Cryostat design

^4He and ^3He cryostats

Guillaume Donnier-Valentin

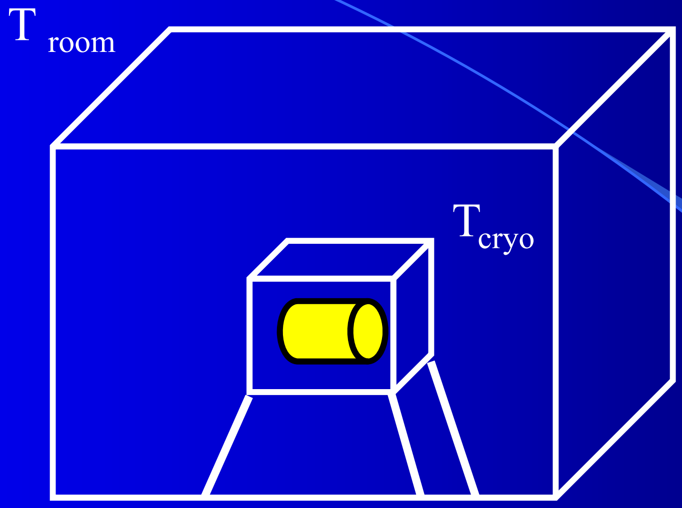
Summary

* **Generalities on cryogenic devices**
  - Description
  - Important parameters

* **The design of cryogenic devices**
  * thermal conception
    - Insulation, calculation, radiation, conduction
    - Cooling down, other phenomena which lead to fluid's evaporation
  * Mechanical design
    - Material resistance at low temperature, material used
    - Differential contraction
    - Mechanical resistance of the cryostats

* **Technology of cryogenic constructions**
  - Welding, brazing, leak tightness test, seals
* **^{4}He cryostats**
  - Glass cryostats, Metallic cryostats, Plastic cryostats
  - Obtaining variable temperature at T > 4.2 K and T< 4.2 K
  - Superfluid under atmospheric pressure
* **^{3}He cryostats**
  - Description of a complete device

Cryogenic Device



Design a system working at very low temperature

➔ Evaluate the importance of the heat flows

➔ Get a good heat insulation compared to the outside

➔Get a good cooling efficiency

The design of cryogenic devices

- Energy balance
  - Available cooling power
    - cryocooler machine or consumption in cryogenic fluid
  - Heat losses
    - from outside (radiation, conduction, convection)
    - Device self losses
- Evolution of the physical properties
  - Mechanics (Tensile strength, fatigue strength, yield strength, thermal expansion....)
  - Specific heat, latent heat of the cryogenic fluids
  - Thermal conductivity
  - Magnetic, electrical properties
- Size, mass (space, cryostat)
- Safety systems (safety valves, safety discs)
  - For Helium, 100 liters of vapor at 4.2 K = 10 m^3 of gas TPN → risk of bursting cryostat in the event of fast reheating

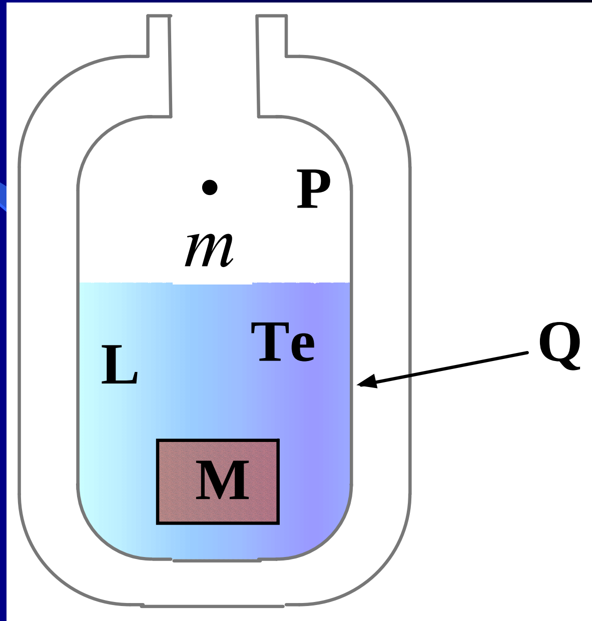
Cryostat design

Thermal design

Fluid evaporation, latent heat

- We have $Q = \dot{m}L$

Q in Watt
$\dot{m}$ in g / sec
L in J / g

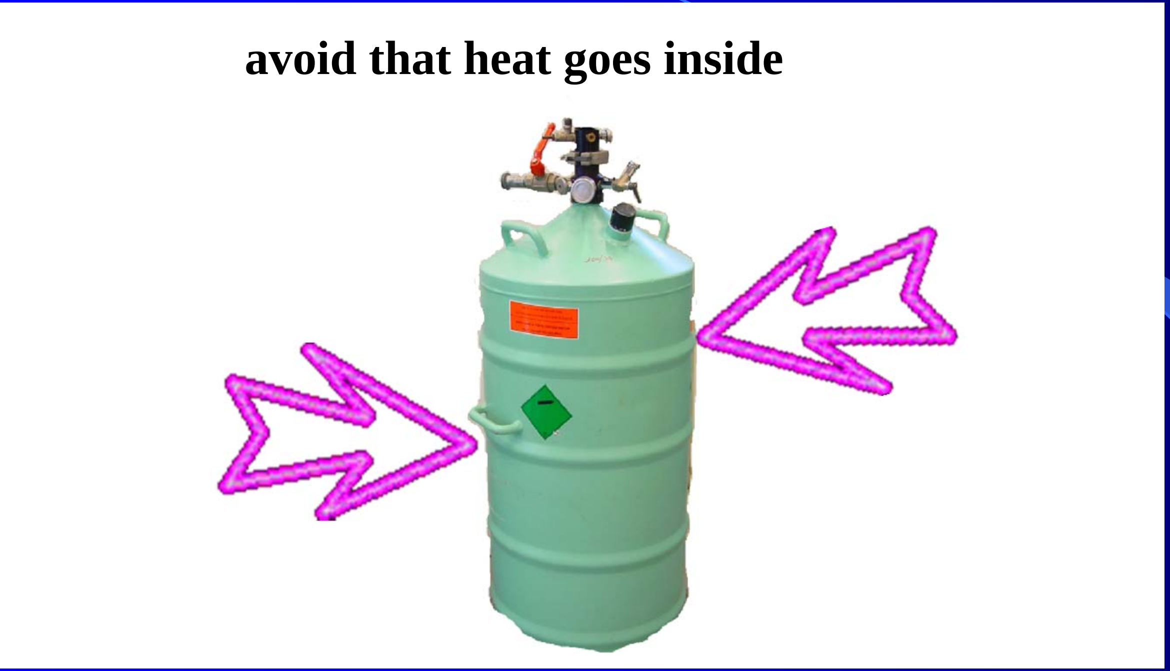


- Some values at boiling temperature

Cryogenic liquid	L (under 1 bar) J/g	L' J/liter liquid	$\dot{m}$ liter liq./h/W
N_2	199	159200	$22.6.10^{-3}$
H_2	445	31150	0.115
^4He	20.5	2562	1.4
^3He	8.2	490	7.3

For the same heating power, helium boil 70 time more than nitrogen

Insulation



- Minimize different ways of heat transport
  - Radiation, conduction, convection

Vacuum $<10^{-4}$ mbar :

Total losses between 2 stainless steel plane plates 300 and 77 K ;

25 to 50 W/m^2

Thermal insulation

- **Foams**
  - Thermal conductivity from 20 to 30 mW/(m.K)
  - (Total losses between 2 plane plates 300 and 77 K; 700 W/m^2 , e = 1cm)
- **Powders** (perlite SiO_2 Al_2O_3 (sous 1 Pa), alumina)
  - Mean thermal conductivity between 300 and 77 K : 2 mW/(m.K)
  - (Total losses between 2 plane plates 300 and 77 K; 50 W/m^2 , e = 1cm)

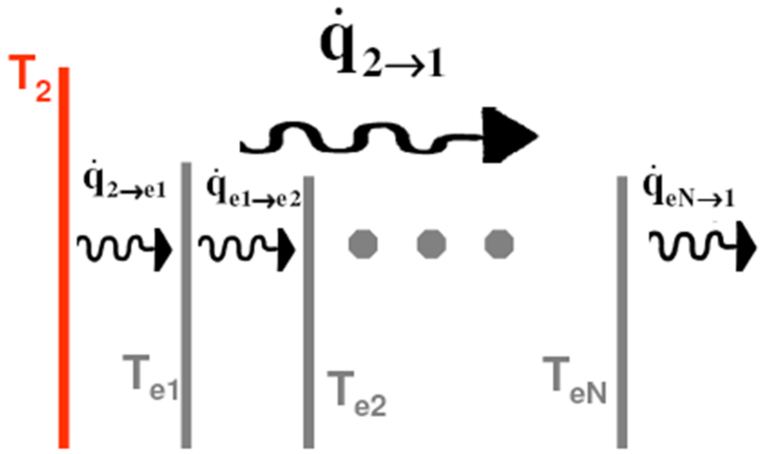
Insulation
T > 80 K

- **Multilayer insulation**
  - Reduction of radiation losses
    (if we placed n thermal shield at fixed intermediate Temperature we divided radiation power by n+1)
  - Vacuum < 10^{-2} Pa (elimination of gas conduction)
  - Solid conduction canceled if we eliminate contact between each layers
  - Mean thermal conductivity between 300 and 77 K : 0.06 to 0.2 mW/(m.K)
  - Total losses between 2 plane plates 300 and 77 K; 0.67 W/m^2 , e = 1 cm
  - Optimum between 20 and 25 layers per cm

Helium
Insulation

- **Solid Thermal shield : copper aluminum**
- **Used of materials with low thermal conduction between T_{room} and T_{cryo}** (optimization between mechanical resistance and thermal conduction)

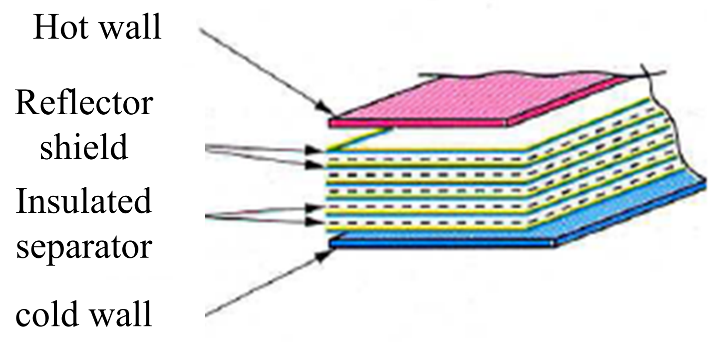
Multilayer insulation

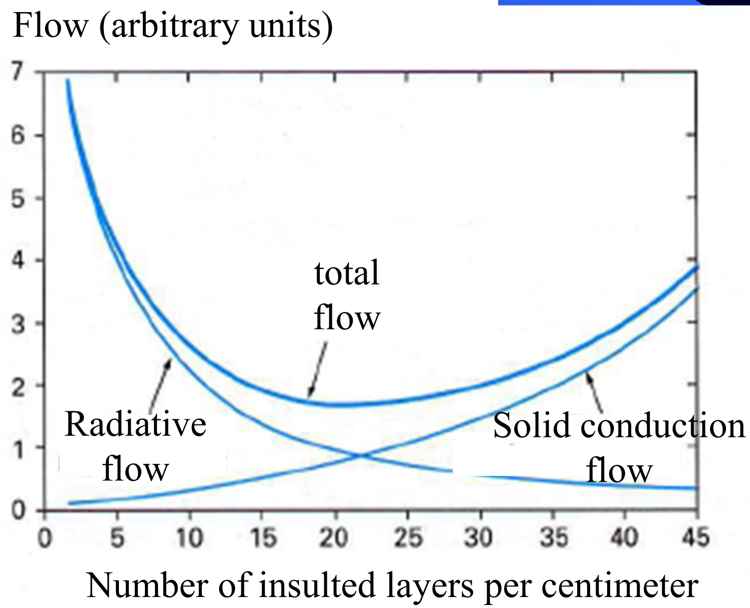


N Identical floating shields

$$\dot{q}_{2\to e1} = \dot{q}_{e1\to e2} = \dots = \dot{q}_{eN\to1}$$

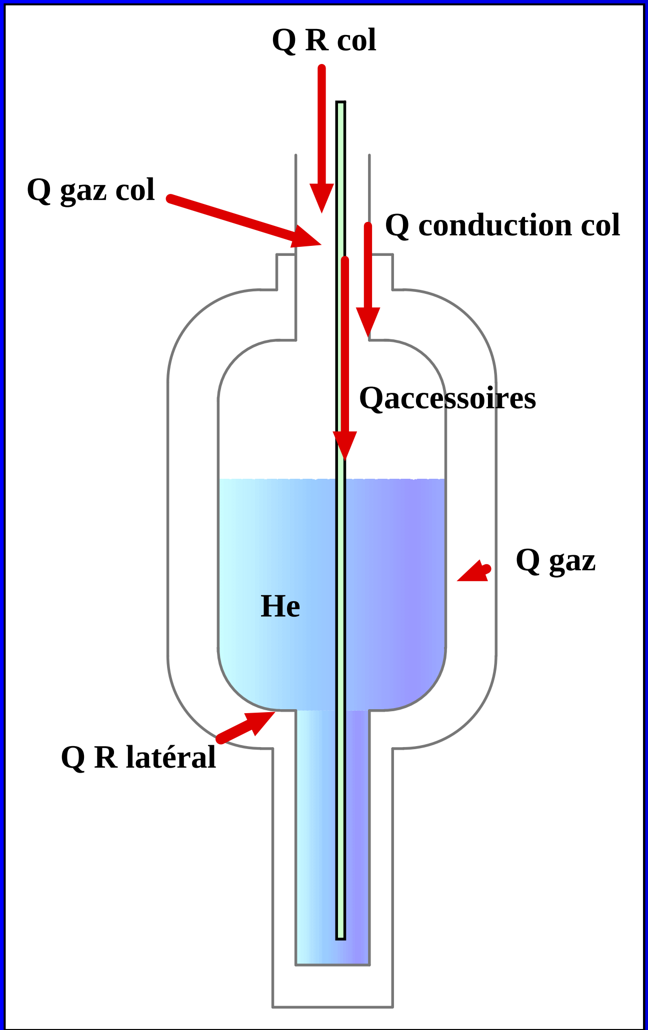
$$\dot{q}_{eN\to1} = \frac{\dot{q}_{2\to1}}{N+1} \quad \text{(Without shield)}$$





Thermal calculation of cryostat

Thermal balance



- We saw that : $\dot{m} = \dfrac{Q_{total}}{L}$
  - With $Q_{total} =$ $Q_{R\ col} + Q_{cond} + Q_{gas} + Q_{R\ lat} + Q_{acc} + Q_{gaz\ col}$
    - $Q_{gaz} \sim 0$
    - Q_{acc} *fixed by experiment.*
    - $Q_{gaz\ col} << Q_{cond}$
- In fact : $Q = L.\dot{m}.\left(\dfrac{\rho_L}{\rho_L - \rho_V}\right) = \dfrac{125}{125-17}.L.\dot{m} = 1.15\,.\,L.\dot{m}$
  - A part of evaporation compensates the decrease of liquid (very dense vapor)

Radiation

Stefan- Boltzmann equation (black body)

The black body completely absorbs the received radiation

$$\dot{q}_{\text{émis}} = \sigma . T^4$$

(W.m^{-2}) (K)

σ = 5,67.10^{-8} W.m^{-2}.K^{-4}

(constante de Stefan - Boltzmann)

T (K)	$\dot{q}_{\text{émis}}$ (W.m^{-2})
4	1,5.10^{-5}
20	9,1.10^{-3}
80	2,3
300	460

$$\frac{\dot{q}_{\text{émis}}(300\text{ K})}{\dot{q}_{\text{émis}}(80\text{ K})} = 200$$

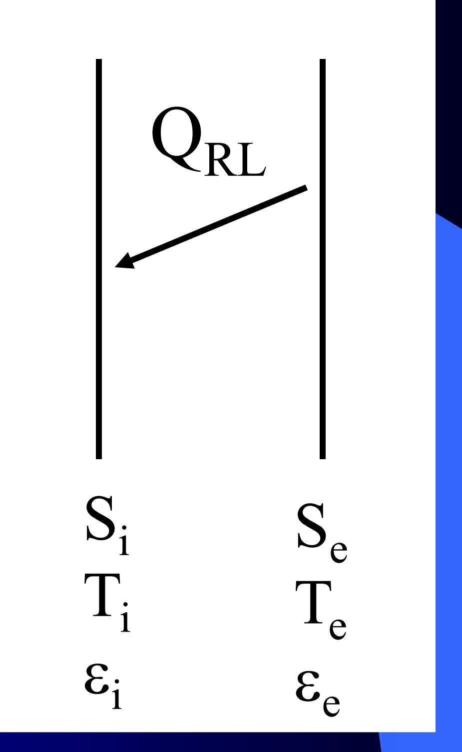
Thermal shields are essentials

Radiation $Q_{R\ side}$

- Heat transfer between 2 neighbouring surfaces

$$Q_{RL} = \frac{S_i}{\frac{1}{\varepsilon_i} + \left(\frac{1}{\varepsilon_e} - 1\right)\frac{S_i}{S_e}} \sigma\left(T_e^{\ 4} - T_i^{\ 4}\right)$$

$$avec\ \sigma = 5.7.10^{-12}\ W / cm^2 / K^4$$



- In general T_i^4 is negligible compared to T_e^4
- S_i/S_e is in the interval between 0.5 and 0.9
- importance of emissivity

Normal total emissivity of a surface at temperature T

$$\text{Emissivity } \varepsilon = \frac{\text{power radiated by a real surface}}{\text{power radiated by a black body at the same temperature}}$$

