INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY
c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE 040-224572 TELEFAX 040-224575 TELEX 460449 APH I

SMR/543 - 6

EXPERIMENTAL WORKSHOP ON HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED MATERIALS
(BASIC ACTIVITIES)

(11 February - 1 March 1991)

" Cryostat Design " - PART III

presented by:

R. HAEFER
Technische Universität Graz
Institut für Festkörperphysik
Petersgasse 16
A-8010 Graz
Austria

R.A. HAEFER, Cryostat Design III

8.2 Thermal load of cryosurfaces

The thermal load transmitted to a cryosurface consists of the sum of heat flow rates produced by thermal radiation ($\dot{Q}_{\mathrm{rad}}$), thermal conductivity of solid ($\dot{Q}_{\mathrm{solid}}$), condensation ($\dot{Q}_{\mathrm{cond}}$), cryosorption ($\dot{Q}_{\mathrm{sorp}}$), and gas heat conduction ($\dot{Q}_{\mathrm{gas}}$). Hence the heat balance equation is given by

$$\dot{Q}_{\mathrm{rad}}+\dot{Q}_{\mathrm{solid}}+\dot{Q}_{\mathrm{cond}}+\dot{Q}_{\mathrm{sorp}}+\dot{Q}_{\mathrm{gas}}-\dot{Q}_{\mathrm{k}}=m_{\mathrm{k}}c_{\mathrm{k}}\,\mathrm{d}T_{\mathrm{k}}/\mathrm{d}t, \qquad (8.3$$

where $\dot{Q}_{\mathrm{k}}$ is the refrigeration power supplied by the cold source, and m_{k} and c_{k} are the mass and specific heat capacity respectively of the cryosurface. In the steady state the right-hand side of eqn (8.3) equals zero. [Values of the specific heat capacity $c=c(T)$ of various structural materials can be found in[26-28]]

$\dot{Q}_{\mathrm{cond}}$ and $\dot{Q}_{\mathrm{sorb}}$ are of special interest for cryopumping; they will not be discussed here.

The emissivity e is defined as the ratio of the radiation flux emitted to that which would be emitted by a black body of the same area at the same temp.

For engineering purposes it is usual to assume that the emissivity equals the absorptivity over the whole of interest. See the table: Emissivities

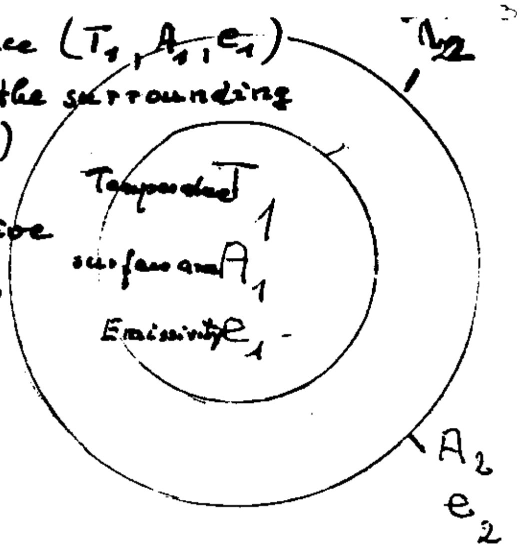
- Emissivities decrease somewhat with decreasing temp. (Al,
- Mechanical polishing results in a higher emissivity than electro polishing because of the workhardening imparted to the surface. (Cu)
- Oxide layers on Cu & Fe produce an increase in e.
- The emissivity of Al & its alloys is consistently low because Al-oxid is transparent to infrared radiation.
- Extremely low e-values are obtained by polishing & coating with Al, Au, Ag, Cu ($e \approx 0,01$) by evaporation or sputtering. (Superinsulation).

The values listed in the table were obtained from carefully prepared, small specimens. During the assembly of large plants, it is difficult to keep areas spotlessly clean. Finger prints ($e \approx 0.9$) and dust on highly polished surfaces are to avoid.

Thermal Radiation

$$\dot{Q}_r = e_r A_1 \sigma (T_2^4 - T_1^4) \leftarrow$$

The cryosurface (T_1, A_1, e_1) receives from the surrounding wall (T_2, A_2, e_2) the flow rate $\dot{Q}_r$ of radiative heat transfer.



$$\sigma = 5{,}67 \cdot 10^{-8}\ \mathrm{W\,m^{-2}K^{-4}}$$

Stefan - Boltzmann - Constant

$$e_r = [e_1^{-1} + A_1 (e_2^{-1} - 1)/A_2]^{-1}.$$

- If $\left.\begin{matrix} A_1 \ll A_2,\ e_2 \to 1 \\ e_r = e_1 \end{matrix}\right\}$: $\underline{\dot{Q}_r = e_1 A_1 \sigma (T_2^4 - T_1^4)}$

T (K)	300	80	20	4	1
$\sigma \cdot T^4$ $\mathrm{W\,m^{-2}}$	460	2,32	0,009	$1.4 \cdot 10^{-5}$	$5.6 \cdot 10^{-8}$
λ_{max} µm	9.66	36.2	145	725	2898

← according t
Wien's Law
$T \cdot \lambda_{max} = 2898\ \mathrm{K}\mu$

In order to keep $\dot{Q}_r$ low, T_2 and e_1 must be sufficiently low.

