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IMPROVED VERSION OF THE CERN CONDENSATION CRYOPUMP

by

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Abstract

The condensation cryopumps developed at CERN and described previously have been modified to provide longer operating times between liquid He fillings. The modification consists in protecting the lateral and top surfaces of the He vessel with a shield cooled by the evaporated helium. It is shown that this additional shield reduces the He consumption by a factor ranging from 2 to 12 depending on the He vessel geometry.

Eight pumps of the improved type and of two different sizes have so far been built. They provide operating times of approximately 200 days and 4'500 and 11'000 ℓ/s pumping speed for H_2.

Geneva, December 1978

1. INTRODUCTION

In the last few years liquid He bath cryopumps of various sizes have been built at CERN[1,2]. These pumps, already described in detail elsewhere[3], are all of the same type, here called 'first series'. The characteristics of these pumps, schematically shown in Fig. 1, were primarily dictated by vacuum considerations, namely :

i) the cryosurfaces are silver-plated to minimise the radiation-induced H_2 saturation pressure[4,5]

ii) for the same reason, the liquid N_2 cooled baffle was designed to minimise the transmission of room-temperature radiation[6]

iii) gas desorption from lateral surfaces of the He vessel, due to liquid He level variation, is prevented by a double side wall. The volume enclosed between these two walls is filled with He gas to aid heat transfer during cool-down, and is subsequently evacuated to make the temperature of the outer wall independent of the liquid He level.

The pumping speed per cm^2 of baffled pumping surface is about 9 ℓ/s for H_2 and 3 ℓ/s for N_2. The two sizes of pumps provide 4'500 and 27'000 ℓ/s pumping speed for H_2. Their capacities are 10 and 75 ℓ of liquid helium and endurances at 4.2 K, are 40 and 80 days respectively. Endurance is about 20% lower when operating at 2.3 K.

The liquid He consumption of the first series pumps is mainly due to radiation emitted from liquid N_2 cooled surfaces and absorbed by the pumping surface and by the protecting wall in amounts proportional to their surface areas. In a He container with a diameter equal to the height, for example, the area of the pumping surface is only about 20% of that of the protecting wall, which is therefore responsible for more than 80% of the total losses. It is unfortunate that these losses mainly originate on surfaces which have no pumping function. On the other hand, only a small fraction of the cooling capacity of the escaping He gas is used, mostly for removing the heat conducted along the neck of the He vessel.

The improvement adopted in the second series of pumps is to protect the outer cylindrical wall of the He vessel with a shield fixed to the neck tube between He and N_2 temperatures and cooled by the escaping gas. This required some design changes as shown in Fig. 2. The volume enclosed by the two walls of the liquid He container is now filled with Ne gas and sealed. The Ne has the function of a thermal switch. Above about 20 K it provides thermal contact between the walls, below this temperature when, in any case, the thermal capacity of the metals is negligible, the Ne condenses leaving a vacuum which provides the desired thermal insulation.

2. ESTIMATION OF THE CRYOGENIC PERFORMANCE OF SERIES TWO CRYOPUMPS

The following notation will be used :

R	radius of the helium vessel
h	height of the helium vessel
d	distance between the helium vessel and the shield
S	real area of the pumping surface
α	ratio of πR^2 to the real area of the pumping surface
$y =$	$\frac{R + 2h}{R}$
$\delta =$	$\frac{d}{R}$
T_H	temperature of the liquid helium vessel
T_s	temperature of the shield
T_N	temperature of the nitrogen bath
σ	Stefan-Boltzmann constant
c_p	specific heat of gaseous helium
ε	radiation exchange coefficient
$\dot{m}$	helium mass flow rate through the neck of the pump
λ	vaporisation heat of liquid helium
ρ_L	density of liquid helium
ρ_G	density of helium gas in the helium vessel
λ'	apparent vaporisation heat of liquid helium, $\lambda' = \lambda \frac{\rho_L}{\rho_L - \rho_G}$
Q	consumption of liquid helium
L	endurance without liquid He refilling

To simplify the mathematical treatment of the problem, a few approximations will be made, namely :

i) the radius R of the helium vessel and that of the lateral cylindrical shield are equal,

ii) T_s is not affected by the 300 K radiation transmitted through the baffle.

iii) $T_H^4 \ll T_s^4$,

iv) the temperature of the shield is uniform.