Material	T (°K)	ε_n
Silver	300 76 4	0.022 0.008 0.0044
Stainless steel 18-8	300 76 4	0.15 0.061 0.034
Aluminum annealing Polish electrolytic	300 76 4	0.03 0.018 0.011
Aluminum commercial rolled Brush Oxydised	 76 76 76	 0.02 0.06 0.21
Chromium	300	0.08
Copper polish electrolytic	300 76 4	0.018 0.015 0.006
Cuivre mecanical polish	300 76 4	0.03 0.019 0.015
tin	300 76 4	0.05 0.013 0.012
Polish brass	300 76 4	0.03 0.029 0.018
Nickel	300 76	0.045 0.022
Gold	300 76	0.02 0.01

$\varepsilon\downarrow$ when $T\downarrow$

$\varepsilon\uparrow$ with the pollution of surfaces (oxidation, impurities, traces of grease)

Some values of Q_{RL}

- Power radiated per cm^2
- Deduced from the preceding table

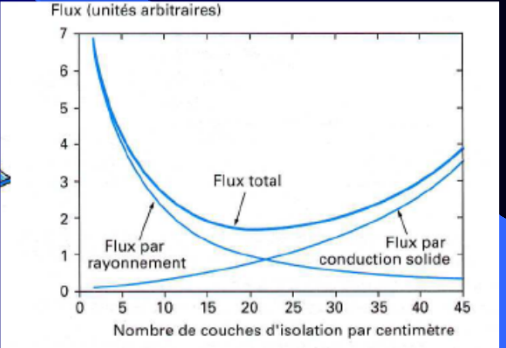
- Black body (glass)
  - *300 on 4 K* → $\varepsilon = 1$ → $Q_{RL} = 42\ mW/cm^2$
- Copper, aluminum
  - *300 on 77 K* → $Q_{RL} = 0.7$ to $1\ mW/cm^2$
  - *77 on 4.2 K* → $Q_{RL} = 1.7$ to $3\ \mu W/cm^2$
- Stainless steel
  - *300 on 77 K* → $Q_{RL} = 3$ to $5\ mW/cm^2$
  - *77 on 4.2 K* → $Q_{RL} = 6\ \mu W/cm^2$

Some values of Q_{RL} measured at MCBT

- Values between 300 and 77 K
- 2 stainless steel walls
  - *Vacuum without activated charcoal* *5 mW/cm^2*
  - *Vacuum with activated charcoal* *3 mW/cm^2*
- External stainless steel wall, interior stainless steel wall covered with Aluminum adhesive
  - *Results Q_{RL}* *0.8 mW/cm^2*
- 2 stainless steel walls + 1 cm of M.L.I.
  - *Results Q_{RL}* *0.07 mW/cm^2*

Radiation : Q_{RL} summary

- The losses are related to:
  - *Interior surface*
  - *emissivity of metal = ε*
  - *Temperature T^4* *(300^4)*
  - *MLI thickness*
  - *MLI compression ratio*



Effet de la densité de couches sur le flux entre deux parois

- Interest of activated charcoal :
  - *cryogenic pumping of residual air by activated charcoal*
    - Air is not solidified on the walls

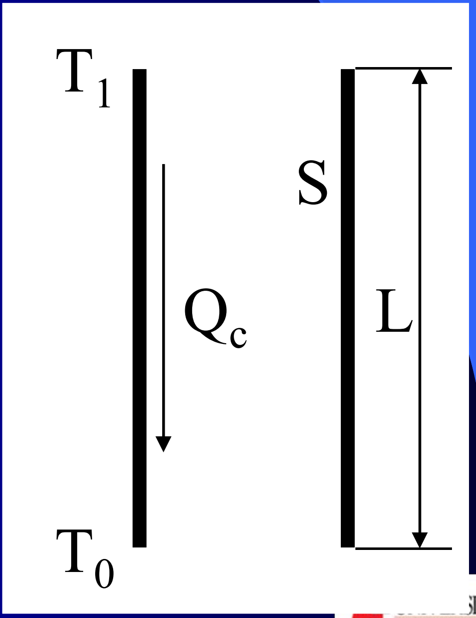
Conduction of neck tube (Q_{cond}) without vapors

- We have in this case :

$$Q_{cond} = \frac{S}{L}\int_{T_0}^{T_1} k(T)dT = \frac{S}{L}K$$

$$K = \int_{T_0}^{T_1} k(T)dT \text{ is given by tables}$$

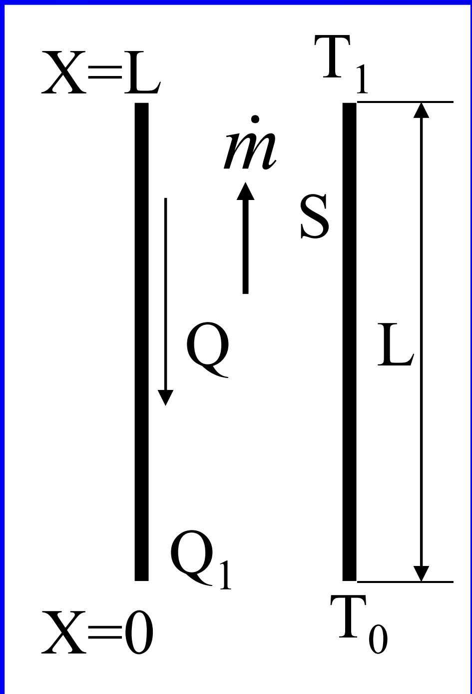
- For stainless steel
  - Between 300 and 80 K
    - ➔ K = 30.6 – 3.49 = 27.11 W/cm
  - Between 80 and 4.2 K
    - ➔ K = 3.49 W/cm
  - Interest to cool the neck with nitrogen



values of the integral k(T) from 4.2K

T (K)	6	8	10	15	20	60	80	300
	W/cm							
Copper extra pure	166	382	636	1270	1790	2960	3090	4000
Copper cold worked	8.0	19.1	33.2	80.2	140	587	707	1620
Silver	320	670	990	1610	1980	2570	2670	3570
Alu. extra pure	73	168	280	600	907	1740	1840	2390
Alu. Commercial	1.38	3.42	6.07	15.2	27.6	170	232	728
Gold	41.0	93.0	149	274	364	612	682	1370
Brass	0.053	0.129	0.229	0.594	1.12	10.4	17.7	172
Lead normal	27.0	37.3	42.4	49.0	52.5	73.8	81.3	160
Titanium	0.115	0.277	0.488	1.21	2.20	15.5	22.6	99.6
Monel	0.0235	0.0605	0.112	0.315	0.618	5.23	8.24	52.5
Stainless steel.	0.0063	0.0159	0.0293	0.0816	0.163	1.98	3.49	30.6
Inconel							3.50	53.7
	mW/cm							
Glass	2.11	4.43	6.81	13.1	20.0	115	194	1990
Teflon	1.13	2.62	4.40	9.85	16.4	93.6	139	702
Plexiglas	1.18	2.38	3.59	6.69	10.1	68.3	110	630
Nylon	0.321	0.807	1.48	4.10	8.23	85.9	142	895
Fiber glass epoxy	1.3	2.8	4.5	10	17	95	160	1250

Conduction of neck tube (Q_{cond}) with vapors



- At a distance x : $Q = S \cdot k(T)\dfrac{dT}{dx}$
- Also : $dQ_{gaz} = \dot{m} \cdot C_P \cdot dT$
- If perfect exchange : $Q - Q_1 = \dot{m}C_P(T - T_0)$
- if k(T) is : $k(T) = k_0 + a(T - T_0)$
- Then we obtain :

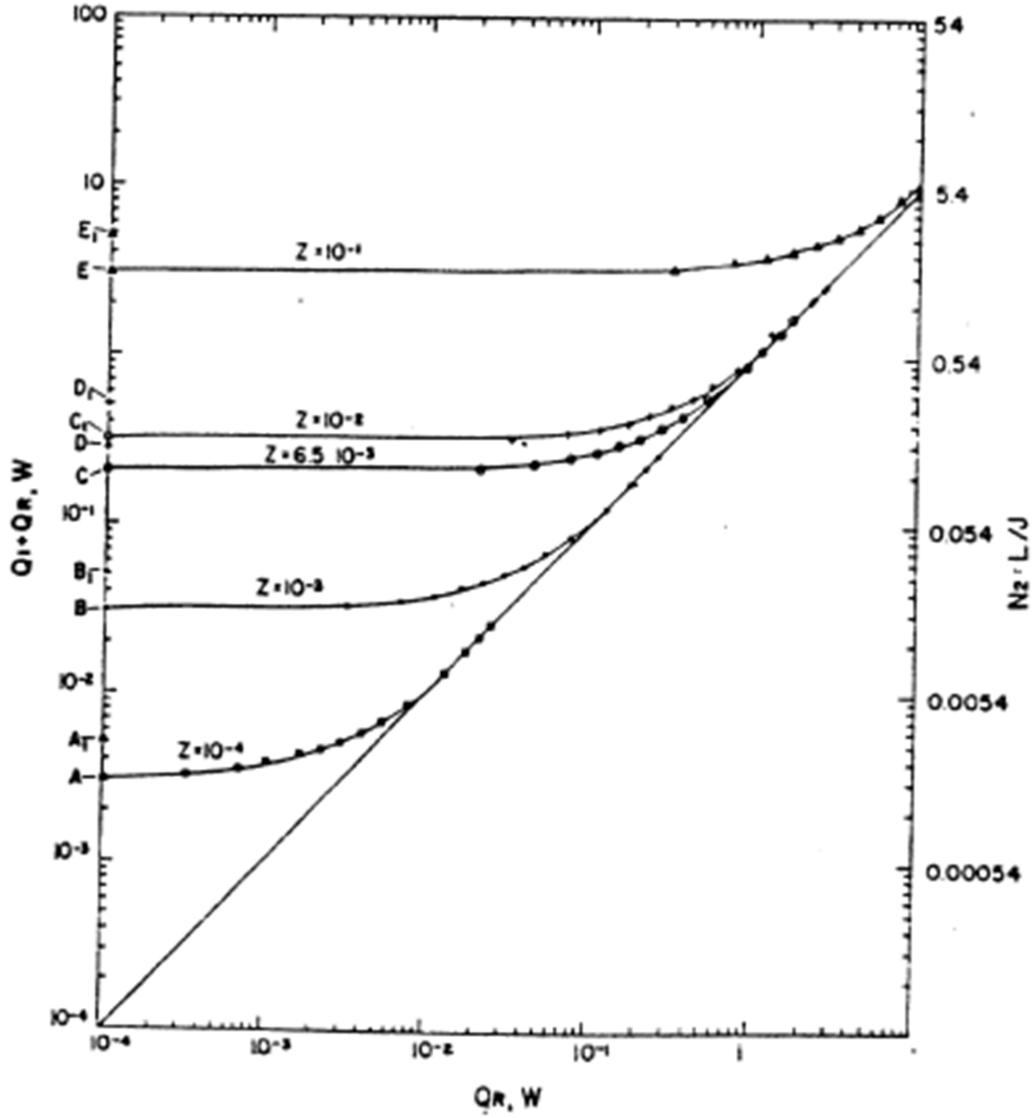
$$S[k_0 + a(T - T_0)]\frac{dT}{dx} = Q_1 + \dot{m}C_P(T - T_0)$$

$$\frac{L}{S} = \frac{1}{\dot{m}C_P}\left[a\Delta T + \left(k_0 - \frac{Q_1 a}{\dot{m}C_P}\right) \cdot \ln\left(\frac{Q_1 + \dot{m}C_P\Delta T}{Q_1}\right)\right]$$

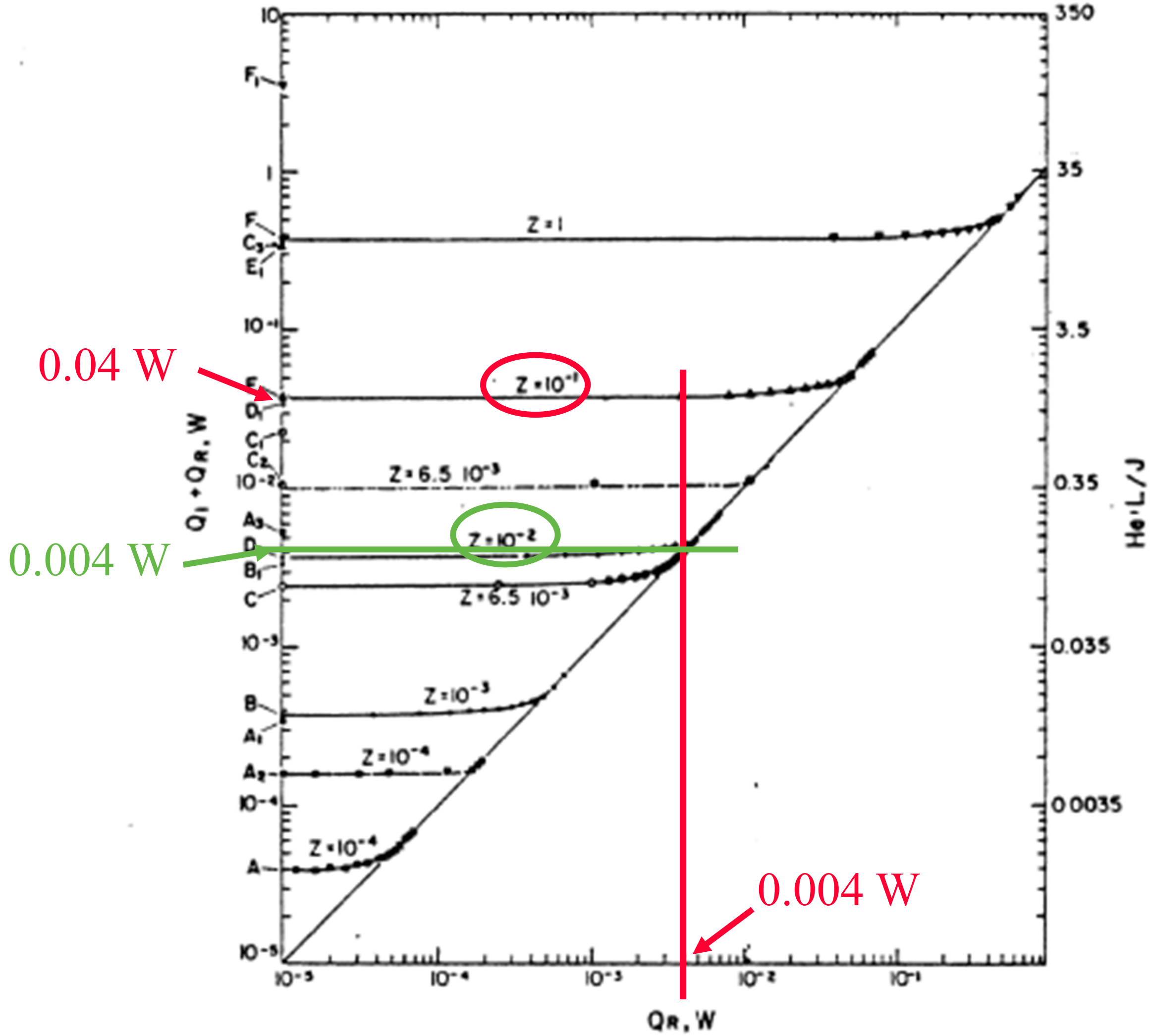
$$with\ \Delta T = T_1 - T_0$$

Conduction of neck tube Q_{cond} with vapors

- Formula not easy to use
- No analytical solution for Q_1
  - We must find solution with computer
- Scott and Conte plot sets of curves giving Q_1 according to L/S and evaporation
  - Conte pages 52-53
  - Take into account of all other thermal contributions



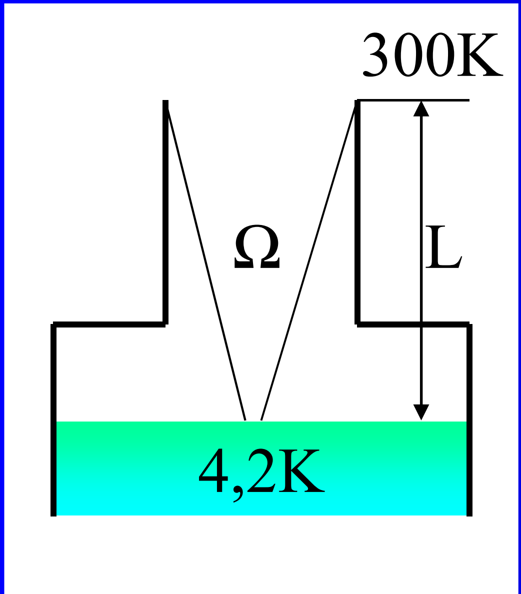
Losses for Nitrogen containers, variation of Qr+Q1 as a function of Qr for a stainless steel neck for different values of Z=S/L (cm)
(Perfect exchange between the neck and cold vapors)



Losses for helium containers, variation of Qr+Q1 as a function of Qr for a stainless steel neck for different values of Z=S/L (cm)
(Perfect exchanges between the neck and cold vapors)

Continuous line : temperature difference between 78 and 4.2 °K
Dotted line : temperature difference between 300 and 4.2 °K