424 APPENDIX

TABLE A. 14 Emissivity *e* of materials[A18–A22] Temperature of radiator: 273–373 K. No distinction is made between normal and hemispherical values of *e*.

Material	Surface temperature (K) 300	80	4
Aluminium: annealed, electrolytic polish	0.03	0.018	0.011
rough	0.08	0.03	
with oxide film 0.25 µm	0.06		
1 µm	0.30		
7 µm	0.75		
with lacquer film 0.5 µm	0.05		
2 µm	0.30		
8 µm	0.57		
Copper: mechanical polish	0.03	0.019	0.015
electrolytic polish		0.015	0.006
black oxidized	0.78		
Steel and Iron: steel 316, polished to 5 µm (r.m.s.)		0.045	
polished to 2 µm (r.m.s.)		0.027	
steel 302 and 18/8, polished	0.08–0.15	0.048–0.061	
cast iron, polished	0.21		
iron, rusty	0.85		
Silver: polished	0.020	0.008	0.004
on copper-plated or nickel-plated stainless steel		0.007	
oxidized		0.036	
Gold: foil 40 µm thick	0.02	0.01	
12 µm on copper	0.04	0.025	
5 µm on steel 304		0.025	
12 µm on glass or plexiglass		0.016	
0.25 µm on glass or plexiglass		0.063	
Metallized Mylar film (metal thickness > 0.1 µm):			
aluminium		0.023	
gold		0.018	
silver		0.012	
copper		0.014	

An important engineering geometry is if <u>$A_1 = A_2$</u>, i.e. a situation which is approximated by two concentric spheres or two infinitely long cylinders of nearly the same diameter. Then the factor e_r reduces to

$$\begin{aligned} e_r &= \left(\frac{1}{e_1} + \frac{1}{e_2} - 1\right)^{-1} \\ &= e/(2-e) \qquad \text{if } e_1 = e_2 = e \\ &= e/2 \qquad \text{if } e \ll 1. \end{aligned}$$

The following table gives the specific heat flux by radiation for two infinite parallel surfaces, assuming each has $e = 0.1$; and corresponding rates of evaporation of LN_2, LH_2 & LHe.

T_2 (K)	T_1 (K)	$\dot{Q}_{rad}/A_1$ (W/m^2)	Evaporation rate ℓ/h per $1 m^2$ surface	1 W $\hat{=}$
300	77	23.0	0.53 LN_2	0.023 $\ell\, LN_2/h$
300	20	23.1	2.6 LH_2	0.112 $\ell\, LH_2/$
300	4.2	23.1	32.4 LHe	1.38 $\ell\, LHe/$
80	20	0.12	0.013 LH_2	
80	4.2	0.12	0,16 LHe	

These numbers demonstrate the importance of the radiation shield at 80 K in equipment containing LHe or LH_2.

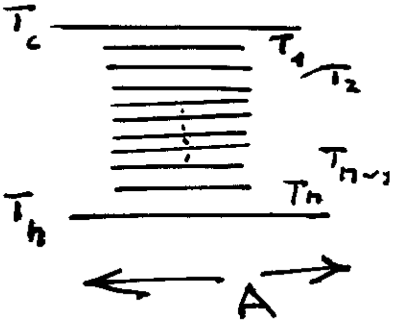
Assuming $e = 0.01$ (instead of 0.1) the evaporation rates would be even 10 times lower!

Thus it is common to install <u>radiation shields</u> in cryogenic equipment with surfaces at $T \lesssim 10$ K.

Sometimes these consist of metal sheets cooled by either

- a LN_2 bath,
- contact with the first stage of the refrigerator,
- a special gas stream from the refrigerator,
- the cold boil-off vapour passing through tubes.

Another possibility is to use "floating", that is uncooled radiative shields. Consider two infinite plane surfaces with n infinite sheets between them*. If the system is in the steady state, the heat flux between adjacent pair of surfaces must be identical, in which case we have, if $e_c = e_1 = \cdots e_n = e_h = e$



$$\frac{\dot{Q}_{rad}}{A\sigma\, e/2} \left.\begin{aligned} &= T_1^4 - T_c^4 \\ &= T_2^4 - T_1^4 \\ &\;\vdots \\ &= T_n^4 - T_{n-1}^4 \\ &= T_h^4 - T_n^4 \end{aligned}\right\} \quad n+1 \text{ equations}$$

$$(n+1)\,\frac{\dot{Q}_{rad}}{A\sigma\, e/2} = T_h^4 - T_c^4$$

$$\dot{Q}_{rad} = \frac{A\sigma e}{2(n+1)}\left(T_h^4 - T_c^4\right)$$

(*) with no convective or conductive heat transfer between the sheets.