It is also assumed that the heat exchange between the escaping He gas and the neck of the pump is perfect and that the heat conduction along the neck to and from the shield is negligible. For the validity of these last two assumptions, see, for example, reference 7.

2.1 Equilibrium Temperature of the Lateral Shield

Under these assumptions and approximations the heat balance of the shield is given by the equation :

$$\sigma\varepsilon(\pi R^2 + 2\pi Rh)(T_N^4 - 2T_s^4) + 2\pi Rd\sigma(T_N^4 - T_s^4) = \dot{m}c_p(T_s - T_H) \tag{1}$$

In this equation the first term represents the radiating power exchange between the shield and the N_2 and He vessels. The second term is the power radiating from the baffle and entering the gap d (in this case ε is unity because both the baffle and the gap are "black"). The last term represents the cooling power of the escaping He gas, the mass flow rate of which is approximated by

$$\dot{m} = \sigma\varepsilon \; \frac{\pi R^2}{\alpha\lambda'} T_N^4 + \frac{\pi R^2 + 2\pi Rh}{\lambda'} T_s^4 \tag{2}$$

In equ. (2) the first term represents the helium evaporation due to radiation from the black baffle at temperature T_N and the second term is the radiation from the shield at T_s. Combining equs. (1) and (2) :

$$y(T_N^4 - 2T_s^4) + \frac{2\delta}{\varepsilon}(T_N^4 - T_s^4) - \frac{c_p}{\lambda'} \; \frac{T_N^4}{\alpha} + yT_s^4 \; (T_s - T_H) = 0 \tag{3}$$

Fig. (3) shows the solution of (3) for T_s as a function of h/R with various combinations of α and δ as parameter. These solutions use $T_N = 77$ K, $T_H = 4.2$ K, $\varepsilon = 1.26 \times 10^{-2}$, $c_p/\lambda' = 0.23$. It can be seen that α affects T_s much more than δ, for which a value of 10^{-2} could probably be fixed for all pump sizes.
The two particular cases of $h < R$ and $h >> R$ are worthy of discussion.

In the first case T_s^4 is much smaller than T_N^4 and all the corresponding terms can be neglected. Equ. (3) simply becomes

$$T_s = \frac{\alpha\lambda'}{c_p}\left(y + \frac{2\delta}{\varepsilon}\right) + T_H \tag{4}$$

T_s is independent of T_N, because any variation of T_N now affects the power absorbed by the shield and by the pumping surface equally. Consequently, T_s, which is determined by the ratio of these two quantities, does not change.

When h is much larger than R, equ. (3) becomes

$$\frac{c_p}{\lambda'} T_s^4 (T_s - T_H) + 2T_s^4 - T_N^4 = 0 \tag{5}$$

In this case α and δ no longer appear because the radiating power entering the gap d or absorbed by the pumping surface is now negligible compared with that absorbed by the other surfaces of the He vessel. This case also represents the situation of a closed shield completely surrounding the He vessel.

Putting T_N = 77 K and T_H = 4.2 K in equ. (5) gives T_s = 42 K. All the curves of Fig. 3 are asymptotic to this value. In contrast with the previous case, T_s now only depends on T_N (for a given T_H). For example, at T_N = 64 K, T_s = 36 K.

2.2 Liquid Helium Consumption

The liquid helium evaporation is almost entirely due to radiation absorbed by the surfaces of the He vessel. The radiation falling on the pumping surface is either produced by the baffle or transmitted through the baffle from room temperature walls. Only 2×10^{-4} of this 300 K radiation is transmitted^6) by the type of baffle used. This is only about 4% of the radiation produced by the baffle itself when operating at 77 K. The net heat flux to a silver-plated surface immersed in a black cavity at 77 K is 2.9×10^{-3} mW/cm^2 or 9.6×10^{-2} cm^3 LHe per day and cm^2. The spread of the experimental data is ± 11%^6). For the lateral and top surfaces of the He container which face the shield these losses are $(T_s/77)^4$ times smaller. The total boil off rate, expressed in units of cm^3 LHe/day is therefore

$$Q = 0.1\ \alpha^{-1}\ \pi R^2 + 9.6 \times 10^{-2}\ (T_s/77)^4\ (\pi R^2 + 2\pi R h) \tag{6}$$

