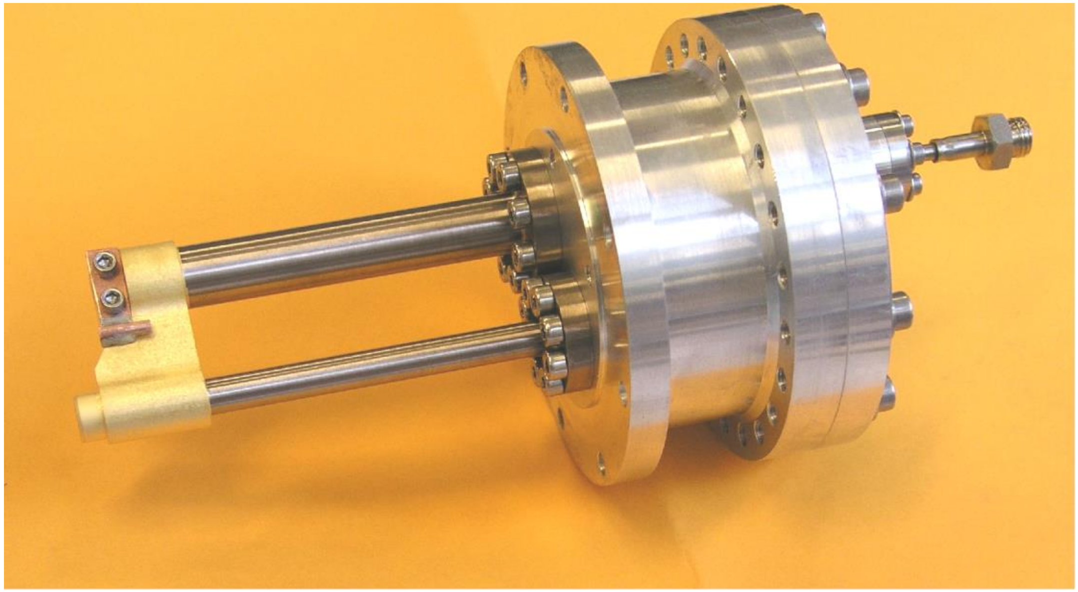


Stirling refrigerator



Pulse tube refrigerator

Mini pulse-tube cryocoolers



ESA MPTC development model – 1W @ 77K

CEA/SBT coaxial PTC– 6W @ 80K

Contents

- Introduction
- Cryogenic fluids
- Heat transfer & thermal insulation
- Thermal screening with cold vapour
- Refrigeration & liquefaction
- Cryogen storage & transport
- Thermometry

Specific cost of bulk He storage

Type	Pressure [MPa]	Density [kg/m³]	Dead volume [%]	Cost [CHF/kg He]
Gas Bag	0.1	0.16	0	300⁽¹⁾
MP Vessel	2	3.18	5-25	220-450
HP Vessel	20	29.4	0.5	500⁽²⁾
Liquid	0.1	125	13	100-200⁽³⁾

(1): Purity non preserved
(2): Not including HP compressors
(3): Not including reliquefier