→ This is the principle of superinsulation: n heat reflecting sheets reduce the radiate heat flux by a factor $n+1$.

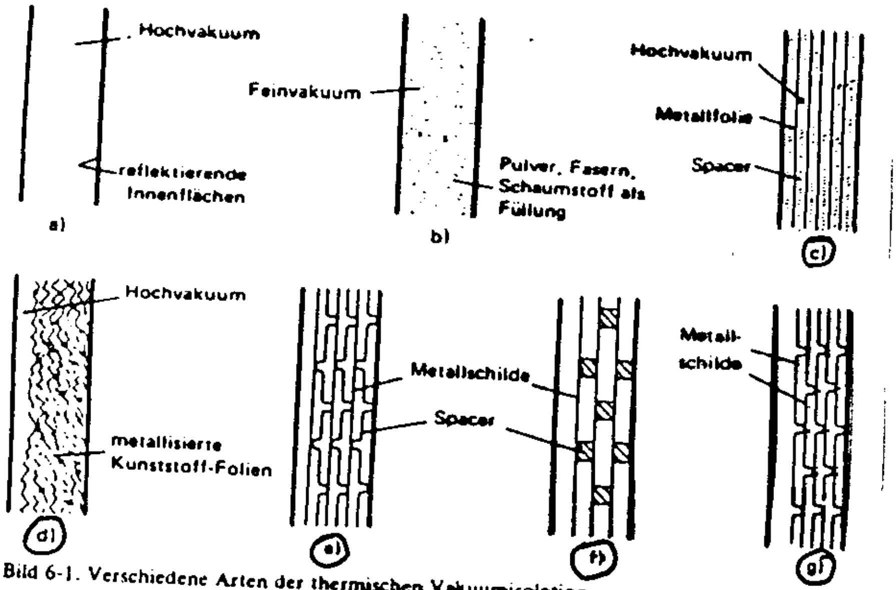


Bild 6-1. Verschiedene Arten der thermischen Vakuumisolation.
a) einfache Vakuumisolation High vacuum insulation
b) evakuierte Pulverisolation evacuated powder insulation
c) bis g) Superisolationen types of super insulation

~~Grundlagen~~ Heat conduction through gases:
~~Wärmeleitung in Gasen~~ ~~bezeichnet man mit~~

Continuum-flow region

$$\bar{\lambda} = \int_{T_1}^{T_2} \lambda \, dT/(T_2 - T_1) \Rightarrow \quad \bar{l} \ll d, \; p > 10^2\,\mathrm{Pa} = 1\,\mathrm{mbar}$$

mean free path ($\bar{l}$), distance between surfaces (d)

(mean value of heat conductivity. In the steady state

(den Mittelwert der Wärmeleitfähigkeit, so ist im stationären Zustand)

$$\frac{\dot{Q}}{A_1 \bar{\lambda}(T_2 - T_1)} = \begin{cases} d^{-1} & \text{(für ebene Flächen,)} \\ (r_1 \ln(r_2/r_1))^{-1} & \text{(für zylindrische Flächen,)} \\ r_2/(r_1(r_2 - r_1)) & \text{(für Kugelflächen)} \end{cases}$$

for plane, $T_2 > T_1$ cylindric, spherical surfaces.

(Bereich der Molekularströmung) Molecular flow region:

$$\dot{Q} = A_1 \, a \, K \, p \, (T_2 - T_1) \quad \text{für } \bar{l} > d \qquad p < 0{,}1\,\mathrm{Pa} = 10^{-3}\,\mathrm{mbar}$$

mit

$$K = (R/8\pi MT)^{1/2}(\varkappa + 1)/(\varkappa - 1) \qquad \varkappa = c_p/c_v$$

und

$$a = [a_1^{-1} + A_1(a_2^{-1} - 1)/A_2]^{-1} = \text{Accommodation Coefficient}$$

Tabelle 6-1. Akkommodationskoeffizient a, Isentropenexponent $\varkappa$, Faktor K und Temperaturen T_1 und T_2 verschiedener Gase.

Gas	T_2 K	T_1 K	a_2	a_1	$\varkappa$	K $\mathrm{W\,m^{-2}\,Pa^{-1}\,K^{-1}}$
N_2	300	80	0,8	1	1,405	1,192
O_2	300	80	0,8	1	1,396	1,137
H_2	300	80	0,3	0,5	1,408	4,417
H_2	80	20	0,5	1	1,63	3,125
^{4}He	20	4	0,6	1	1,67	2,116

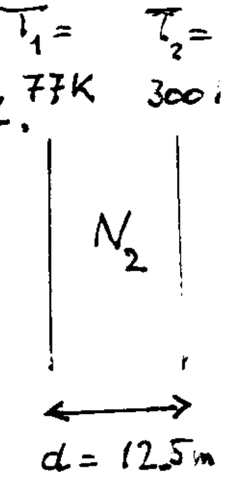
- The thermal heat conductivity on the basis of kinetic theory is given by $\lambda = \frac{1}{3} m \bar{l} n \bar{v} c_v$ for $\bar{l} \ll d$.

m : mass of one molecule, $\bar{l}$: mean free path, n : number of molecules/Volume
$\bar{v}$: mean velocity, c_v spec. heat capacity at constant Vol.