Radiation of neck : Q_{Rcol}



- We have : $Q_{Rneck} = S\varepsilon_e \sigma T^4 \cdot \Omega$

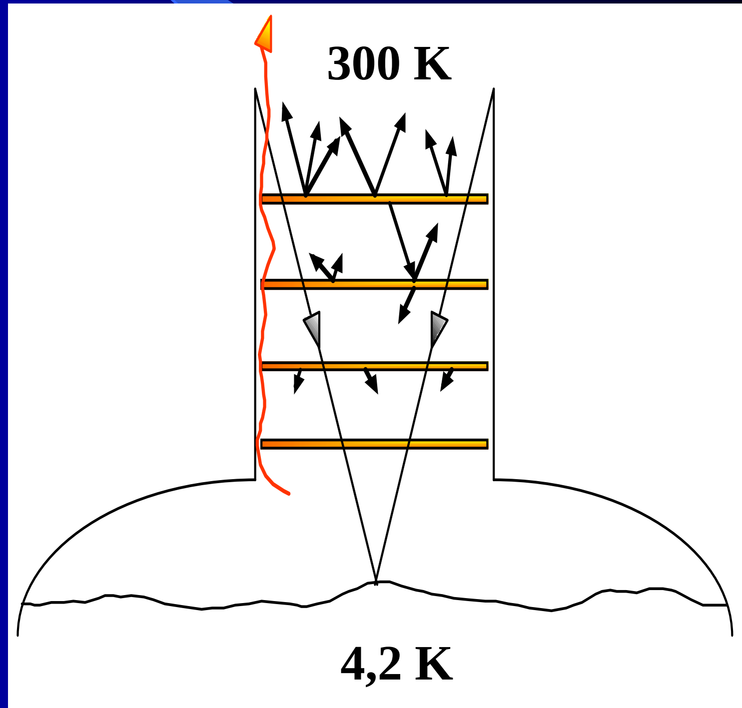
$$with\ T^4 = 300^4$$

$$\Omega = solid\ angle = \frac{R^2}{R^2 + L^2}$$

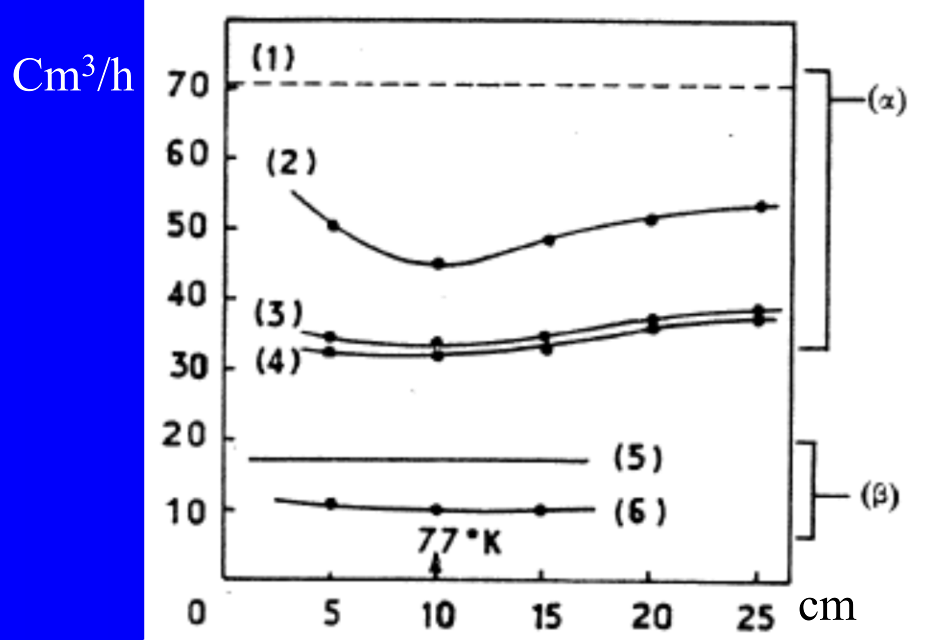
- Example
  - Ø = 150 mm then, S = 180 cm^2
  - L = 300 mm
  - εΩ ~ 0.05 (typical value)
- Qr_{neck} = 0.38 watt
- high values

Radiation of neck : Q_{Rcol}

- The cover plate radiates directly on the bath
  - Important losses!
- Solutions
  - *Thermal shields distributed along the neck*
  - *Low emissivity ($\varepsilon < 0.1$)*
  - *The heat recovered by the shields is evacuated by the vapors*



Radiation of neck : Q_{Rcol}



Copper thermal shields separated by 4 cm

Relation between the flow of evaporated helium, the number and the position of the copper screens in a Dewar with nitrogen guard

Curve (1) : no thermal shield

Curve (2) : 1 thermal shields

Curve (3) : 2 thermal shields

Curve (4) : 4 thermal shields

Curve (5) : no thermal shield

Curve (6) : 2 thermal shields

α) Neck diameter = 7.5 cm; Z=S/L= 1/27 cm

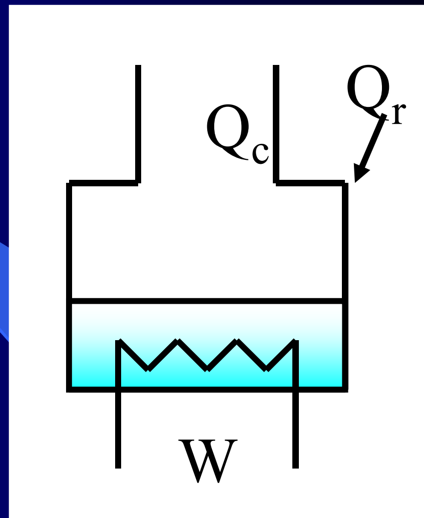
β) Neck diameter = 3.8 cm; Z=S/L= 1/70 cm

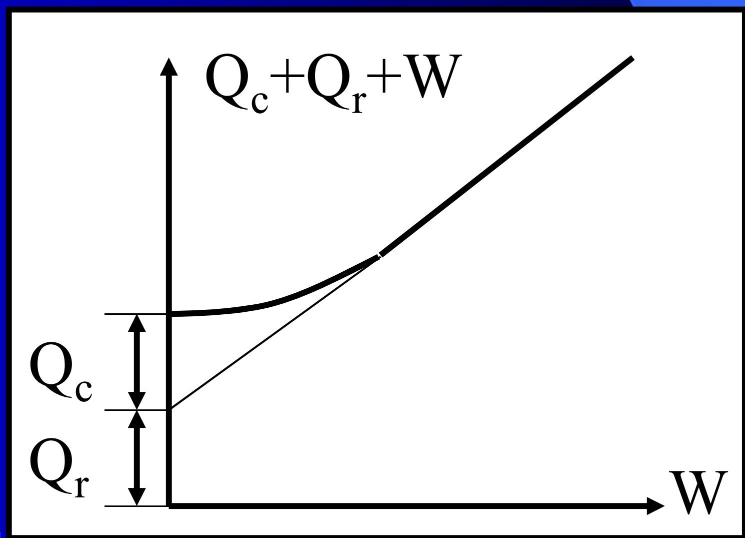
In Y-axis the evaporation in cm^3/h at constant helium level

In X-axis the shield position compared to the top of the tank

Determination of Q_R and Q_{cond}

- We heat the bath
  - we release a heat W
- The curve is plotted
  - Total evaporation according to W
  - We interpolate towards 0
- We obtain Q_R and Q_c





Cooling down

- Remove the heat "stored" in material
  - ➔ Enthalpy of the material H
  - Between 2 temperatures, we have : $\Delta H = \int_{T_1}^{T_2} C_P dT = H_2 - H_1$
    - H expressed in J/g
    - Enthalpy H(T) of some materials (J/g)

T(°K)	1	4	15	20	60	80	300
Aluminum	$2.5.10^{-5}$	$4.63.10^{-4}$	$1.8.10^{-2}$	$4.8.10^{-2}$	3.64	9.37	170.4
Chromium	$1.42.10^{-5}$	$2.37.10^{-4}$	$0.53.10^{-2}$	$1.28.10^{-2}$	0.904	2.77	78.9
Copper	$0.6.10^{-5}$	$1.3.10^{-4}$	$1.07.10^{-2}$	$3.4.10^{-2}$	2.58	6.02	79.6
Iron	$4.5.10^{-5}$	$7.42.10^{-4}$	$1.45.10^{-2}$	$3.16.10^{-2}$	1.43	3.84	81.1
Nickel	6.10^{-5}	$9.8.10^{-4}$	$1.85.10^{-2}$	$4.1.10^{-2}$	1.79	4.56	82.1
Niobium	4.10^{-5}	$7.3.10^{-4}$	$2.6.10^{-2}$	$6.6.10^{-2}$	2.76	5.8	59.2
Titanium	$3.5.10^{-5}$	$5.99.10^{-4}$	$1.56.10^{-2}$	$4.0.10^{-2}$	2.59	6.37	101.4
Zinc	5.10^{-5}	$1.4.10^{-4}$	$3.4.10^{-2}$	$12.5.10^{-2}$	5.01	9.70	87.1
Teflon		10.10^{-4}	21.10^{-2}	52.10^{-2}	7.02	12.52	144.6

Cooling down

- Starting from these data.
  - Calculation of the quantity of fluid which will be evaporated to cool a given mass
  - Exemple for 1 kg of Copper
    - Cooled by helium from 300 to 4 K
    - $\Delta H = (79.6-13.10^{-5})*1000 = 79600$ Joules
    - Helium evaporated = 79600/2562 = **30.3 Liters!**

$$\frac{\Delta H * m}{L} = V$$

ΔH in j/g
m in g
L in J/l
V in l

Starting temperature	^4He	H_2	N_2
300 K	30.3 liters	2.5 liters	0.49 liters
77 K	2.1 liters	0.17 liters	

- *Interest of pre-cooling with liquid nitrogen! !*

Vapor cold energy recovery

- The vapor generated by the evaporation of the liquid can also extract some heat

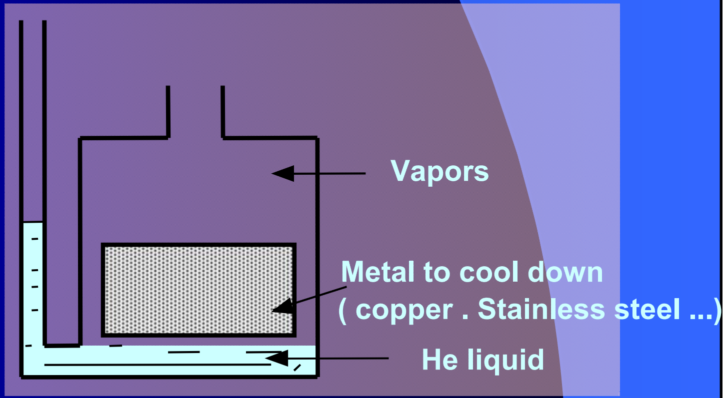
- Example for helium
  - *L_{vap} = 2562 Joules/litre*
  - *Specific heat between T_{Eb} et 300K = m.Cp.Δt = 193 750 joules/litre*
  - *Specific heat / **L_{vap} = 74 !***
  - *Very cooling vapors → recover cold energy is very interesting*
- For nitrogen
  - *L_{vap} = 159200 Joules/litre*
  - *Specific heat between T_{Eb} et 300K = m.Cp.Δt = 188730 joules/litre*
  - *Specific heat / **L_{vap} = 1.18 only !***

Vapor cold energy recovery

- Quantity of liquid evaporated for 1kg of copper with total recovery of cold energy

Starting temperature	^{4}He	H_2	N_2
300 K	0.4 liters	0.28 liters	0.2 liters
77 K	0.1 liters	0.07 liters	

- Consequence:
  - *Interest to transfer at the lower part for cooling large masses*



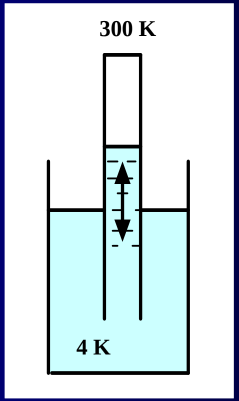
Other phenomena which lead to fluid's evaporation

For ⁴He only

Taconis effect

Evaporation ~ 1/10 l/h to 10 l/h!!

Ocur when a closed tube is immersed into liquid He bath

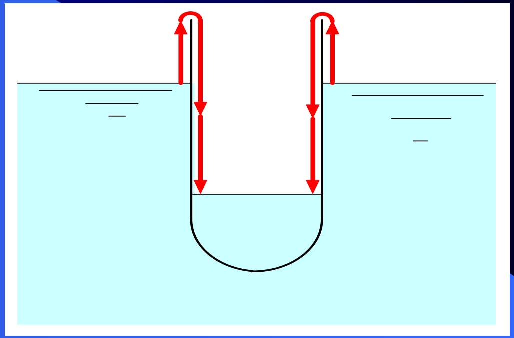


Superfluid film

The film goes up along the neck tube of the cryostats and along the pumping line

$$0.19\ liters\ /\ hour\ /\ cm$$

$$smallest\ \ perimeter\ encountered\ at\ TPN$$



Mechanical design

- Strength of materials at low temperature
- Material used
- Differential contraction
- Mechanical calculation

Mechanical strength of materials at low temperature

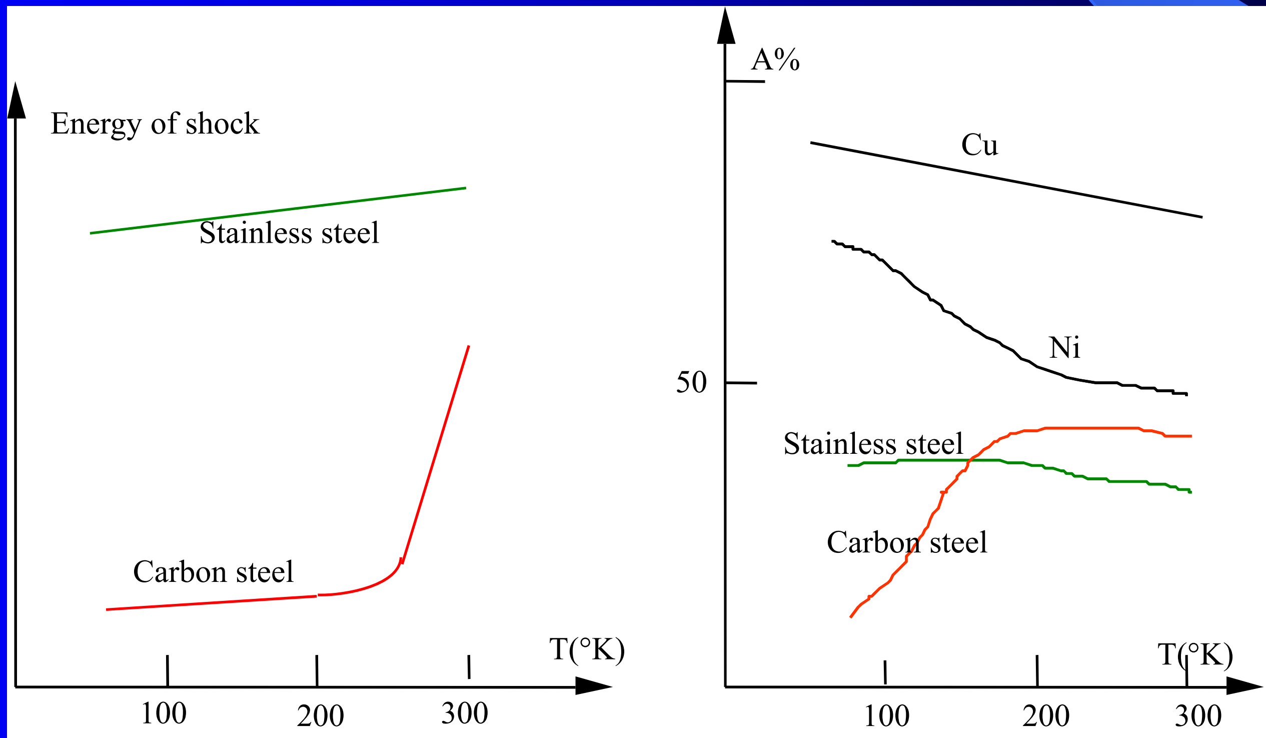
- In a general way :
  - When we decrease the temperature
    - Improvement of the material's resistance
      - *Tensile strength increases*
      - *Yield strength increases*
      - *Fatigue limit at 10^6 cycles increases*
      - *Young's Modulus remains stable*

Example	300 K	300 K	77 K	77 K	20 K	20 K
	R (kg/mm2)	E (kg/mm2)	R (kg/mm2)	E (kg/mm2)	R (kg/mm2)	E (kg/mm2)
Stainless steel 304L or 316L	60	20	130	24	150	24
Copper	20	10	40	15		

- However:
  - For certain materials, phenomenon of embrittlement
      - *Elongation at break decreases (A%)*
      - *impact strength decreases (energy of shock)*

Mechanical resistance of materials at low temperature

- Embrittlement of certain materials at L.T.
  - Example : The carbon steel
    - The energy of shock and elongation strongly decrease



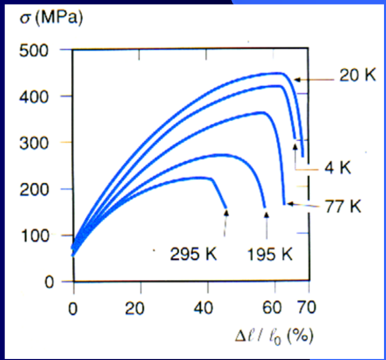
Mechanical strength of materials at L.T.

- Embrittlement = related to the crystallographic structure
  - Importance to know materials which become brittle!