Bulk helium storage solutions

11000 gallon liquid container

2 MPa gas tanks

20 MPa gas cylinders

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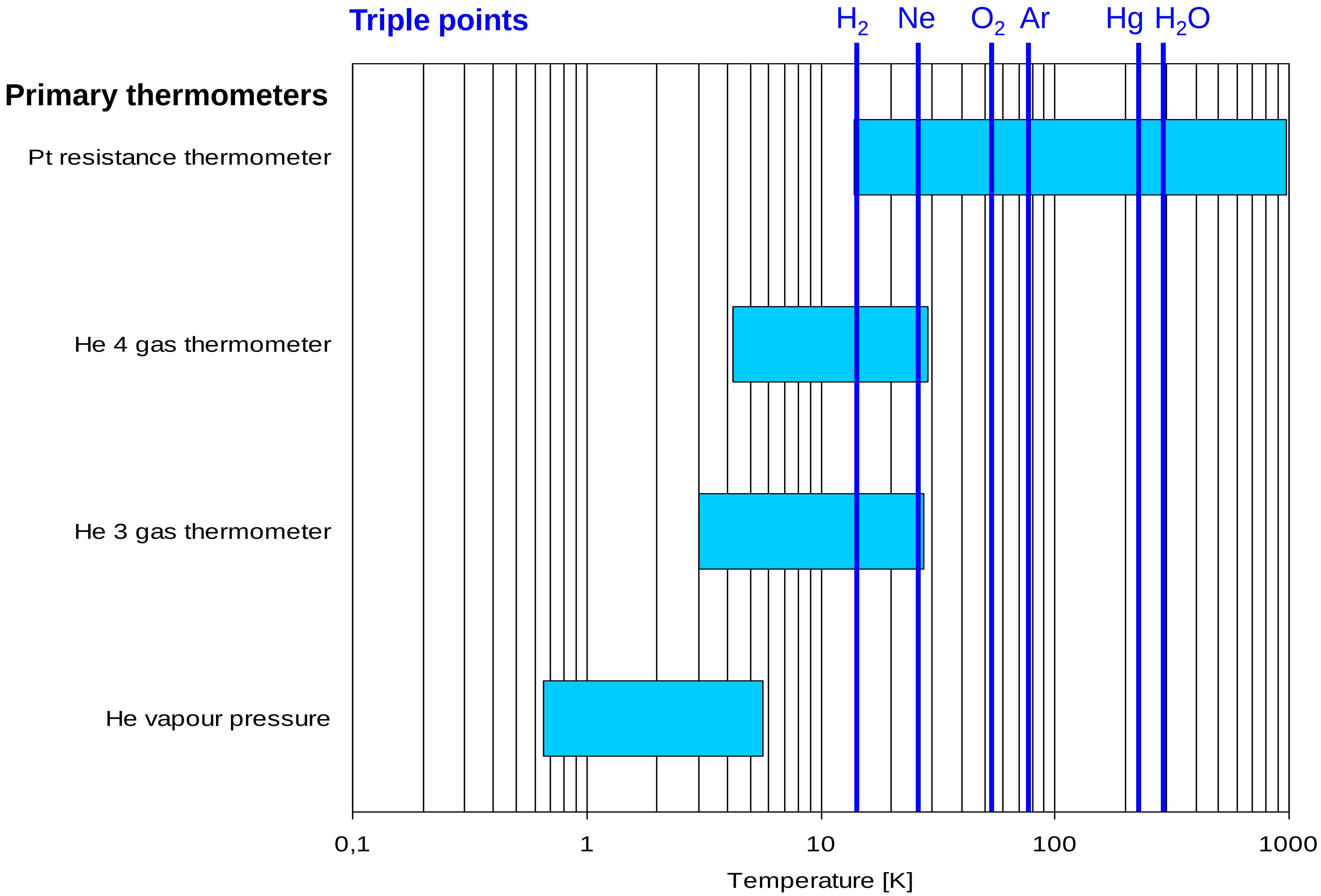
Definition of ITS90 in cryogenic range