Consider two parallel surfaces, separated by the distance d. Then the heat flow rate by conduction through the gas can be represented by

$$\dot{q} = \frac{\dot{Q}}{A} = \lambda_{eff} \frac{T_2 - T_1}{d}$$

On lowering the pressure in the space between the parallel surfaces the effective thermal conductivity passes three regions:



I <u>Continuum flow region</u>: $\bar{l} \ll d$ (Curve I)
Since $\bar{l} \propto \frac{1}{p}$, λ is pressure independent.
λ has a small temperature dependence. Hence
$\lambda_{eff} = \frac{1}{2}\left(\lambda(T_1) + \lambda(T_2)\right) = 1.8 \times 10^{-2}\ W m^{-1} K^{-1}$
Curve 1 in the next figure.

II <u>Molecular flow region</u> $\bar{l} > d$ (Curve II)

$$\lambda_{eff} = \underset{\overset{\uparrow}{0.83}}{a}\ \underset{\overset{\uparrow}{1.192 \frac{W}{m^2 Pa K}}}{K}\ p = 1.24 \cdot 10^{-2} p$$

$\lambda(T_1) = 0.99 \cdot 10^{-2} \frac{W}{m}$
$\lambda(T_2) = 2.61 \cdot 10^{-2} \frac{W}{m}$
$e_1 = e_2 = 0.04$
$a_1 = 1,\ a_2 = 0.8$
$a = 0.83,\ e_r = 0.02$

The boundary between the regions I x II is given by $\bar{l} = d = 12.5$ mm.
As $\bar{l} p = 6.7$ mm Pa for N_2,
the boundary is at $p = 0.53$ Pa $= 5.3 \cdot 10^{-3}$ mbar,
that is near the upper break in the λ_{eff}-p-curve.

III <u>High vacuum region</u>: $p < 10^{-2}$ Pa $= 10^{-4}$ mbar (Curve III)
The heat transfer by radiation is dominant.

$$\lambda_{eff} = \frac{\dot{Q}_r\, d}{A\,(T_2 - T_1)} = e_r \sigma \left(T_2^4 - T_1^4\right) \frac{d}{T_2 - T_1} \qquad \text{with } \varepsilon_r = 0.023$$

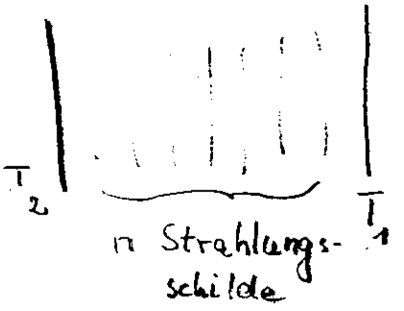
$$\lambda_{eff} = 5.7 \cdot 10^{-4} \frac{W}{mK}$$

Superisolation

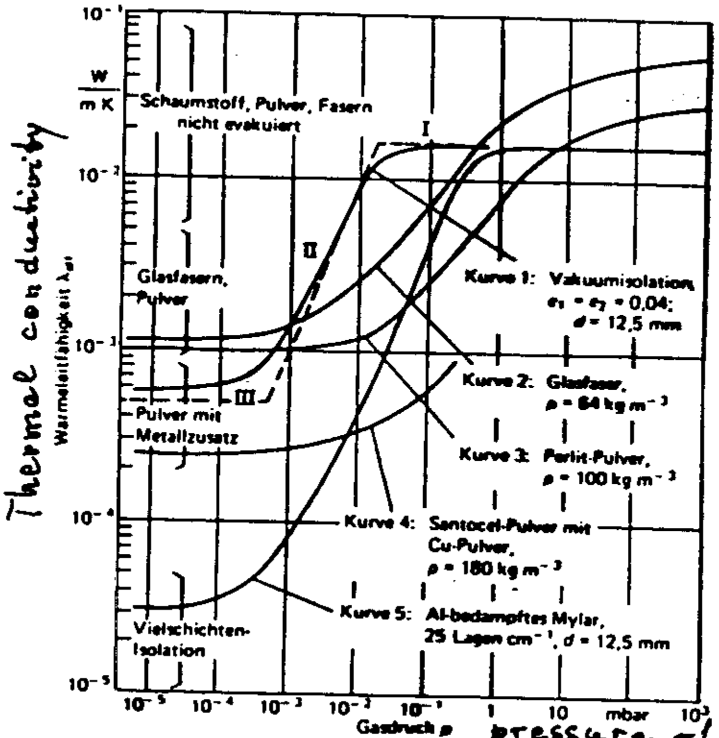
$$e_{tn} = \left\{ \sum_{i=1}^{n+1} A_1 \left[(A_i e_i)^{-1} + (e_{i+1}^{-1} - 1)/A_{i+1} \right] \right\}^{-1}$$

für $A_i = A$, $e_i = e$

$$\dot{Q} = A\, e\, \sigma (T_2^4 - T_1^4)/(2(n+1))$$



Einfluß des Gasdrucks auf die effektive Wärmeleitfähigkeit



See example on the preceding page:

Curve 1: Vacuum Insulation

Curve 5: The same system, but with 30 layers Superinsulation

Bild 6-3. Effektive Wärmeleitfähigkeit in Abhängigkeit vom Druck für verschiedene Isolationen zwischen 300 K und 77 K mit Stickstoff als Füllgas.