- Materials forbidden for cryogenic applications
  - *Iron, carbon steels*
  - *Body-centered cubic crystal structures*
  - *Certain stainless steel (ferritic ex: Z8C17 (stainless steel 430) chromium (up to 30%), martensitic ordinary steels, Resists badly to the corrosion, Contain approximately chromium 15% + carbon)*

- Materials used without problem
  - *Copper, Nickel and its alloys, Aluminium and its alloys, lead, Silver, gold, platinum, brasses (<30% Zn), Titanium*
  - *faces centered cubic crystal structures*
  - *austenitic stainless steel containing + 7% of Nickel*

    (12 to 30% chromium and 7 to 25% of Nickel)
    - Z_3CN 18.10 (304L)
    - Z_2CN 17.13 (316L)



Tensile test

Materials used

- Stainless steel 18.10
  - Z3CN 18.10 or 304L
  - Austenitic
  - Sometimes 316L (more expensive)

  - Low thermal conductivity
  - A little magnetic (especially 304L)

  - Sometimes porosities or cracks in the component
    - *Round bar; thick plate; convex bottom; tubes*
  - Difficult to solder with tin

Materials used

- Copper
  - Good thermal conductor
  - Not easy to do leak tight welding using TIG process
  - Nonmagnetic
  - Several varieties:
    - *CuA1 : profile (round, square, etc...)*
      - contains a little oxygen (bubbles to the welding)
      - Avoid if possible (risk of leak)
    - *Cu.b : tubes, thin or thick plates*
      - Oxygen free variety, better appropriate for welding and stamping than CuA1
      - Contain Phosphorus → thermal and electrical properties lower than CuA1 CuC2
    - *CuC2 : still better, rare, expensive, Oxygen-Free, High Conductivity Copper*
      - Combine the best of Cu.b and CuA1

Materials used

- Brass
  - ATTENTION : round bar in UZ36 Pb2 (lead) forbidden ➔leak + magnetic at low temperature
  - To take thick plate in UZ36
  - Not welding with TIG
  - Brazing without problem

- Light alloys
  - pure Aluminum (A5) : very soft, good thermal conduction (used for thermal shields)
  - Aluminum magnesium Alloys (AG3 or AG5) : soft, poor thermal conductor, welded well
  - Dural (AU4G) and Fortal (7075) : poor thermal conductor, easy to machine
  - Bonding Aluminum/stainless steel difficult

Materials used

- Copper / Nickel Alloys (cupronickel 60/40)
  - Recommended for the capillary tubes (welding tin)
  - poor thermal conduction (insulator)
    - Similar to stainless steel

- Nickel alloys
  - *The Invar (36%Ni + Fe) low thermal expansion coefficient (construction without expansion bellows)*
  - *The Monel (67%Ni + Cu) fine mechanical properties, high corrosion resistance*

Materials used

- General precautions (leak)
  - Observe the global aspect of the materials (cracks)
  - Caution with the minimal thicknesses
    - *Different according to the materials*
      - Stainless steel (0.1 mm), Copper (1 to 2 mm), etc…
  - Leakage possible in parallel to the extrusion direction

Materials used

- Plastic materials
  - Interesting properties of insulation
  - shaping often difficult
  - Varying characteristics
  - high anisotropy in certain cases

Use of plastics at LT

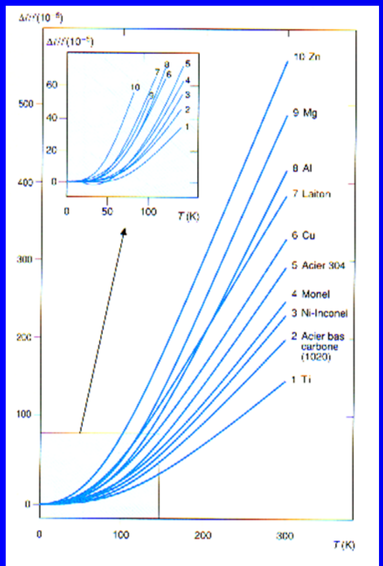
- Porosity with helium (especially at room temperature)
- outgassing (caution for the tests)
- Emissivity of a black body (cover with aluminum...)
- Avoid the sharp angles (incipient crack)

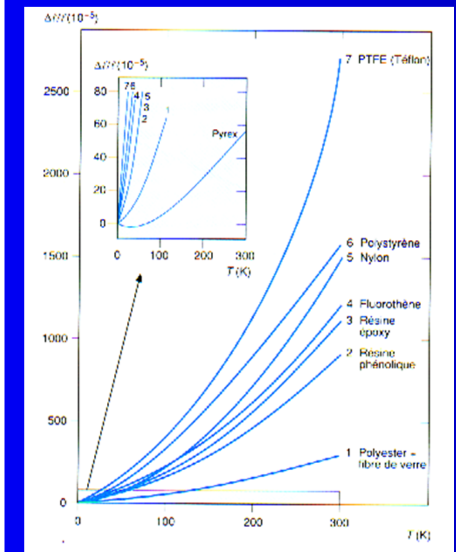
Properties of plastic materials at cryogenic temperatures

- The mechanical strength increases
- But the majority become brittle
- Problem :
  - *Bad thermal conduction*
  - *high coefficient of contraction*
  - ➔ *significant stresses appear when cooling down*
  - ➔ *major risks of break*
- Very resistant = Kapton (polyimide)
  - R = 30 kg/mm^2 at low temperatures
- Fiber glass Epoxy (G11 type)
  - R = 40 to 50 kg/mm^2

Problems of contraction

- Cooling = contraction of the materials
  - Major part of the contraction between 300 and 80 K (95%)
  - Behavior very different depending on the materials
    - *Some values of ΔL/L (mm/m) between 300 and 80 K*

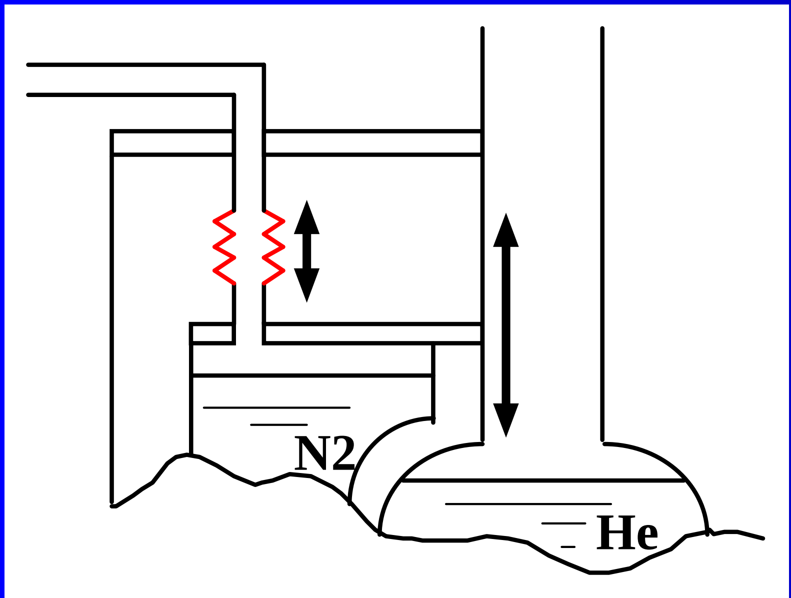




Materials	dL/L (mm/m)
Teflon	20
Nylon	15
Araldite pure	10
Alu, brass	4
Copper	3.4
Stainless steel	3
Glass epoxy (perp. with fibers)	6
Glass epoxy (para. with fibers)	2
Pyrex	0.8

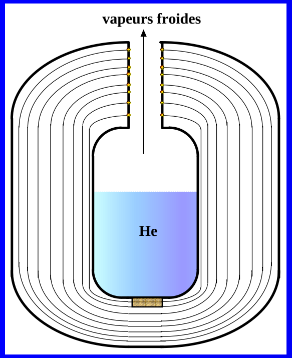
Problems of contraction

- Precautions to be taken
  - For the brazing of 2 different metals
    - The material which contracts more must be around the other
  - Large precautions for the plastics
    - Orientation = anisotropic
  - Choices of the bolts
    - Must contract more than the supports to be tightened
  - Expansion bellows for the tubes in parallel



Mechanical resistance of cryostats

- Cylindrical cryostat, case of internal pressure



- P : internal pressure in bar
- D : diameter in mm
- e : thickness in mm
- R : tensile strength in kg/mm^2
- X : Safety Coeff (taken very often equal to 5)

$$P.D.X = 200.e.R$$

- Example for tensile strength
  - Stainless steel 18/10 : R = 20 kg/mm^2 = 200 MPa
  - Copper : R = 15 kg/mm^2 = 150 MPa

- Example of calculation : ø 200 mm, e = 1.5 mm, Stainless steel 18/10
  - We find :

$$P = \frac{200 \times 1.5 \times 50}{200 \times 5} = 15\,bar$$

Mechanical resistance of cryostats

- Cylindrical cryostat, case of internal pressure
  - Calculation of the bottom of cryostat
    - convex bottom = with the same thickness than the cylindrical shell
    - flat bottom must be thicker
      - *Circular flat bottom welded (welded plates)*
        - P : internal pressure in kg/mm^2
        - r : radius in mm
        - e : thickness in mm
        - R_P : tensile strength in kg/mm^2

$$e = 0.866.r.\left(\frac{P}{R_P}\right)^{\frac{1}{2}}$$

      - *Bolted flat bottom (supported plates)*

$$e = 1.1.r.\left(\frac{P}{R_P}\right)^{\frac{1}{2}}$$

Mechanical resistance of cryostats

- External pressure : to hold the vacuum ($\Delta P = 1$ bar)
  - *Take care !*
    - Phenomenon of avalanche as soon as a deformation appears
    - Buckling : more complicated formulas
  - Long tubes : L > 10 D
    - *Behaviour independent of the length*
    - *Depends on metal, the thickness, the diameter*
    - *For stainless steel : $e = 8.10^{-3}.D$*
    - *For copper, brass : $e = 1.10^{-2}.D$*
  - Short tubes : L < 10 D
    - *Use of formulas or abacs which give the thickness you need*
    - *Abacs are valid ONLY for ΔP < 1 bar*

$$P_c = \frac{2E}{1-\sigma^2}\left(\frac{e}{D}\right)^3$$

E = Elasticity modulus

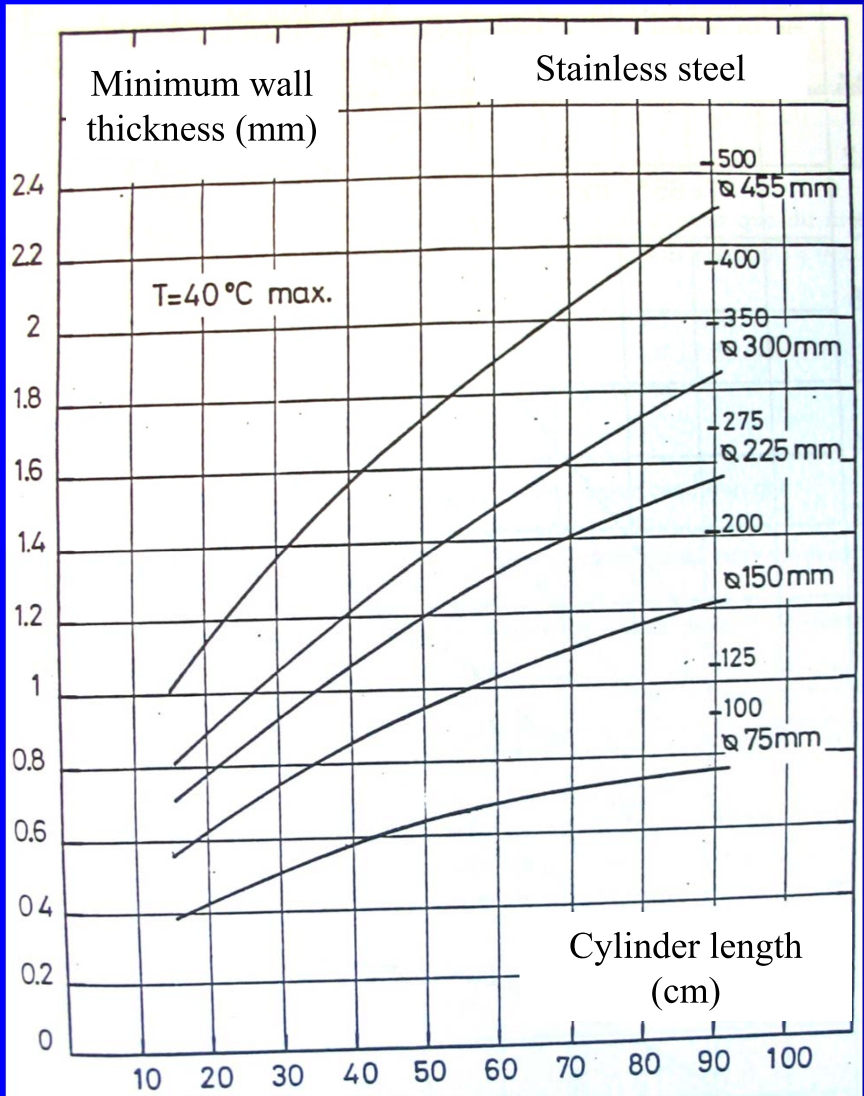
σ = *poisson ratio* = 0.3

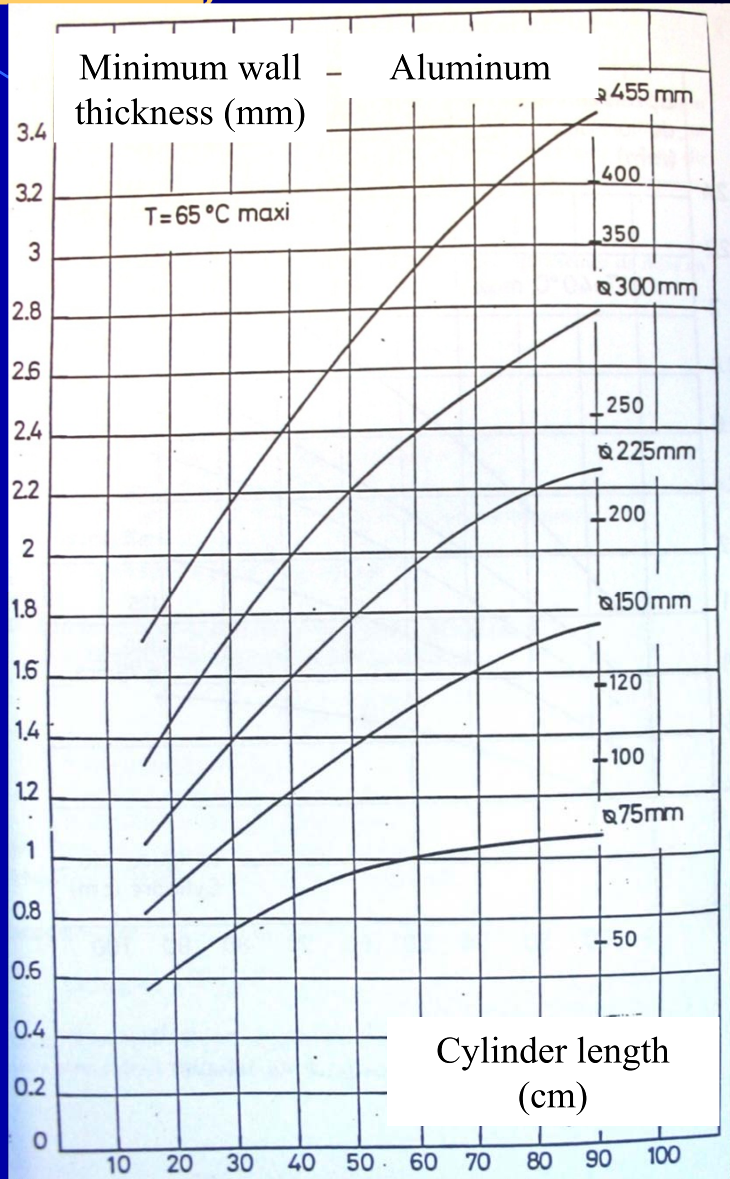
without safety coefficient

Data MCBT

thickness of wall for vacuum capability

(external pressure, $\Delta P \leq 1$ bar)





Mechanical resistance of cryostats

- External Pressure : to hold the vacuum (ΔP = 1 bar)

  - Short tubes : L < 10 D

$$P_C = \frac{2,4 \cdot E\left(\frac{e}{D}\right)^{\frac{5}{2}}}{\left(1-\sigma^2\right)^{\frac{3}{4}} \cdot \left[\frac{L}{D} - 0,45\left(\frac{e}{D}\right)^{\frac{1}{2}}\right]}$$

Without saffety coef

$\sigma = Poisson\ coef$

$Pc = buckling\ critical\ pressure\ (bar)$

$E = Young\ \mathrm{mod}ulus\ (bar)$

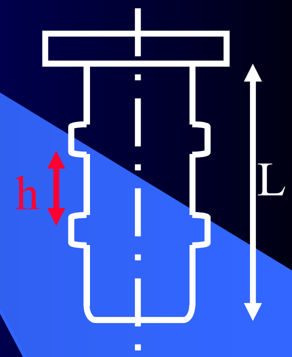
$$\frac{e}{D} = 4.10^{-3}\left(\frac{L}{D}\right)^{0.4}\ for\ stainless\ steel$$

$$\frac{e}{D} = 5,5.10^{-3}\left(\frac{L}{D}\right)^{0.4}\ for\ copper, brass$$

$with\ saffety\ coeff\ 5\ and\ for\ \Delta P = 1\ bar$

Mechanical resistance of cryostats

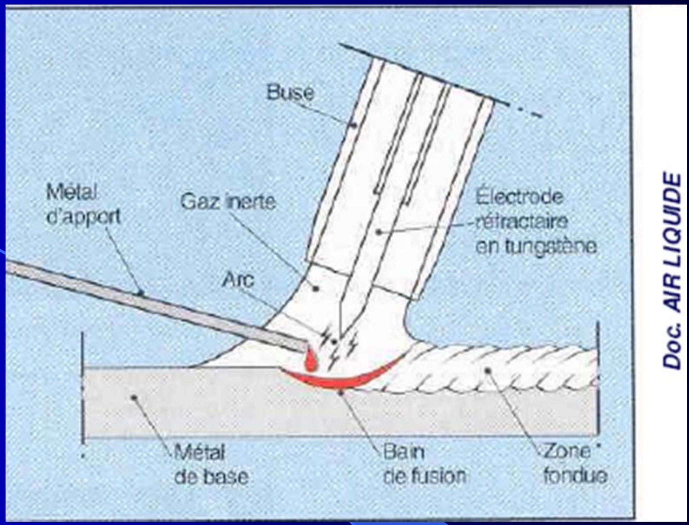
- Precautions to be taken
  - These formulas are valid only if :
    - *Quite cylindrical tubes*
    - *Constant thickness*
    - *if small bead : to take the real length (L)*
  - if bead
    - *Half-circles with large curvature radius, be able to use the length between 2 bead (h)*
  - Think about possible overpressures
  - Think about the rises in temperature which reduce the mechanical resistance (plastics)