(R and h in cm), in which the two terms on the right hand side represent respectively the heat load on the pumping surface (corrected for room temperature radiation and effective surface area) and on the shielded surfaces of the He vessel. By dividing by πR^2 one obtains

$$Q/\pi R^2 = 9.6 \times 10^{-2}\ (T_s/77)^4\ (1 + 2h/R) + 0.1\ \alpha^{-1} \tag{7}$$

which represents the LHe consumption, in cm^3, per day and per cm^2 of pumping surface. When plotted versus h/R and for given δ and α, this quantity is represented by a curve crossing the vertical axis at about $0.1\ \alpha^{-1}$ and approaching asympotically a straight line. A family of these curves, obtained for the same values of δ and α as in Fig. 3, is shown in Fig. 4. It is interesting to note that for h/R < 1.5 the He consumption is simply given by

$$Q = 0.1\ S\ \text{cm}^3\ \text{LHe/day} \tag{8}$$

where S is in cm^2.

For $T_N = 64$ K, as obtainable for instance by pumping over the N_2 bath just above its triple point, and for $h/R < 1.5$, the radiating power from T_N becomes 2.3 times lower whilst that from 300 K and from the shield do not change. The radiation losses are therefore reduced by about 50%. It is, however, necessary to recall that the conditions for negligible thermal conduction along the neck7) are now more stringent because, for the same temperature difference $T_s - T_H$, Q is reduced. The ratio of the neck cross-sectional area to the neck length must therefore be reduced. Similar precautions should also be adopted for the upper part of the neck which connects T_s to T_N, although in this case the situation is less critical because T_N is now lower.

2.3 Operational Endurance without Liquid He Refilling

The endurance, L, of the pump is the ratio of the liquid He volume to the He consumption. When expressing L/R as a function of h/R one obtains

$$L/R = \frac{h/R}{0.1\ \alpha^{-1} + 9.6 \times 10^{-2}\ (T_s/77)^4\ (1 + 2h/R)} \tag{9}$$

The corresponding family of curves, for the values of the parameters already used for Figures 3 and 4, is shown in Figure 5. For $h/R < 1.5$, equ. (9) simply becomes

$$L = 10\alpha h \tag{10}$$

with L in days and h in cm. The endurance is independent of R because both the He consumption and volume are proportional to R^2. Consequently, all pumps with the same h value (and α) will have equal L. At the other extreme, one obtains

$$\lim_{h/R \to \infty} L = 62\ R \tag{11}$$

which is the value asympotically approached by all curves of Fig. 5.

3. RESULTS

3.1 Preliminary Measurements and Measuring Apparatus

Preliminary tests were carried out on a cryostat which provided easy access to the inner and new part of the pump. The liquid helium container, the shield and the part of the neck which operates at temperatures below 78 K were enclosed in a stainless steel container which was immersed in a large N_2 dewar open at the top. The function of the container was to replace the N_2 container and the baffles of a cryopump in such a way that only a single weld had to be cut for access to the essential part of the pump. With this cryostat we checked

i) the heat exchange between the He gas and the neck of the pump,

ii) the geometry of neck required to make the heat conduction to and from the shield negligible,

iii) the temperature of the shield and its homogeneity,

iv) the consumption of liquid He when operating the pump at 4.2 and 2.3 K for various values of α, and

v) the cooling time of the shield and the transient additional He consumption.

This information was derived from the measured temperatures at various points of the shield and from He evaporation rates. Temperatures were measured by means of gold + 0.07% atomic iron versus chromel thermocouples to within ± 1 K. Three such thermocouples were used to detect the presence of temperature gradients along the shield. The rate of the He evaporation was obtained to within ± 5% by circulating the escaping gas through a homogeneously heated tube and by measuring the temperature rise. For both temperature and flow rate measurements, a careful stabilisation of the pressure over the He bath was necessary (maximum accepted He pressure variation 50 Pa per day).

3.2 The Pumps

In order to avoid confusion the cryopumps of the first and second series will be designated by the numbers 1 and 2 respectively, followed by R (radius of the pumping surface, as in equation (1)), expressed in cm.
According to this notation, the pumps of the first series become 1 R 12.5 and 1 R 31 (models E and D in reference 3 respectively), whilst those of the second series are 2 R 13 and 2 R 20. Six units of model 2 R 13 and two units of model 2 R 20 have been built to date. Their dimensions are given in Table 1.