Methoden der Wärmeisolation

Isolationen ohne Vakuum

Tabelle 6-4. Eigenschaften von nicht-evakuierten Isoliermaterialien [6-13; 6-14].

Material	Dichte ρ $\mathrm{kg\ m^{-3}}$	Korn- oder Faserdurchmesser mm	Wärmeleitfähigkeit λ_{eff}*) $10^{-2}\ \mathrm{W\ m^{-1}K^{-1}}$
Pulver:			
Perlit	50	0,1 bis 1	2.6
Perlit	210	< 0,1	4,4
Silica Aerogel	80	10^{-4}	1,9
Faserstoffe:			
Glasfaser-Wolle	110	10^{-3}	2,5
Mineralwolle	130 bis 320	10^{-2} bis 10^{-1}	2,9 bis 4,3
vorgeformte Stoffe:			
Schaumglas	170		5,2
Kork	110		3,2
Polystyrolschaumstoff	15		2,4
Polyurethanschaumstoff	49		2,5

*) Diese Werte wurden zwischen 300 K und 90 K und unter Atmosphärendruck gemessen.

- After installing 30 metallized (Al) mylar foils into the vacuum space the heat transfer rate by radiation is reduced by approximately the factor 25. (see curve 5 in the figure of the preceding page.
- On the other hand, the pressure region of the regime II is shifted to the right-hand side by a factor of ~ 30. The reason: The condition "mean free path $\bar{l} \approx$ distance between adjacent surface" is now fulfilled at a 30 times higher pressure.

TABLE A. 13 Thermal conductivity integrals [A17]. Application references, see equation (8.5).

	$\int_4^T \lambda\, dT\,(\mathrm{kW\,m^{-1}})$ kW									$\int_4^T \lambda\, dT\,(\mathrm{W\,m^{-1}})$ W			
Temp. T(K)	Stainless steel:	Aluminium cold drawn		Copper annealed			Copper annealed	Brass	Monel drawn	Plastics			Glass:
	Mean of types 303, 304 316, 347 18/8	commercial 99%	99.99%	electrolytic 99.95%	OFHC 99.95%	high purity 99.999%	Phosph. deox. 99%			Teflon PTFE	Nylon	Plexiglass (perspex)	Mean of pyrex, quartz and borosilicate glass
6	0.00063	0.138	7.35	0.80	0.61	16.6	0.0176	0.0053	0.00123	0.113	0.0321	0.118	0.211
10	0.00293	0.607	28.0	3.32	2.52	63.6	0.0785	0.0229	0.00629	0.44	0.148	0.359	0.681
20	0.0163	2.76	90.7	14.0	11.0	179	0.395	0.112	0.0364	1.64	0.823	1.01	2.0
40	0.0824	9.62	153	40.6	33.8	270	1.64	0.476	0.173	5.08	3.85	3.30	5.86
60	0.198	17.0	174	58.7	49.6	296	3.55	1.04	0.388	9.36	8.59	6.83	11.5
76	0.317	22.0	182	68.6	58.6	307	5.39	1.62	0.592	13.0	13.1	10.1	17.5
80	0.349	23.2	184	70.7	60.6	309	5.89	1.77	0.647	13.9	14.2	11.0	19.4
100	0.528	28.4	190	80.2	70.0	318	8.58	2.65	0.940	18.7	20.4	15.5	29.2
120	0.726	33.0	196	89.1	78.8	327	11.5	3.65	1.26	23.7	26.9	20.0	40.8
140	0.939	37.6	201	97.6	87.4	336	14.6	4.78	1.59	28.7	33.6	24.7	54.2
160	1.17	42.0	206	106	95.6	344	18.0	6.03	1.95	33.8	40.5	29.4	69.4
180	1.41	46.4	211	114	104	352	21.5	7.38	2.32	39.0	47.5	34.2	85.8
200	1.66	50.8	216	122	112	360	25.3	8.83	2.71	44.2	54.5	39.0	103
250	2.34	61.8	227	142	132	380	35.3	12.8	3.73	57.2	72.0	51.0	150
300	3.06	72.8	239	162	152	400	46.1	17.2	4.80	70.2	89.5	63.0	199