Technology of cryogenic constructions

- Starting from mechanics and boiler making
- Fine welding
- leak tightness = crucial problem
  - the leak increase at low temperature
- No carbon steel

Welding and brazing



- TIG Welding
  - Under Argon
  - autogenous welding
  - Need for a good protection
  - Thickness: not too thin sheet
  - Design:
    - *Free passage of the welding torch :*
    - *Lips of welding*
  - Preparation:
    - *Degreasing*
      - do not pollute weld bead

- Very advised on stainless steel
  - *Reliable in time*
  - *Clean*
- Not recommended on Cu
  - Bubbles
  - Yes for the thermal shields
- Difficult to do something leak tight on light alloys

Welding and brazing

- Silver brazing
  - Heterogeneous (“gluing")
  - Example, at MCBT :
    - Castolin 1802
      - fusion 608 to 615°C
    - Rod 1020F (pink)
      - fusion 625 to 655°C
    - Castolin 1804
      - fusion 710 to 750°C
    - Castolin 1806
      - Fusion ~ 778°C

- Necessary for bonding :
  - *Copper / Copper*
  - *Copper / stainless steel*
  - *Brass / stainless steel*
- Cleaning before and after
  - *Flux material (preparation)*
- Ageing
  - *thermal cycling*
- Not good : stainless steel / stainless steel
  - *Risk of detachment*
- Less guaranteed than TIG
- Take care with the design

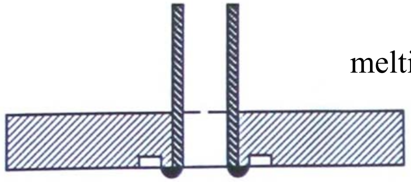
Welding and brazing

- Soft Solder (Tin)
  - Low mechanical resistance
    - Avoid if stress or pressure
  - Difficult on stainless steel
  - Used if
    - *Welding close to brazing*
    - *If we don't want to deform*
  - Easier on the capillaries (Cu Ni) than Ag brazing
  - Easily detachable (tests) but less reliable
  - Important preparation and cleaning

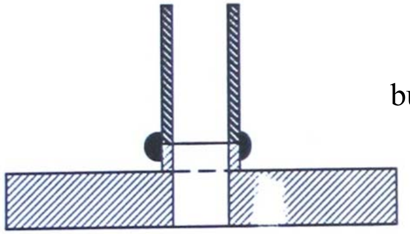
Welding and brazing

- Problems of deformation (TIG and brazing)
  - Choice a suitable geometry
    - Risk to deform flange
  - Consider possible re-work of the flange
    - Never machine again the welding or brazing = leak
  - Take care with the differences in thermal contraction
    - Copper around stainless steel

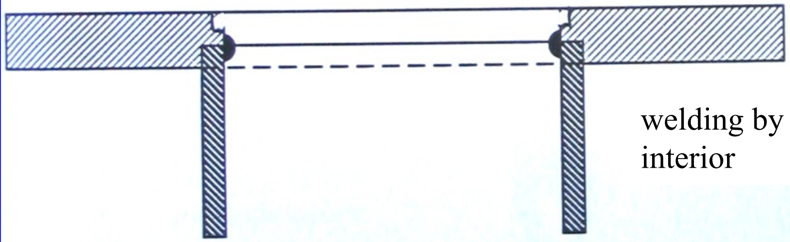
TIG welding
some advised geometries



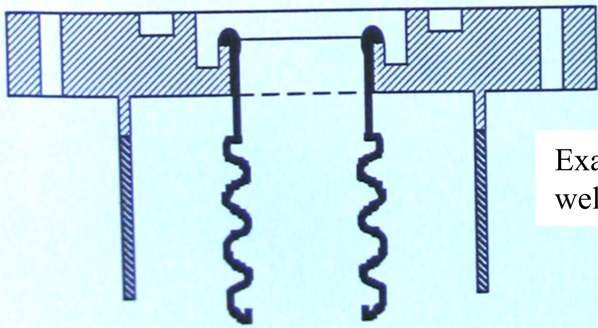
melting of the top edge



butt weld

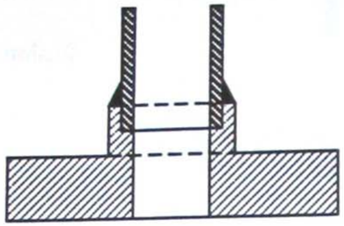


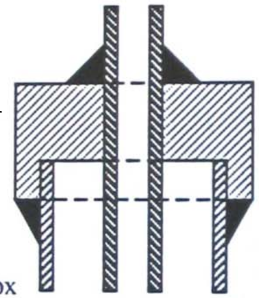
welding by the interior

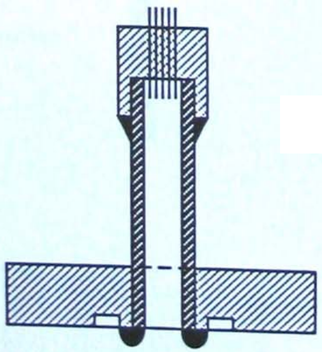


Example with 2 welding

Silver brazing
some advised geometries





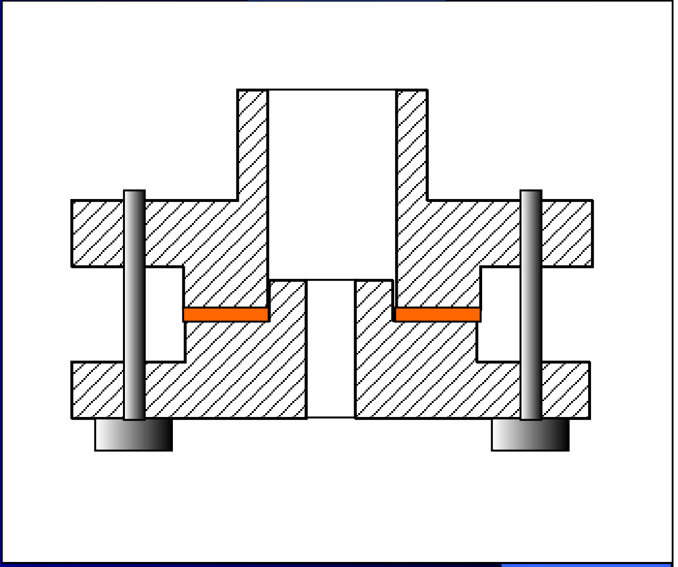


Leak tightness tests

- Helium mass spectrometer
- General principle
  - To test each element separately before integration
  - To test the whole with each new element
  - Take care with the problems of accessibility after assembly
- Test method
  - Cleaning
    - *hot water + acid + rinsing*
    - *thermal shocks (liquid nitrogen)*
  - Stove in order to completely dry the piece
    - *Remove water in the porosities*
  - Careful handling (fingers, greasy substance...)

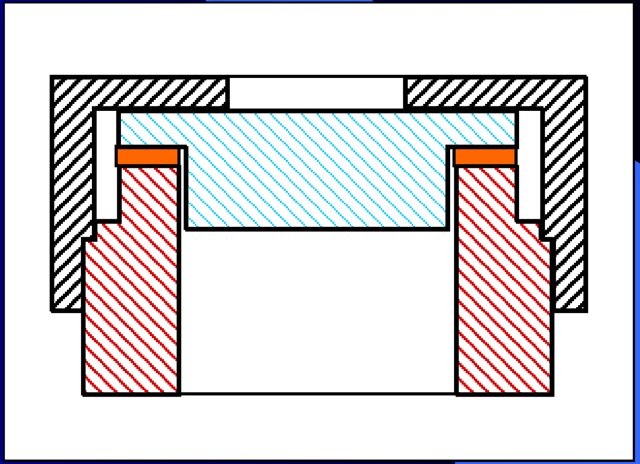
Seals at low temperature

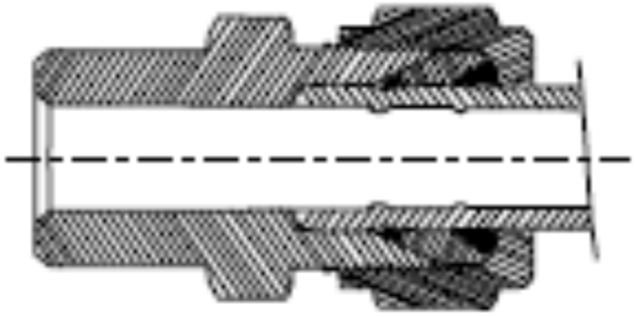
- commercial seals
  - Helicoflex, Kenol
- Soft metals seals
  - Indium, Aluminum, lead
  - Need important tightening
  - Ø joint = approximately 1 mm
  - Problem of differentials contraction
    - Flanges of different materials + screw
  - To plan disassembly



Seals at low temperature

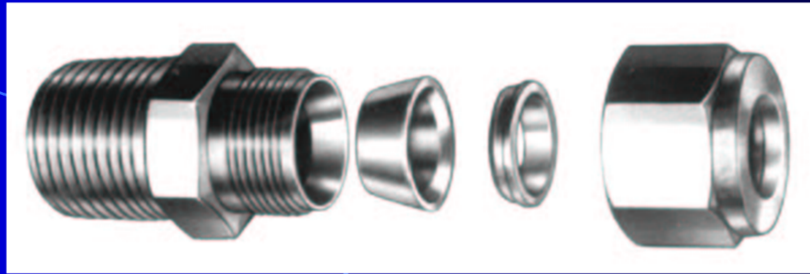
- Silicone seals (sylastene)
  - Interest: less cumbersome than Indium
    - Less tightening required
  - Need for awaiting polymerization
    - 1 to 2 hours according to product
  - To plan disassembly
- Glue
  - Stycast, Eccobond
    - allows to glue plastic metal
    - Suitable coefficient of contraction
  - Araldite
    - For the plastics between them

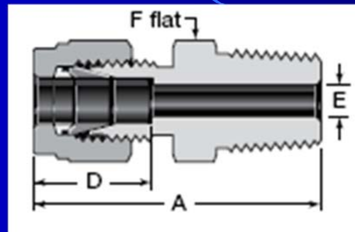


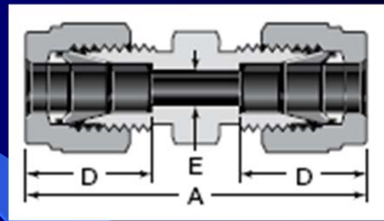


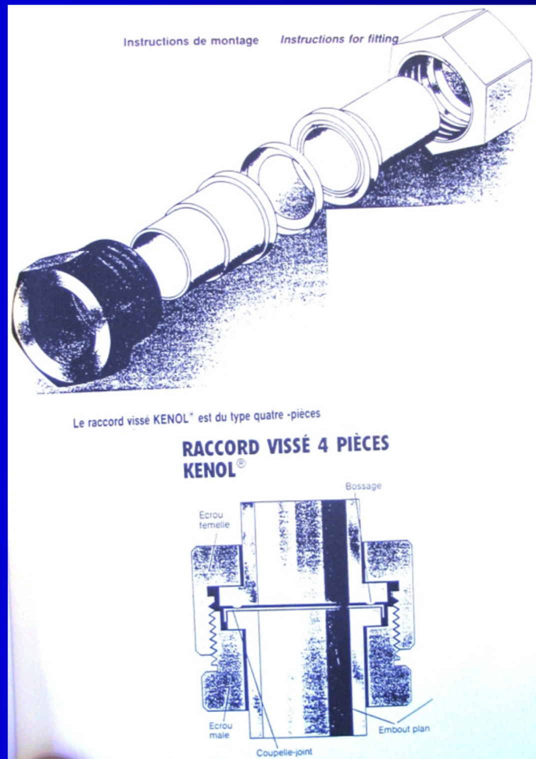
Double ring fittings

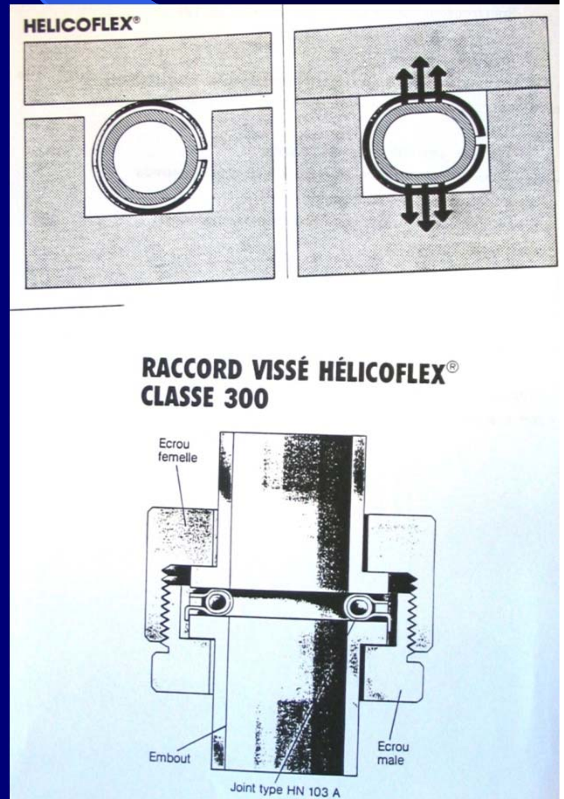
Raccord VCR











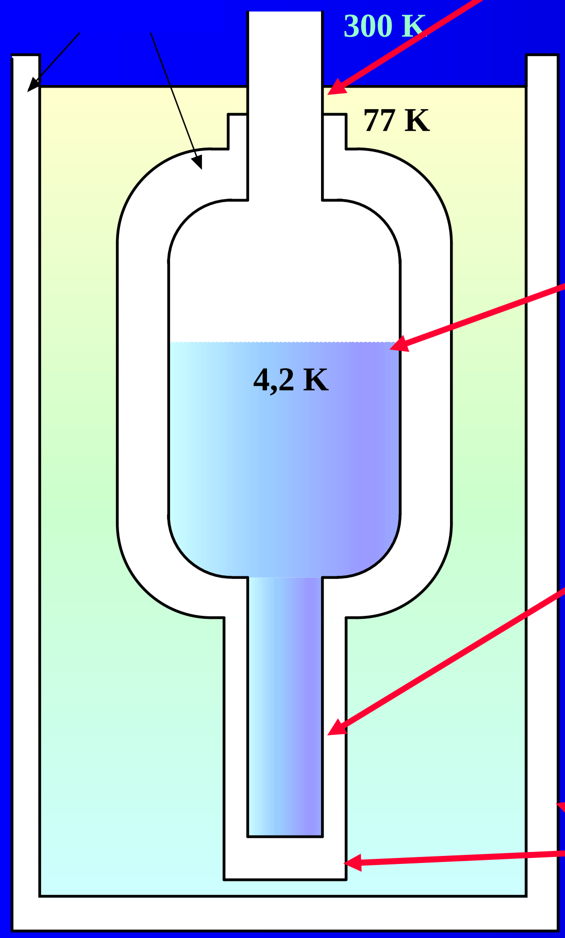
^{4}He Laboratory cryostats

Metallic cryostats

Fiberglass cryostats

Glass cryostats

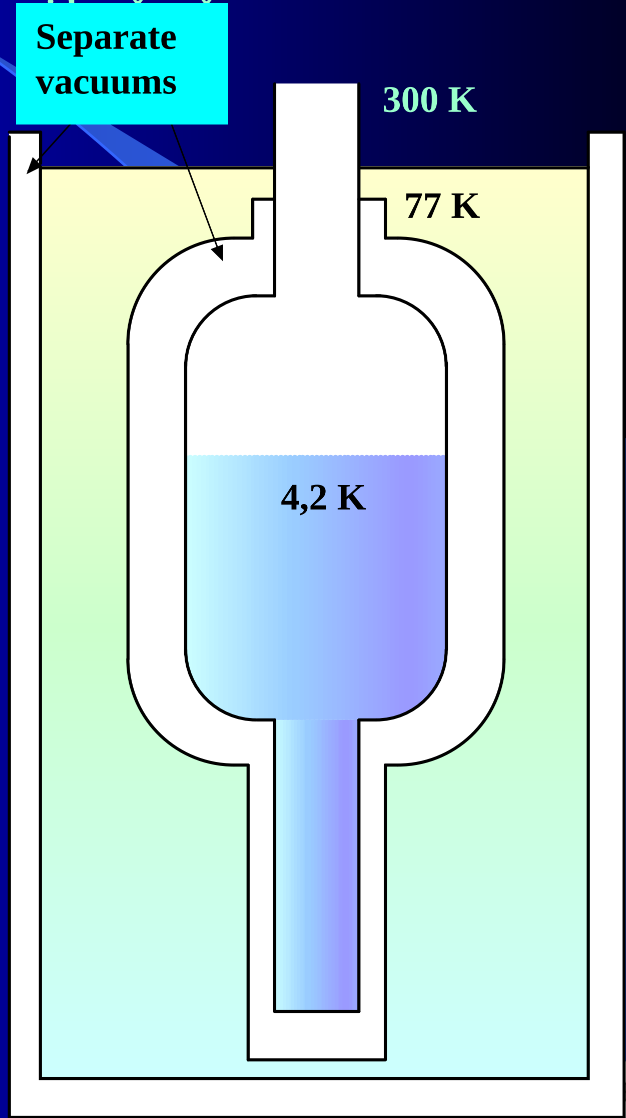
Metallic cryostats : general description



- Neck tube :
  - *Low conductive heat losses (thin stainless steel tube)*
  - *If liquid helium, intermediate point at T N_2 (77K)*
- Reserve : (function of use)
  - *Not wall too thick (for cooling)*
  - *to approach a spherical geometry*
- Tail :
  - *shape adapted to the experiment*
  - *Varied materials (depends on)*
  - *Sometimes dismountable, windows*
- External wall
  - *Must resist to the vacuum*