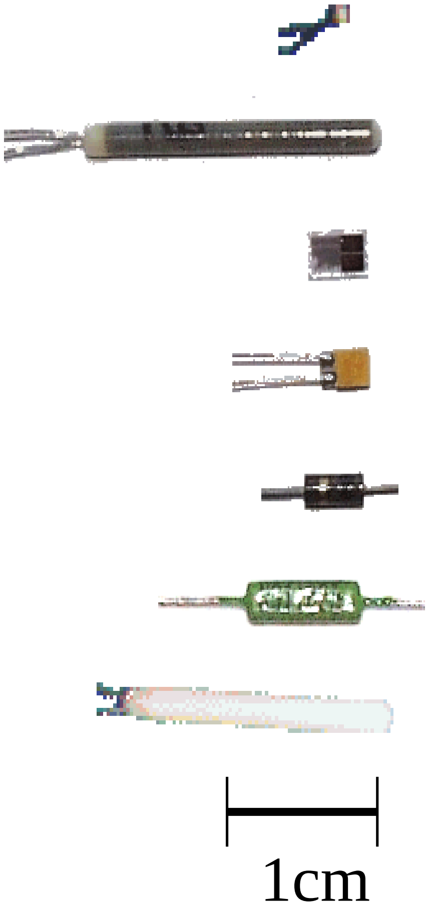


Primary fixed points of ITS90 in cryogenic range

Fixed point	Temperature [K]
H_2 triple point	13.8033
Ne triple point	24.5561
O_2 triple point	54.3584
Ar triple point	83.8058
Hg triple point	234.3156
H_2O triple point	273.16 (*)