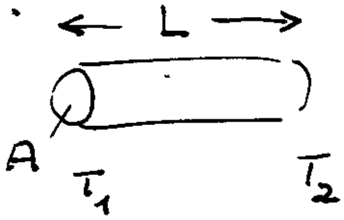
$$\dot{Q}_{\mathrm{solid}} = \frac{A}{L}\int_{T_2}^{T_1} \lambda \mathrm{d}T.$$

$$\int_{T_2}^{T_1} = \int_{4}^{T_1} - \int_{4}^{T_2}$$

Heat transfer through solids

The thermal conduction flow $\dot{Q}$ through a solid of cross-section A under a temp. gradient $\partial T/\partial x$ is given by

$$\dot{Q} = \lambda(T)\, A\, \frac{\partial T}{\partial x} .$$



Thus, if the ends of a solid bar of uniform cross-section A and length L are at temp.^{s} T_1 & T_2

$$\dot{Q} = \frac{A}{L} \int_{T_2}^{T_1} \lambda(T)\, dT \quad , \; T_1 > T_2 .$$

Values for the thermal conductivity integral, for which $\int_{T_2}^{T_1} = \int_4^{T_1} - \int_4^{T_2}$ is valid, are given in the following table.

This table indicates: The conductivity integrals are

- $10^2 .. 10^3$ times larger for high purity Cu than for stainless steel, and
- for stainless steel much larger than for Plastics & glass.

Example: St. Steel tube 2 cm ϕ, 0.3 mm wall thickness
Length 0,1 m, $A = 2\pi \times 10^{-2} \times 3 \times 10^{-4}\, m^2 = 18.8 \cdot 10^{-6}\, m^2$

For 300 → 80 K : $\dot{Q} = \frac{18.8 \cdot 10^{-6}}{0.1} (3.06 - 0{,}348)\, kW = 0.51\, W$

" 80 → 10 K : $\dot{Q} = \frac{18.8\, 10^{-6}}{0.1} (0{,}348 - 0{,}0029)\, kW = 0.068\, W$

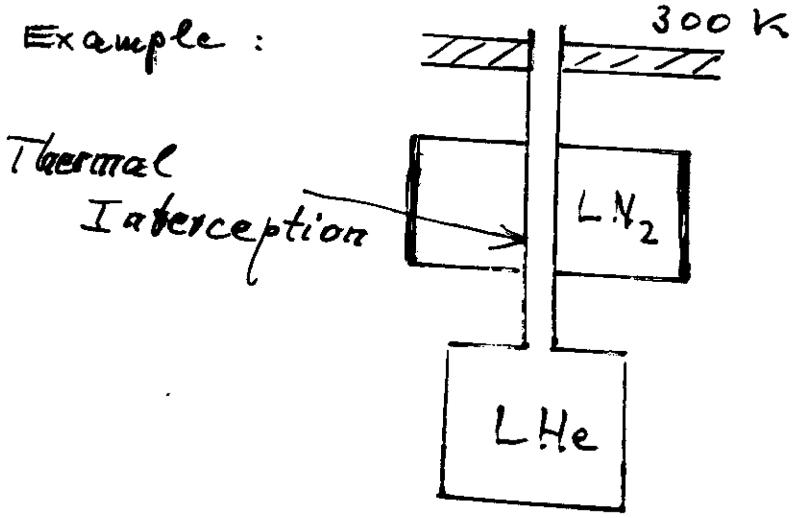
Solid state heat conduction in supports, supply lines etc. must be kept to an adequately low level by the constructional geometry, the choice of materials & their dimensions. This requirement is facilitated by the fact that the thermal conductivity of alloys (18/8 Cr Ni steel, Monel, German silver) suitable for support rods & pipe lines is relatively small and decreases with T.

On the other hand, pure metals (Cu, Al, Ag), because of their high thermal conductivity, even at low temperatures, are used where a good thermal contact is needed with the cold surface, such as in LN_2 cooled baffle or specimen holder.

There are two methods for reducing the heat flow by conduction as follows:

1. Thermal interception: In this case the heat penetrating from room temp. is intercepted by a bath of LN_2, so that the heat conduction to the colder surface is determined only by the temp. difference $(77 - T_c)$ K.

Example :