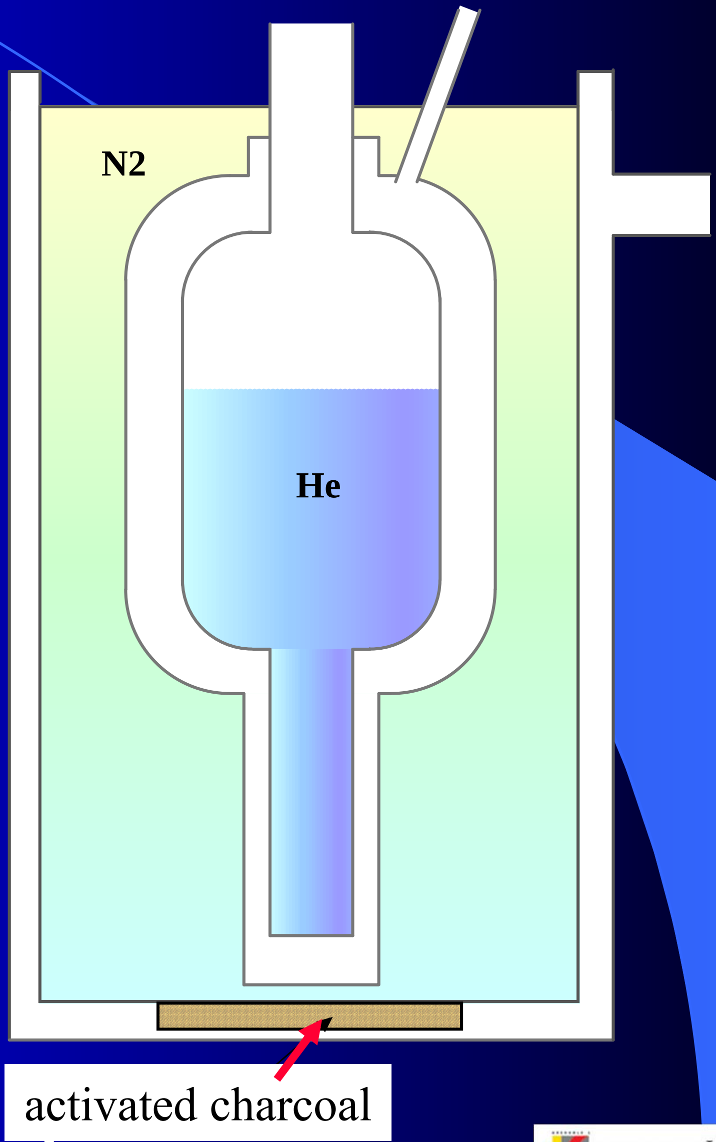
Helium cryostats : with « nitrogen guard »

- Radiation
  - External wall at 77 K
    - Heat which arrives on the internal wall is divided 230 ($300^4 / 77^4$)
    - Useless activated charcoal on the 4K
      - *Air solidified on the walls*
- Neck conduction
  - Heat coming from 300 K dissipated in N_2
  - thinnest and longest neck as possible
  - Conduction between 77 and 4 K lower than 300K→4K



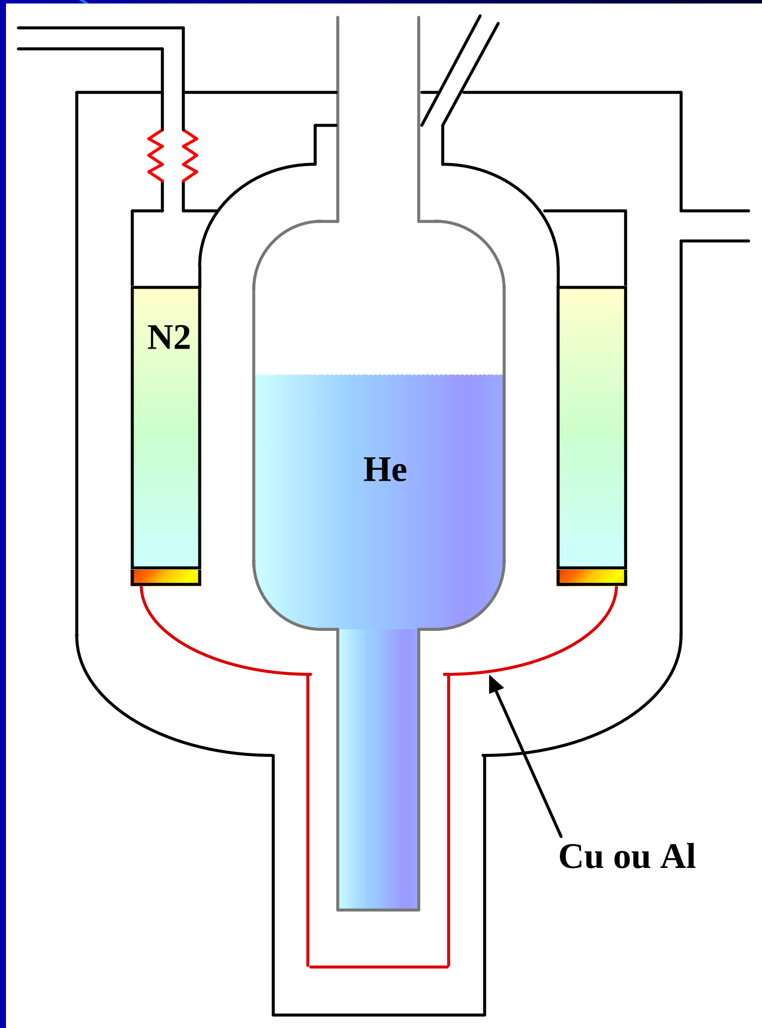
Different geometries : 1

- Each unit is less heavy
- Easier to repair
- Fast heating
- Interest of 2 separate vacuums:
  - allows to precool the cryostat with nitrogen



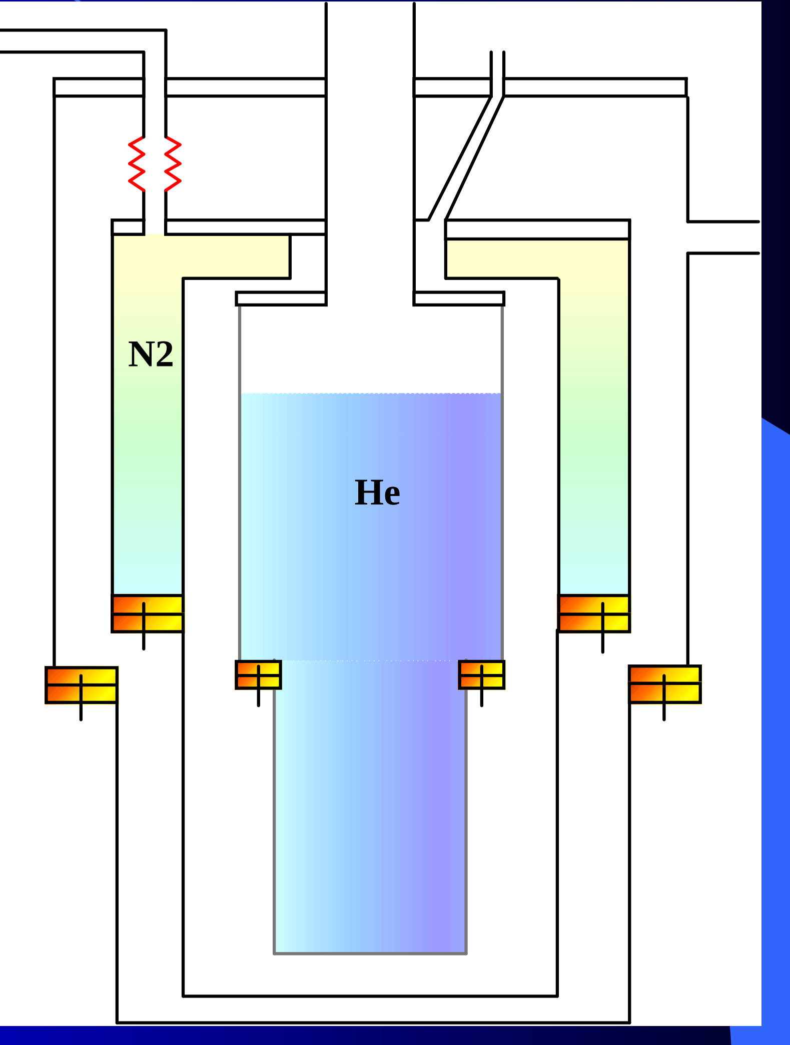
Different geometries : 2

- Less cumbersome tail
  - One wall in less
- Need for expansion bellows on N_2 filling and He vacuum tubes
- Possibility to have only one vacuum



Different geometries : 3

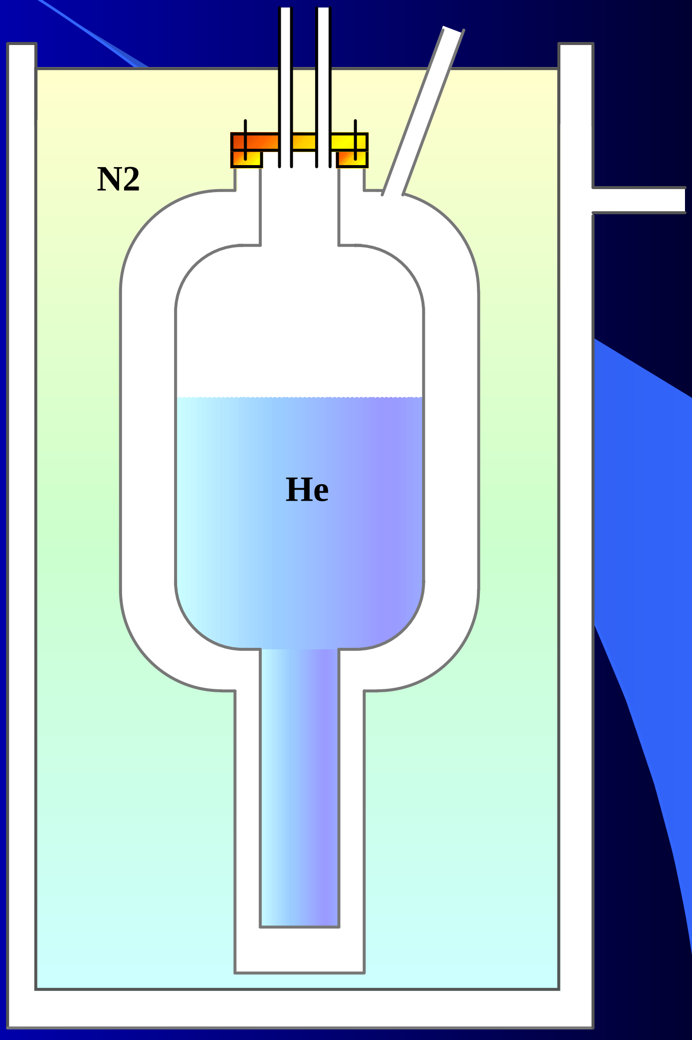
- Interchangeability of the tails
- Expensive and heavier
  - Additional flanges
- Accessibility inside
- Essential for neutrons
  - Tails in light alloys



Different geometries : 4

- Good blocking of the thermal flow at 77 K

- Requires to plan at the beginning all the things which go inside



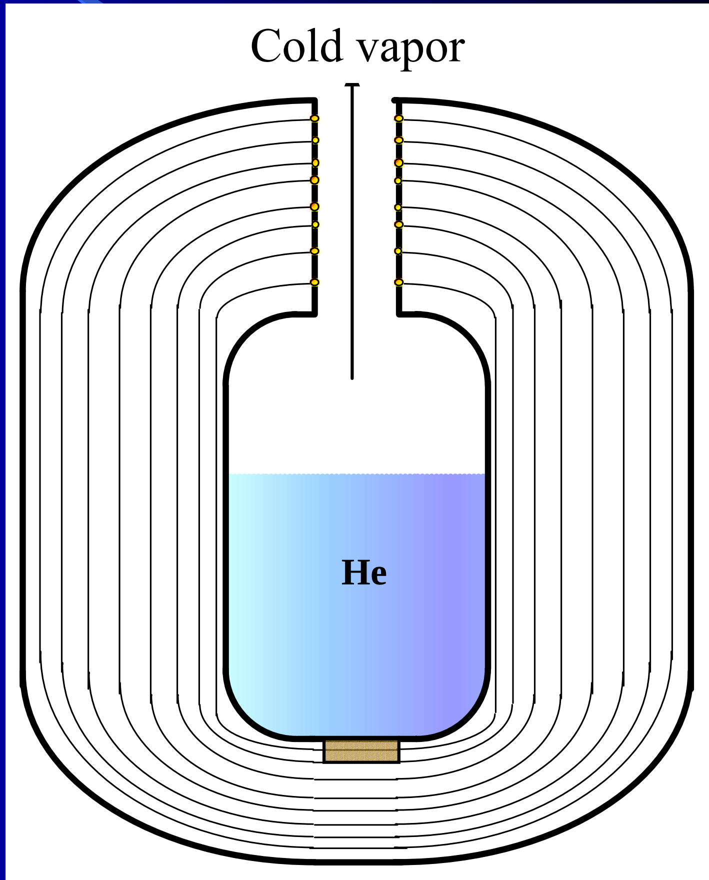
Helium cryostats : without « nitrogen guard »

- Neck conduction
  - Critical because $\Delta T = 300 - 4 = 296$ K
    - *Rather choose "plastic" neck*
      - Conduction 20 times lower than stainless steel
  - but conduction attenuated by the cold energy of the vapors
    - *Only a part of heat reach the bath*
    - *that depends on heat exchange between neck - vapors*
- Example for a100 L helium commercial vessel
  - Plastic neck ø50 mm, thickness = 1 mm, length = 400 mm + MLI → Total losses = 30 mW so 1 l/day → 1% per day
- 5000 liters He vessels : 0.2% per day

He⁴ Storage and transport vessels

- 2 types of vessels
  - stainless steel
  - Aluminum with fibre glass neck (standard G11)

- To minimize the losses
  - cryostats with MLI
  - Vapor cold energy recovery
    - allows to cool down the various layers of S.I. .
    - Contact with the neck
  - Activated charcoal
    - Must be placed in the vacuum
    - In contact with the cold wall



Interest of activated charcoal

- Example of radiation on nitrogen cryostat
  - 30 liters cryostat: Ø = 30 cm, h = 40 cm
    - Vacuum alone: not very good !
      - Q = 25 watts
      - 0.5 l/h or 12 l/day
    - Vacuum + activated charcoal : better
      - Q = 15 watts
      - 0.33 l/h or 8 l/day
    - Vacuum + activated charcoal + MLI : still better
      - Q = 2 watts
      - 0.044 l/h or 1 l/day

Helium cryostats : without « nitrogen guard »

- Problems with the "plastic" neck
  - Anisotropic contractions
  - Gluing sensitive ➔ be careful with the behaviour at low temperature
  - Porous for helium at room temperature
    - Keep the cryostat cold
    - Metal barrier deposited on the plastic
    - Use compact fiber glass (standard G11)
      - *Limit but not sufficient*
    - ➔ after each reheating, the vacuum becomes progressively bad
      - *it is necessary to remake the vacuum on the vessel*
        - In spite of activated charcoal

Plastic cryostats

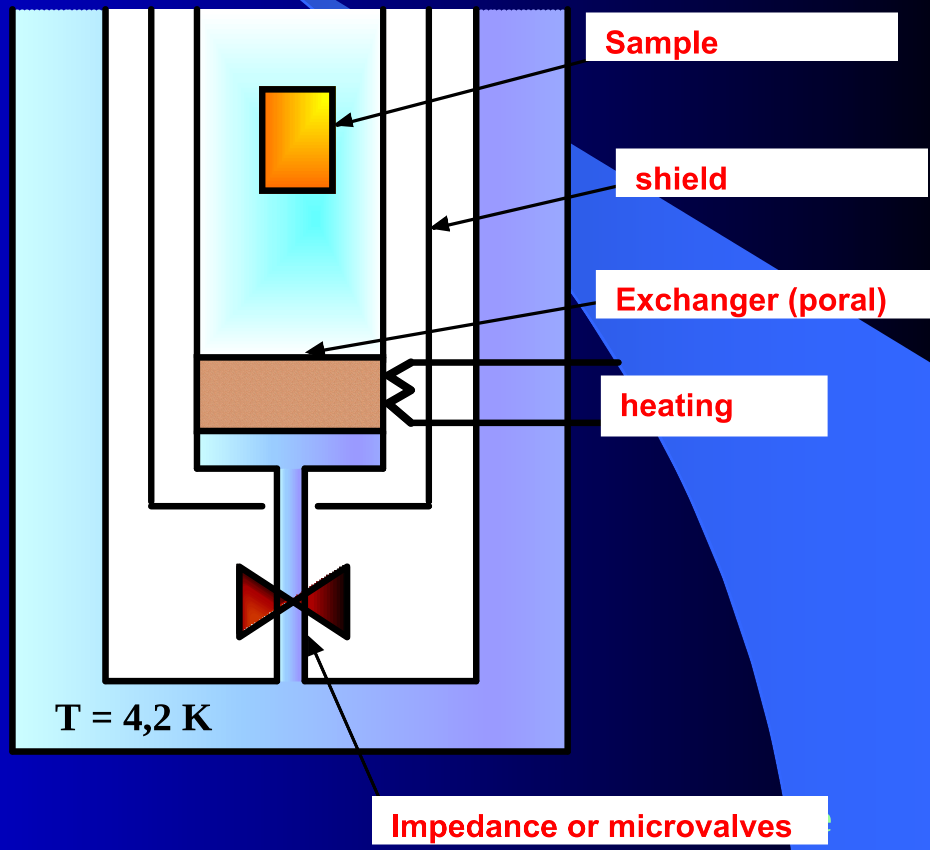
- Suitable for magnetic measurements and for experiments in intense and variable magnetic fields
- Problems with this type of cryostats
  - In intense and variable magnetic fields experiments, the thermal shields and the MLI must prevent the development of eddy current (use of MLI in which the aluminum deposit consisted in small squares of 5mm width separated from each other by an insulated barrier)
  - There are no standard components (tubes, flanges)
  - Plastic - plastic gluing (Araldite, Ecobond)
  - Plastic metal gluing (Ecobond)