3.2.1 The Shield

Shields must be structurally rigid because even minor deformations could lead to contact with the He vessel. They were made of stainless steel, 0.5 mm thick for the cylindrical part and 1.5 mm thick for the top cover in both pump models. The outer surfaces of the shield are plated with about 20 μm of silver to minimise the absorption of radiation and to provide the required thermal conductivity. A thick layer of copper (about 0.2 mm) was deposited electrolytically on the neck of the shield between the top cover and the connection to the neck of the pump for the same reason (see Fig. 2). The inner surfaces of the shields are blackened (as are the baffles, see ref. 3 and 5) to ensure that only a small fraction of the thermal radiation entering the gap is absorbed on the walls of the He container.

Precise temperature measurements in equilibrium conditions were only carried out for two of the 2 R 13 pumps. The T_s values of 28 K and 29 K measured with $T_H = 4.2$ K, agree well with the value of 27 K obtained from equation (3). In this case, α is very close to 1 and $\delta = 8 \times 10^{-3}$.

3.2.2 The Neck

The design of the neck represents a compromise between thermal conductivity and mechanical strength. To improve the latter, Hastalloy C was used instead of stainless steel. The neck diameter of both pump models is 10 mm and the neck lengths between the shield and the He and N_2 vessels are 100 and 150 mm respectively. The wall thickness is 0.2 mm for the 2 R 13 pumps and 0.5 mm for the 2 R 20 pumps. According to ref. 7, for these dimensions the heat conduction along the necks of the pumps is negligible. A 9 mm diameter steel rod is inserted in the neck to prevent it from bending during transport and installation.

3.2.3 Baffles and Liquid Nitrogen Consumption

The baffles used for the pumps of the second series are blackened with a paint providing 90% absorptivity for 300 K radiation and have a chevron angle of 120° with 0.2 overlap. The baffle transmissivities for molecules and radiation are then 0.21 and 2×10^{-4} respectively$^{5)}$.

The baffles are normally bolted to the N_2 container and in this case they reach equilibrium temperature (about 81 K) four hours after N_2 filling. In two of the 2 R 13 pumps the baffles were welded to the N_2 container, and in this case an equilibrium temperature of about 79 K was reached in only half an hour.

10^{-8} Pa in 5 minutes, it fell below 10^{-9} Pa after 3 hours and eventually reached $\simeq 10^{-10}$ Pa after 24 hours (all pressures measured at room temperature and N_2 equivalent). These results are practically the same as those obtained with the pumps of first series under similar circumstances. The temperature of the shield was then lowered rapidly to about 5 K by pumping on the He bath. Any significant contribution to the equilibrium pressure due to H_2 released from the shield should then be suppressed. The observed pressure variation was smaller than 10^{-11} Pa. Pumping over the He bath was then stopped and both the shield temperature and the He bath pressure allowed to increase. After about 2 days the He temperature was still below 2.3 K, T_s was slightly below 40 K, and the H_2 pressure again $\simeq 10^{-10}$ Pa. At T_s of 40 K, a sharp pressure increase was noted. This is consistent with previous observations that macroscopic pumping of H_2 begins at temperatures as high as 40-45 K$^{5)}$. One can conclude that any T_s variation in the range 10 to 40 K has no effect on the H_2 pressure at least for quantities of H_2 of the order of that pumped in this experiment.

4. CONCLUSIONS

With the pumps of the second series the consumption of liquid He has been reduced by a factor ranging from 2 to 12. The two extremes correspond to values of the height of the He vessel tending to zero and infinity respectively. For vessels of the usual shape (height approximately equal to diameter), the improvement factor is about 5. This improvement has made possible the construction of pumps with an operating time between liquid He fillings of the order of 200 days at 4.2 K and vacuum below about 10^{-6} Pa. An additional increase of a factor two in the endurance should be possible by cooling the baffles to about 64 K. The improved performance has been obtained without deteriorating the good vacuum performance already achieved or significantly increasing the mechanical complexity of the pumps.