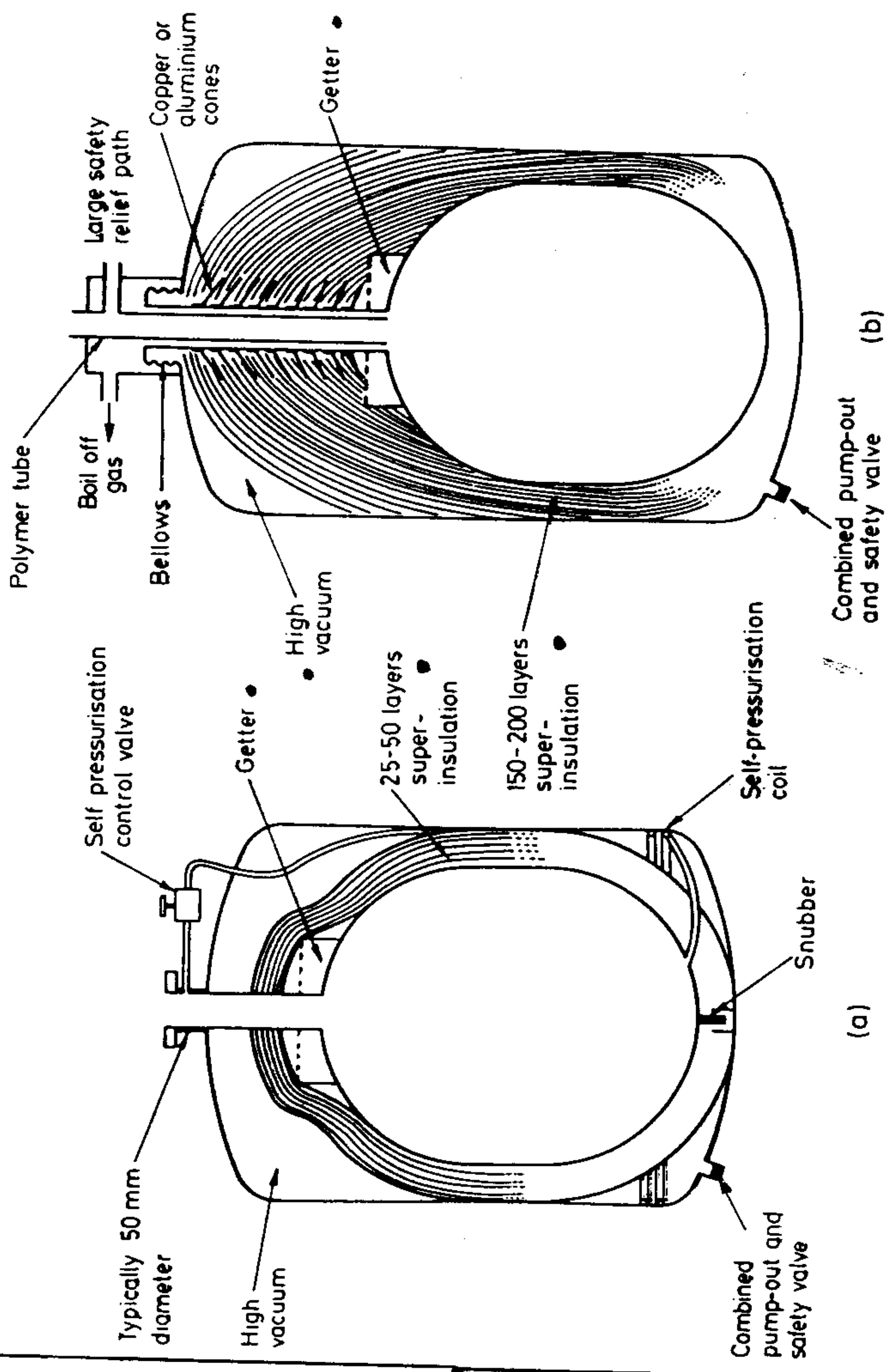


Fig. 4.16 (a) Dewar for storing the higher boiling-point cryogens. (b) Dewar for storing liquid helium. (Courtesy of E. M. Rowe, Wessington Cryogenics Ltd, Washington, England.)

2. Convection cooling : Here the enthalpy of the evaporating refrigerant is used to cool the neck tube of the container or the supports, electrical leads, etc.

Material	Temperature difference K	$(I\ell/A)_{opt}$ 10^6A/m	$(\dot{Q}/I)_{min}$ mW/A
Aluminium, very pure	300 to 4,2	8,0	40
Copper, very pure	300 to 4,2	5,0 to 6,0	42 to 45
Aluminium *	77 to 4,2	26 to 32	8,0
Copper *	77 to 4,2	10 to 40*	8,5 to 9,6

ℓ = length

* normal electrical quality, i.e. $\frac{\rho(4.2K)}{\rho(300K)} \approx 100$ = "resistivity ratio."

Electrical Leads

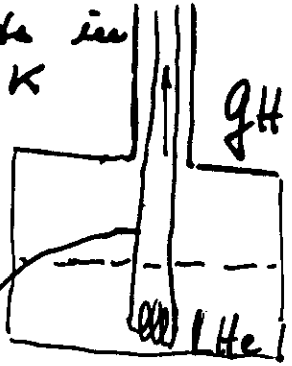
With the development of superconducting magnets it is necessary to carry large currents ($\gtrsim 100$ A) into cryostats, and therefore to optimize the size of current leads. McFee (1959) calculated the optimum dimensions for Cu x Al wires:

1. Assuming no convection cooling by the evaporating He gas, the results in the table are achieved. For Cu and the temp. difference 77 to 4.2 K there is a minimum heat inflow

$$(\dot{Q}/I)_{min} \approx 9\,mW/A \quad at \quad (I\ell/A)_{opt} \approx 10 \times 10^6\,A/m$$

2. Using the convection cooling one finds a minimum heat inflow

$$(\dot{Q}/I)_{min} \approx 1\,mW/A \quad at \quad (I\ell/A)_{opt.} \approx 2.5 \times 10^7\,A/m$$



In this case an electrical lead for 2500 A and 1 m length has a cross-section $A = 1\cdot10^{-4}\,m^2 = 1\,cm^2$ (which is split into many strands), and produces a heat inflow of 2.5 W, which corresponds to an evaporation rate of 0.12 g/s helium.