Glass cryostats

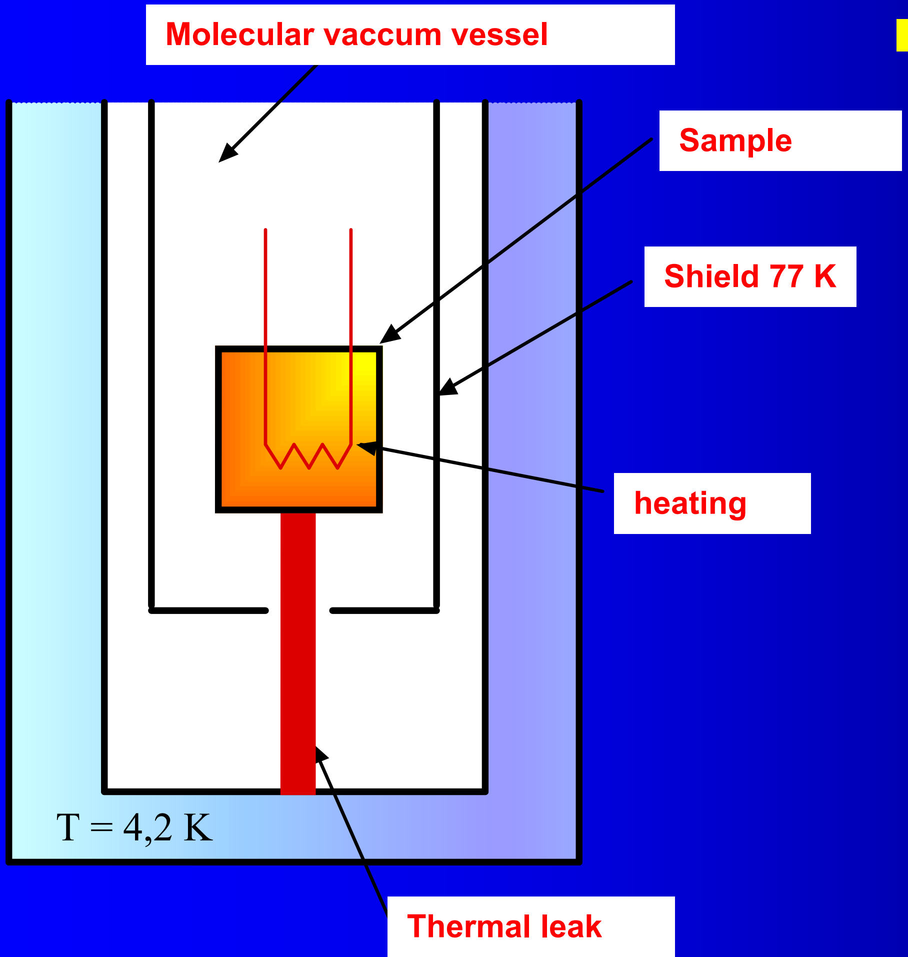
- Advantages :
  - *possible observation*
  - *Nonmagnetic , but more cumbersome tail*
- Disadvantages:
  - *brittle, they should be annealed regularly*
    - Release of the constraints accumulated after several cooling
  - *Helium porosity (5.10^{-7} mbar.l/sec)*
    - Need for permanent pumping or special glasses
  - *ε = 1 (black body) ➔ silvering necessary*
    - Plan the windows
    - important losses by radiation
- Especially teaching interest

Obtaining variable temperatures at T > 4.2 K

- He gas circulation + heating
- Cooling down fast
  - Difficulty of stabilization
    - *T = f (flow and W)*
  - Sample well thermalized under gas flow
  - Easy replacement of sample



Obtaining variable temperatures at T > 4.2 K



- Fixed thermal leak
  - Better stabilization of the temperature
  - More delicate cooling down
    - *exchange gas pump again*
    - *By the thermal leak*
      - → *take some time*
      - → *small sample*

Obtaining temperatures lower than 4.2 K

- Interests: :
  - Appearance of physical phenomena which cannot be seen at 4.2 K
  - Refrigeration of superconducting magnets in He superfluid
    - *at 4.2 K*
      - Heat exchange 0.5 to 1 W/cm^2 according to orientation of surface in free convection and < 0.1 W/cm^2 in a blind channel
    - *at 1.8 K*
      - Heat exchange 5 W/cm^2 even in narrow channels
      - Cp of helium close to T_λ is high

Better stability of superconducting magnets and improvement of the performances

Ic $\uparrow$ when T $\downarrow$

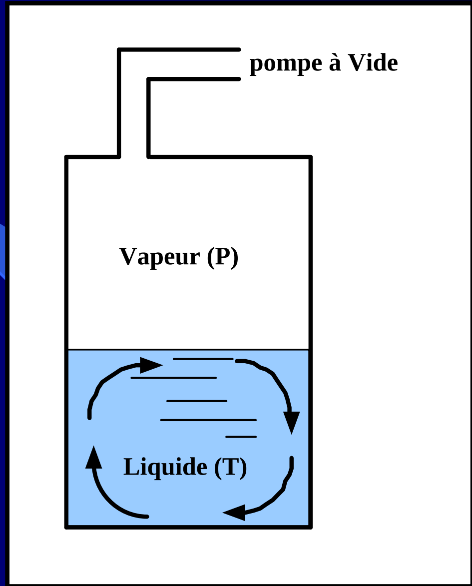
Obtaining temperatures lower than 4.2 K

- Direct pumping on the bath
  - Transient state = loss in liquid
    - Q to be extracted is such as:

$$Q = L \cdot dm = mC_P dT$$

$$\ln\left(\frac{m}{m_0}\right) = \int_T^{4,2} \frac{C_P(T)}{L(T)} dT$$

    - L(T) changes little with T
    - C_p(T) strongly changes towards T_λ
  - Below the transition
    - There remains only half of the liquid



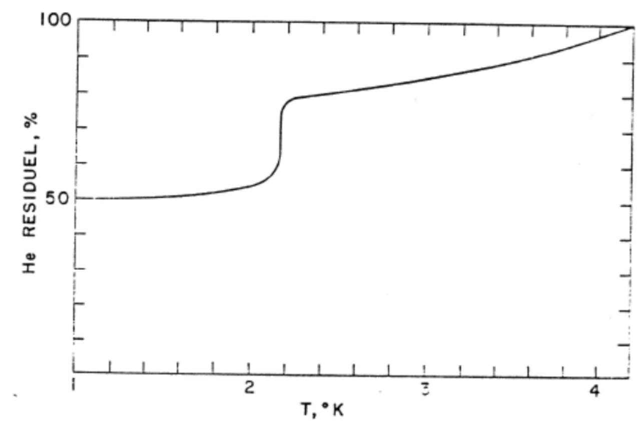
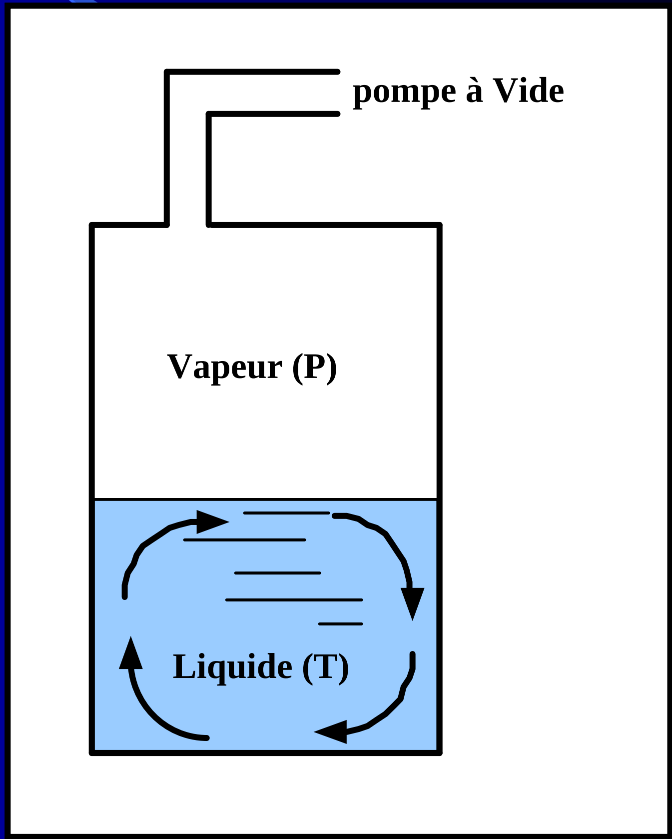


FIG. 6-1. — *Quantité d'hélium restant après refroidissement de 4,2 °K à la température T* (6).

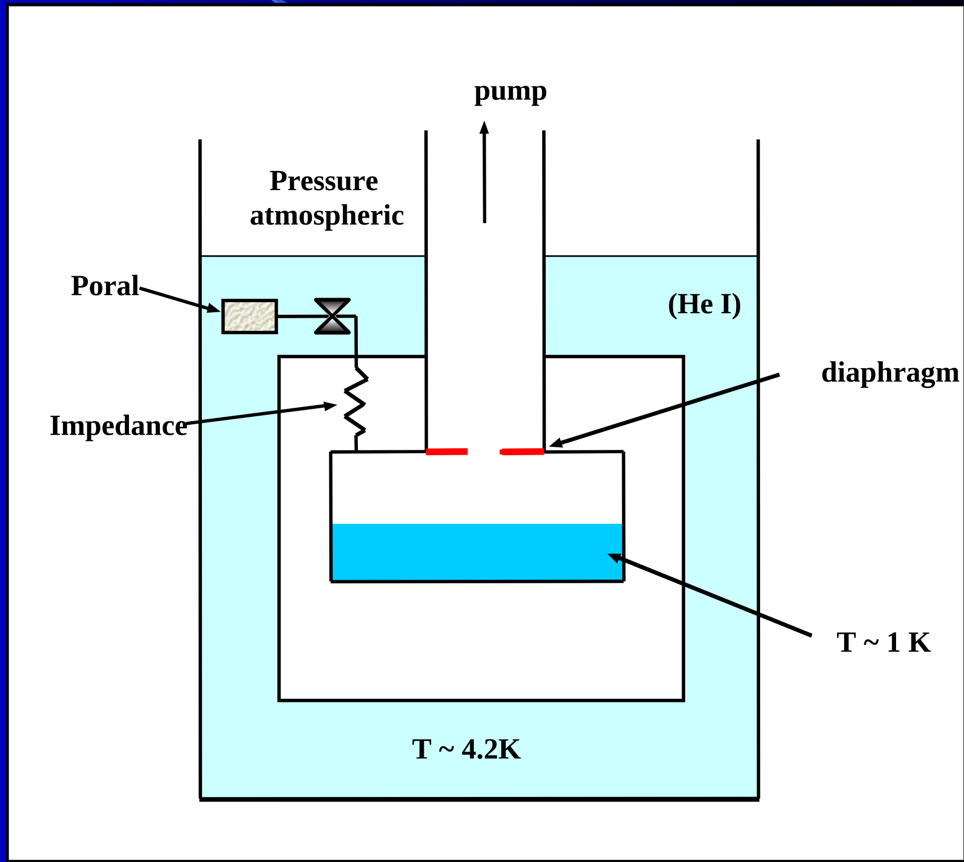
Obtaining temperatures lower than 4.2 K

- pumping on the bath
  - T minimal depends on :
    - Cryostat losses
    - Pumping flow
    - Pressure drop in the pumping line
  - order of magnitude
    - 12 m^3/h + Ø 15 mm + 16,5 mbar
      - ➔ *T = 1.8 K*
    - 60 m^3/h + Ø 40 mm + 4,8 mbar
      - ➔ *T = 1.5 K*
    - 170 m^3/h + Ø 100 mm + 0,6 mbar
      - ➔ *T = 1.15 K*



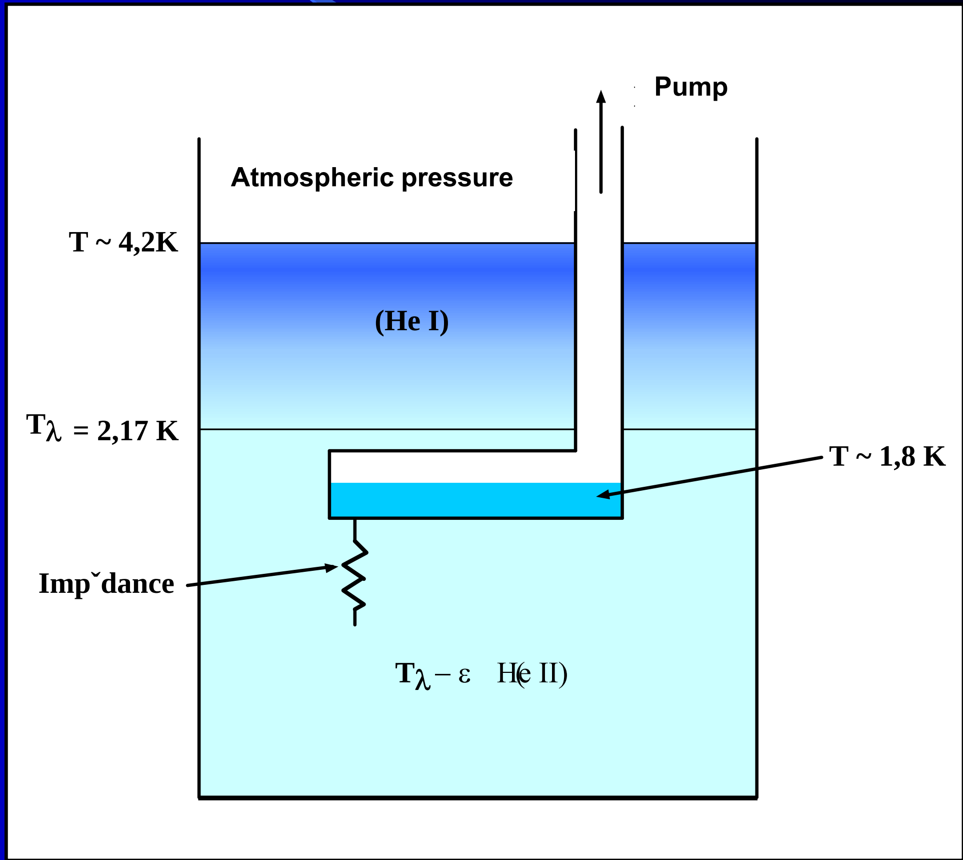
Obtaining temperatures around 1K

- The double bath
  - « 1 K box»
  - A few milliwatts
  - If pump at 30 m^3/h
    - T ~ 0.9 K if closed valve
    - T ~ 1.5 K to 1.8 K if impedance (pressure drop)



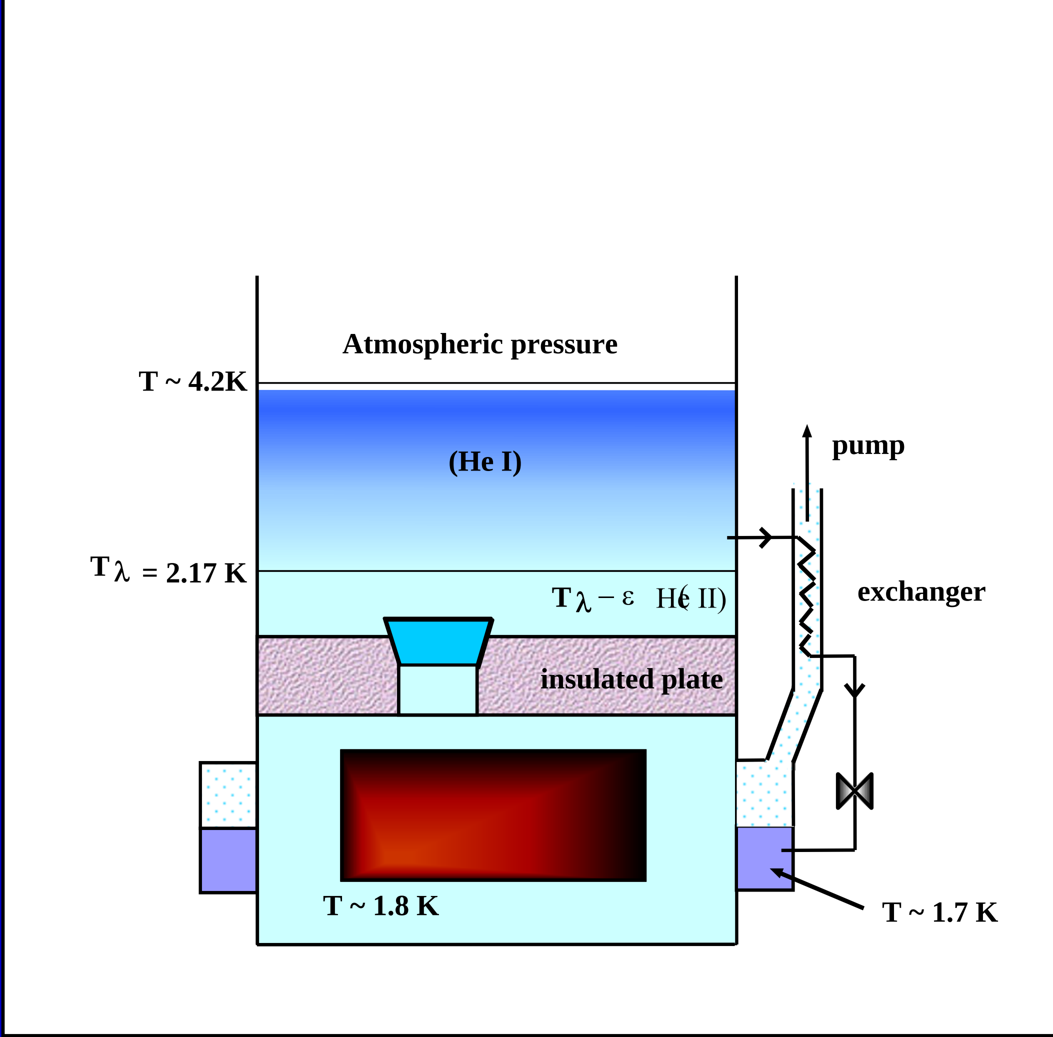
Superfluid under atmospheric pressure

- Roubeau bath
  - Superfluid Helium
  - $T \sim T_\lambda - \varepsilon$
  - Rigorously constant temperature
  - No stratification