(*) *exact by definition*

From temperature sensor to practical thermometer



Ge

RhFe wire

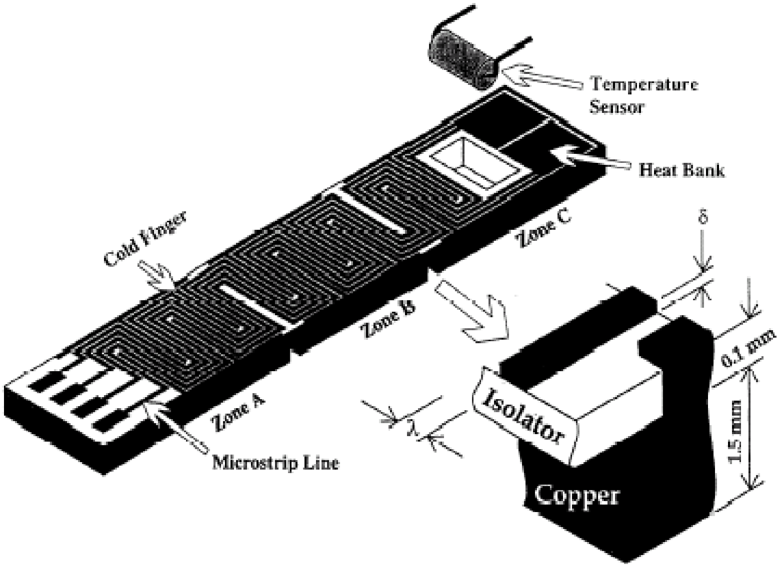
RhFe thin film

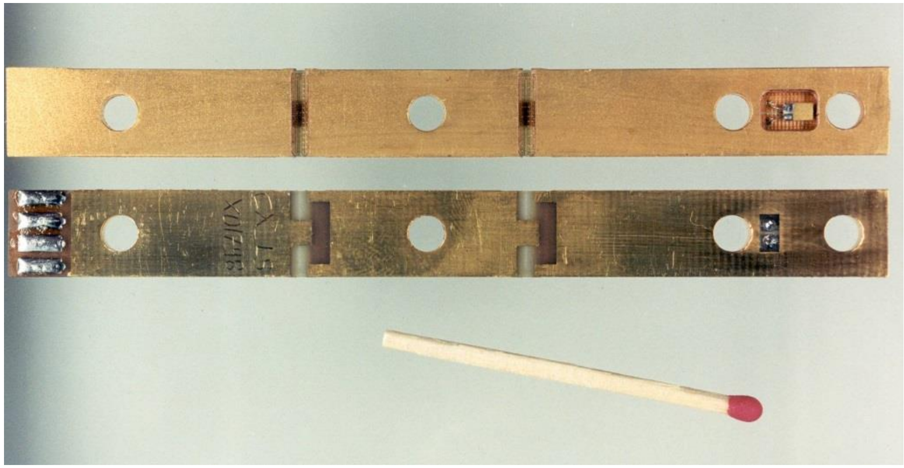
Cernox

Carbon A-B

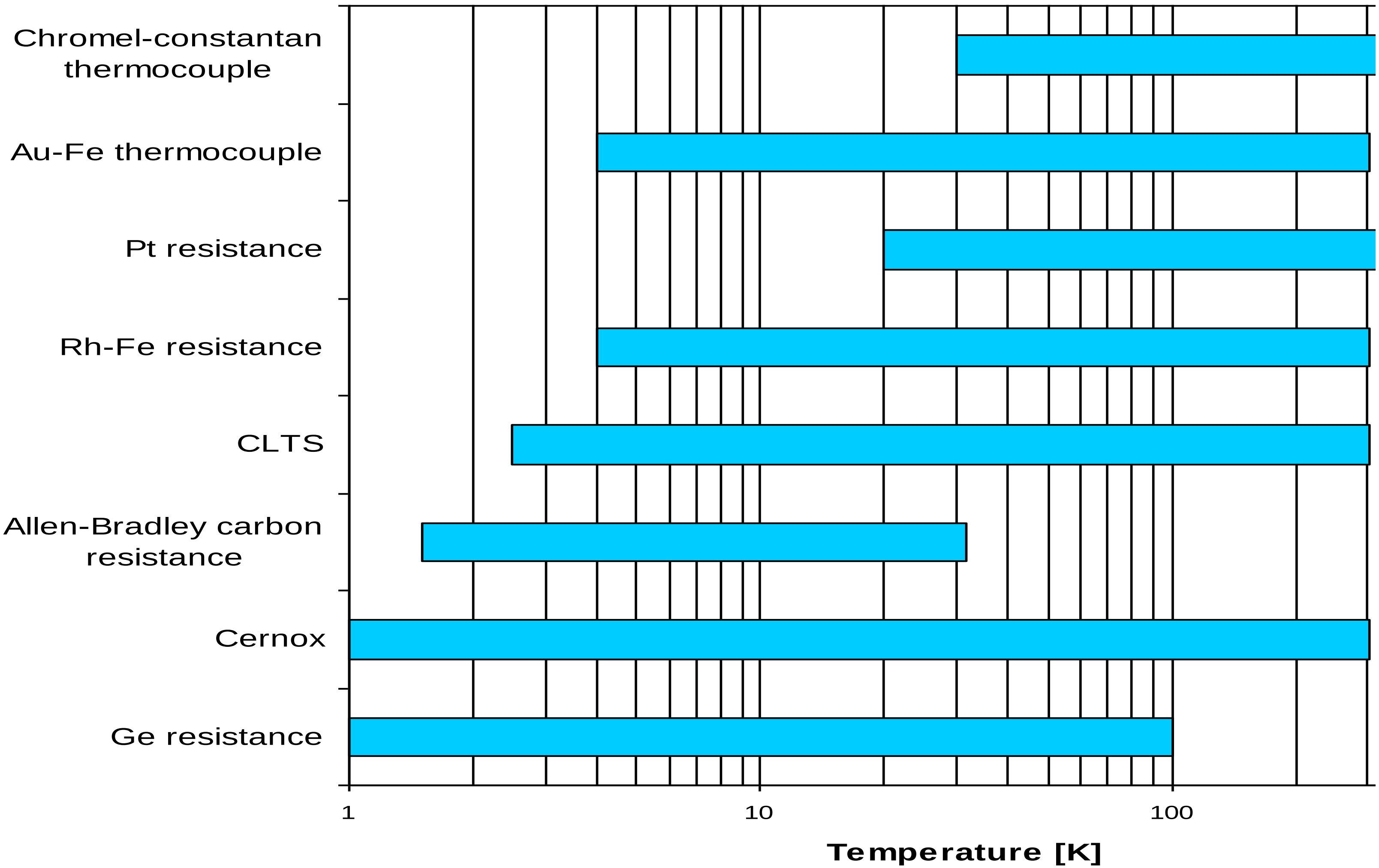
Carbon TVO

CBT





Practical temperature range covered by cryogenic thermometers



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