Thermal energy for cooling surfaces

To cool a body of mass m from T_1 to T_2, thermal energy

$$E_t = m \int_{T_2}^{T_1} c_p(T)\, dT = m\big[\underset{\text{Enthalpy}}{h}(T_1) - h(T_2)\big]$$

must be withdrawn from it.
The primary aim is to achieve e.g. cooling to $T_s = 4.2$ K using the smallest possible amount of LHe.

The mass m_{fl} of refrigerant needed to cool the solid mass m from T_1 to T_2 is essentially dependent on how the cooling process is carried out.

In the <u>worst case</u>, only the evaporation enthalpy l of the refrigerant is utilized. In that case

$$\left(m_{fl}/m\right)_{max} = \frac{\int_{T_s}^{T_1} c_p(T)\, dT}{l_v}.$$

In the <u>best case</u>, the evaporation enthalpy <u>and</u> the cold content of the vapour is utilized, i.e. the enthalpy of the vapour between the initial Temp. T_1 of the solid & the boiling temp. T_s of the refrigerator. In this case

$$\left(m_{fl}/m\right)_{min} = \int_{T_s}^{T_1} \frac{c_p(T)\, dT}{l_v + \int_{T_s}^{T} \underbrace{c_p'(T)}_{\text{spec. heat cap. of vapo}}\, dT'}$$

Jacobs has calculated these equations as a function of the initial Temp. T_1 for Cu, Al & st. steel, and for the refrigerants LHe, LH_2 and LN_2.
The results are listed in the following table.

Refrigerant consumption for cooling metals ($\frac{\text{litre Refrig}}{\text{kg Metal}}$

Refrigerant	Helium		Nitrogen
Final temp. of metal (K)	4.2		77,3
Initial " of metal (K)	300	77	300
Use of:			
Evaporation enthalpy			
Al	64.0	3.20	1.0
st. steel	30.4	1.44	0.53
Cu	28.0 •	2.16 •	0.46
Evaporation and vapour enthalpy			
Al	1.60	0.24	0.64
st. steel	0.80	0.11	0.34
Cu	0.80 •	0.16 •	0.29

- For example: to cool 1 kg Cu from 300 K to 4.2 K, the LHe consumption is 28 l, if only the evaporation enthalpy is utilized, whereas with supplementary utilization of the vapour enthalpy it is only 0.8 l.
- If Cu is previously cooled by LN_2 to 77 K, then these values decrease to 2.16 and 0.16 l resp.
- The strong influence of LN_2 precooling on the LHe-consumption is a consequence of the T^3 law of the specific heat capacity of solids.

To keep the LHe requirement as low as possible, the following points should be noted:

- Thin-walled structures
- Materials of low spec. heat capacity
- Precooling of the LHe container and the specimens to approx. 80 K by heat exchange with LN_2 cooled surfaces and/or by charging a primary cooling coil with LN_2.

References

B.A.Hands,Cryogenic Engineering, Academic Press 1986

H.Frey and R.A.Haefer: Tieftemperatur-Technologie, VDI-Verlag, Düsseldorf 1981

R.A.Haefer: Cryopumping,Theory and Practice, Clarendon Press, Oxford . . 1989

G.K.White: Experimental Techniques in Low-Temperature Physics, Clarendon Press, Oxford 1989

Johnson, V.J., "Properties of Materials at Low Temperature" Pergamon Press, London (1961)

Eldridge, E.A., H.W. Deem "Report on Physical Properties of Metals and Alloys from Cryogenic to elevated Temperatures" ASTM Spec. Techn. Publ. 296, Philadelphia (1961)

Schwartzberg, F.R., S.H. Osgood, R.G. Herzog, M. Knight (Compiler, Air Force Materials Laboratory) "Cryogenic Materials Data Handbook", Martin Marietta Corp., Denver (1970)

Childs, G.E., L.J. Ericks und R.L. Powell "Thermal Conductivity of Solids at Room Temperature and below" Nat. Bur. of Standards, Cryogen. Div. Monograph 131, Boulder (1973)

"Handbook on Materials for Superconducting Machinery: Mechanical, Thermal, Electrical, and Magnetic Properties of Structural Materials" Metals and Ceramics Inf. Center, Batelle, Columbus (1975)

Touloukian, Y.S., et al. "Thermophysical Properties of Matter" Band I-XIII, Plenum Press, New York (1970-1979)

Klipping, I.," Datensammlung zur Kryotechnik" VDI-Bildungswerk (BW 2407), Düsseldorf (1979), in diesem Handbuch

Rosenberg, H.M., "Low Temperature Solid State Physics" Clarendon Press, Oxford (1965)