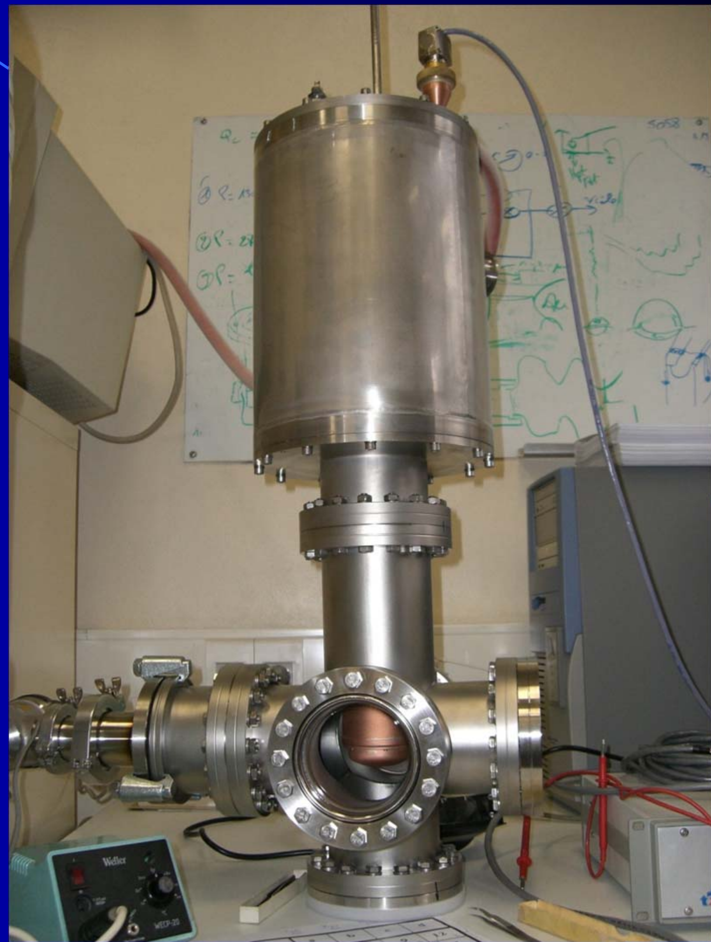
Superfluid under atmospheric pressure

- Claudet bath
  - Superfluid Helium
    $T < T_\lambda \sim 1.8$ K
  - Uniform temperature
  - Interest: performance of superconducting coil + current leads at atmospheric pressure..
  - Safety valves !



He^4 cryogenic fluid device

Optical cryostat 6 K - 77 K :
Magneto optical experiments on HTC superconducting tapes



CryoFIB
4 K He Emission

He^3 cryostats

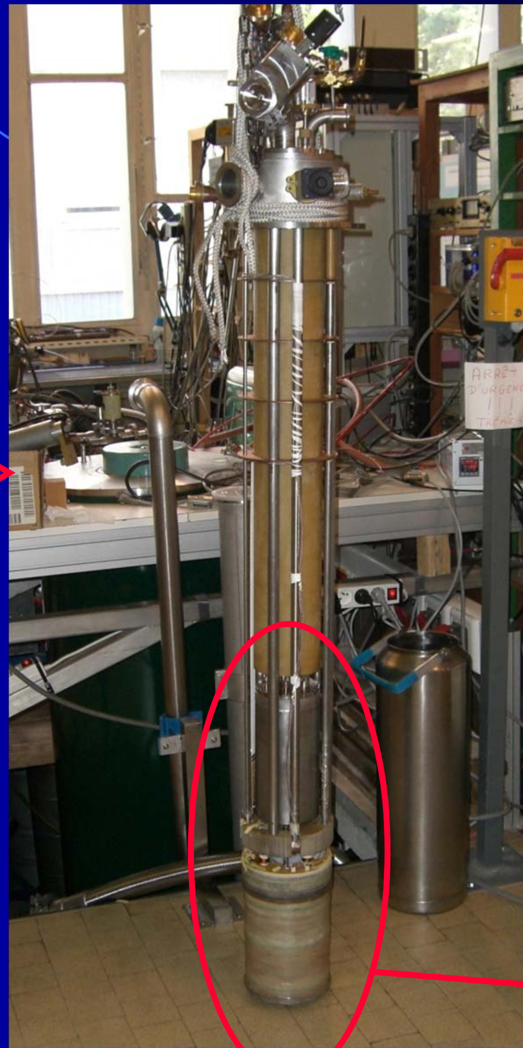
- To reach temperatures lower than 1 K
  - What is ^3He
    - He^3 is an isotope of ^4He : he has 2 protons 1 neutron
    - Boiling point 3.2 K
    - Superfluid temperature 2.5 mK
    - He is used for dilution systems

    - We can reach 270 mK by pumping directly on ^3He bath
      - ^3He filling line must be heat sunk by means of 1K ^4He box

He3 device description

Coil support +
Roubeau bath

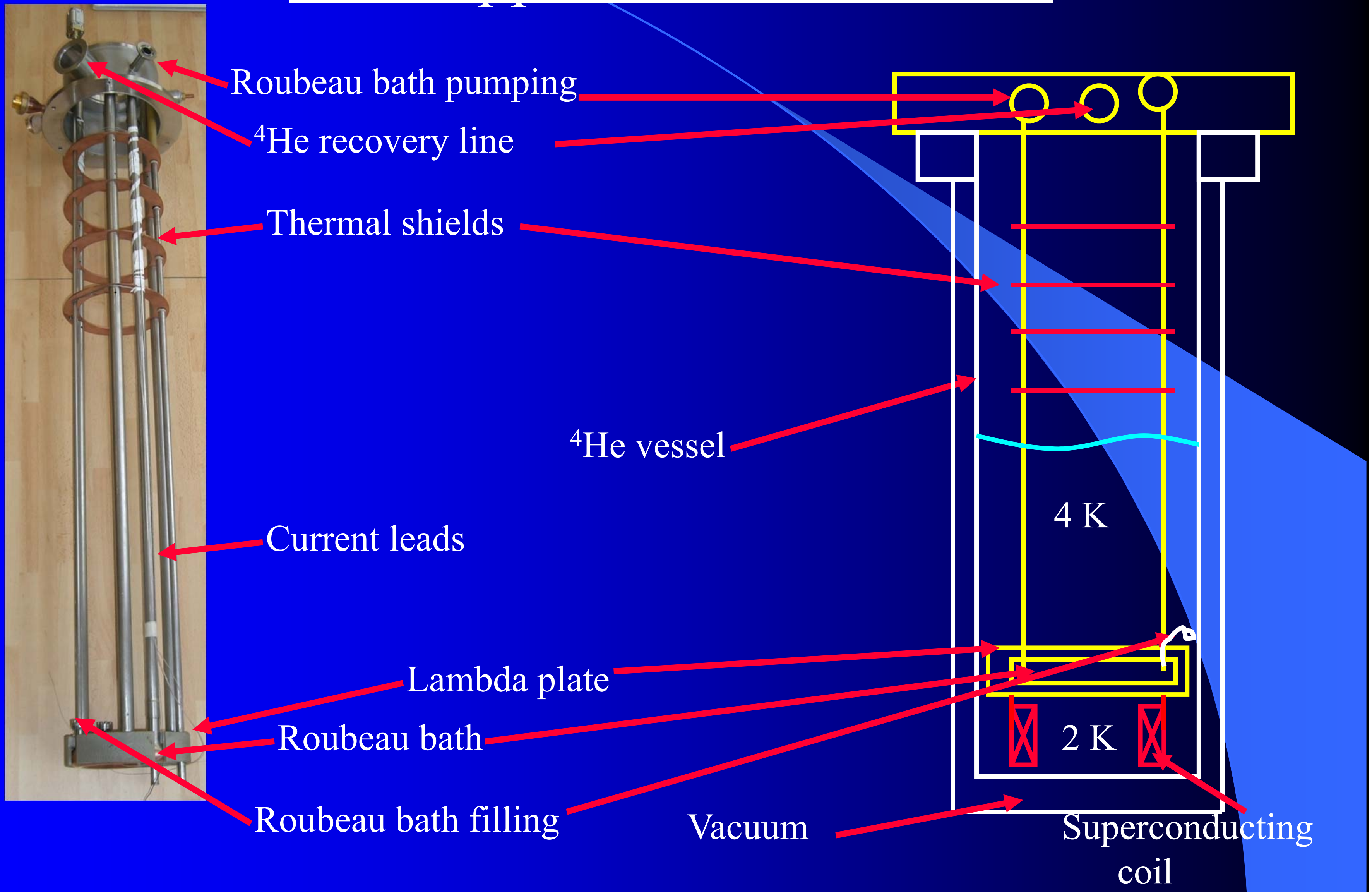
He 3 insert



The entirety

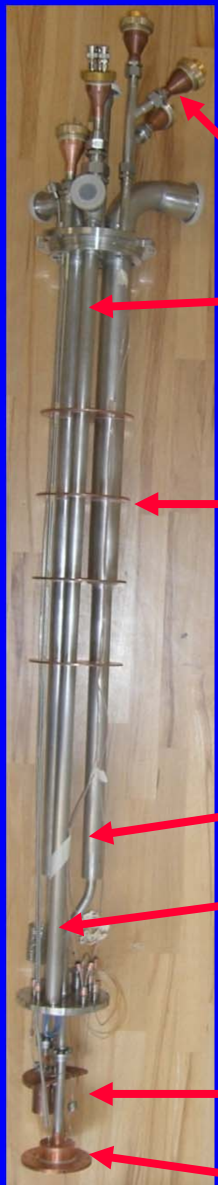
He^3 device description

Coil support + Roubeau bath



^{3}He device description

^{3}He insert



Jaeger instrumentation

Inner vacuum pumping line

Thermal shields

^{3}He box pumping

^{4}He box pumping

^{4}He box (1 K)

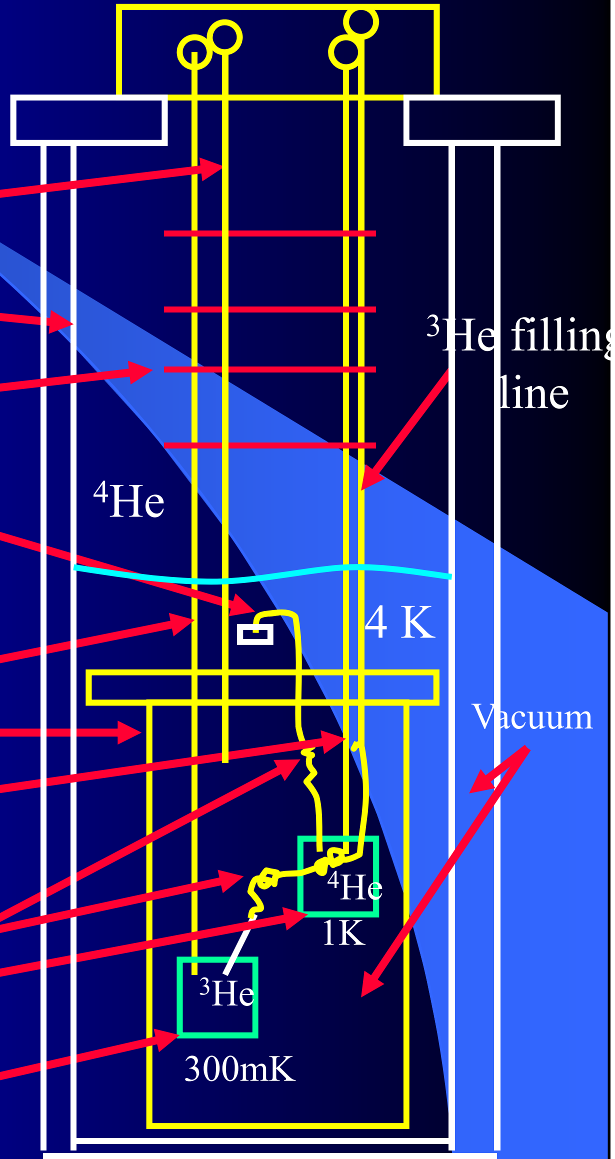
^{3}He box (300 mk)

^{4}He cryostat

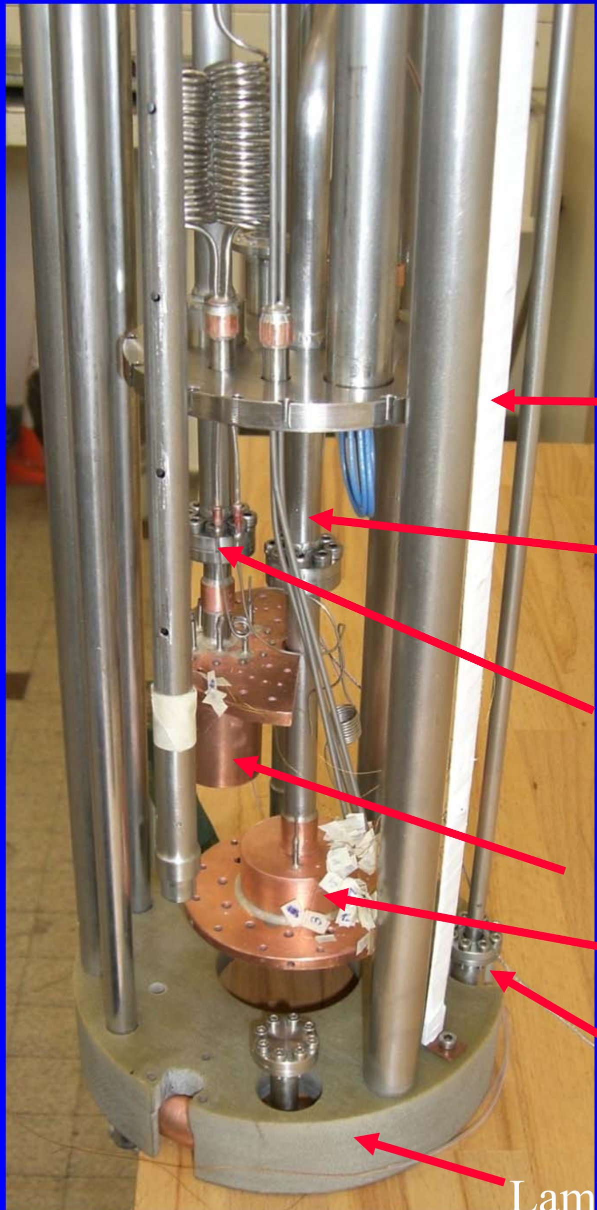
^{4}He filling line

Vacuum vessel

impedances



Complete device



Liquid He level sensors

^{3}He box pumping line

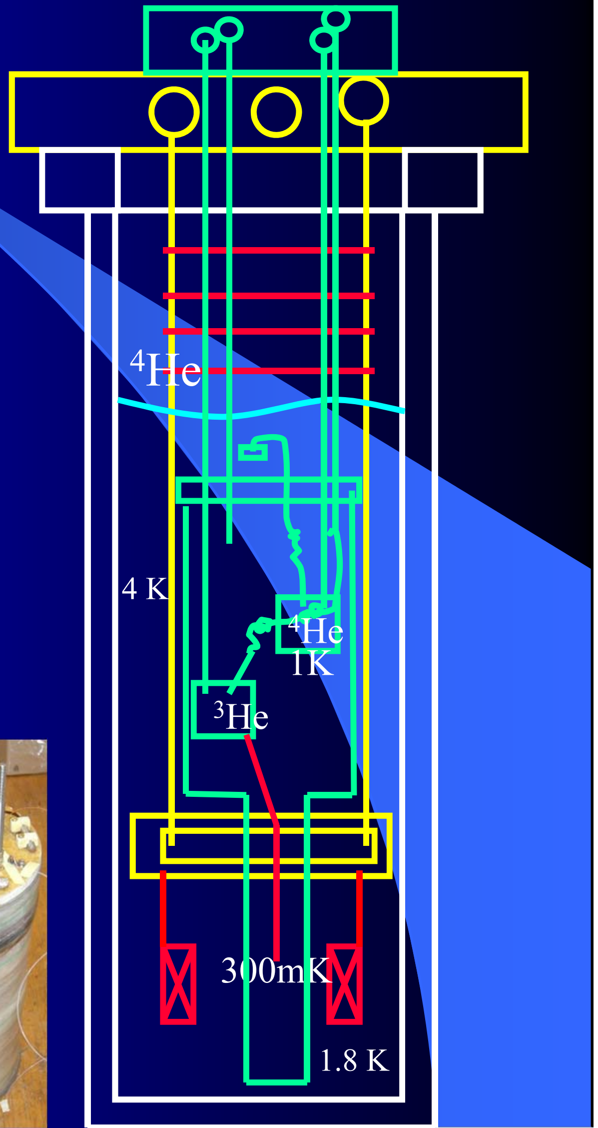
^{4}He box pumping line

^{4}He box (1.2 K)

^{3}He box (300 mk)

Cryogenic valve for Roubeau bath filling

Lambda plate



References

- Handbook of cryogenic engineering J.G. Weisend II
- Cryogenic engineering Thomas M. Flynn
- Matter and Methods at Low Temperatures F.Pobell
- Eléments de cryogénie R.R Conte