5. ACKNOWLEDGEMENTS

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Fig. 1

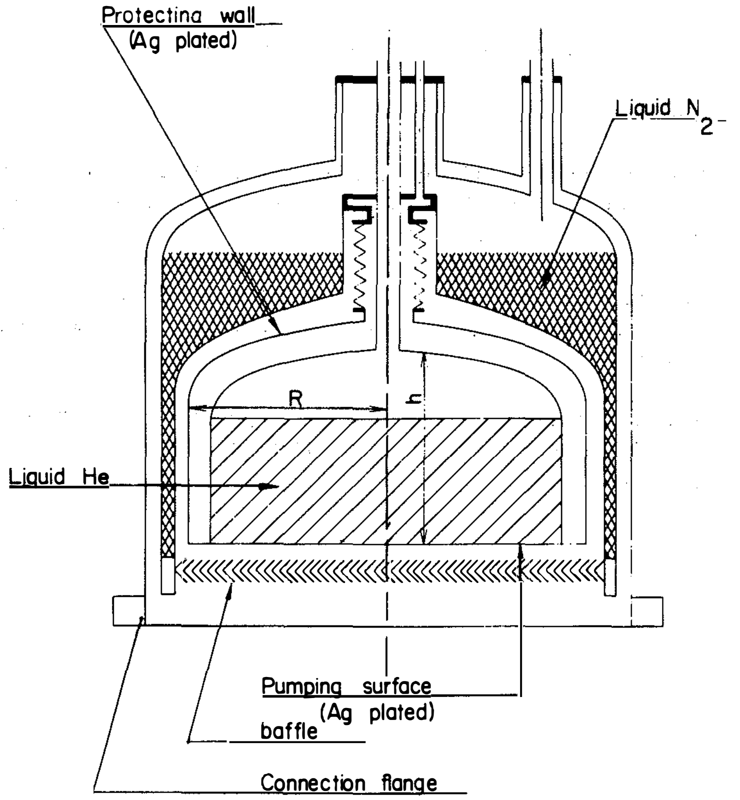
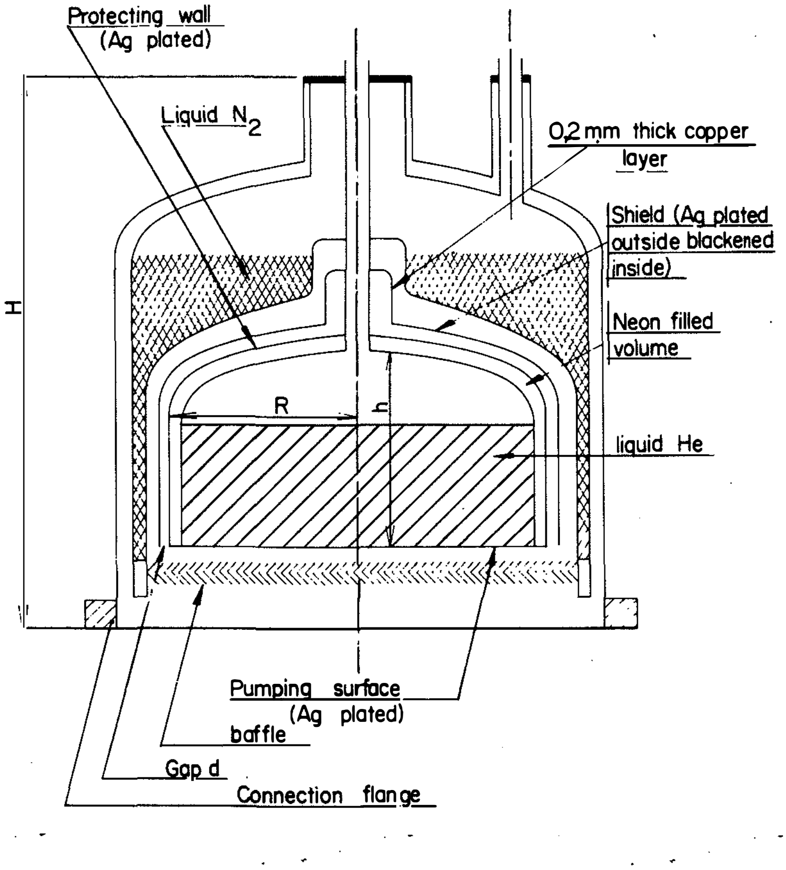

Protecting wall
(Ag plated)
Liquid N_2
R
h
Liquid He
Pumping surface
(Ag plated)
baffle
Connection flange

Fig. 2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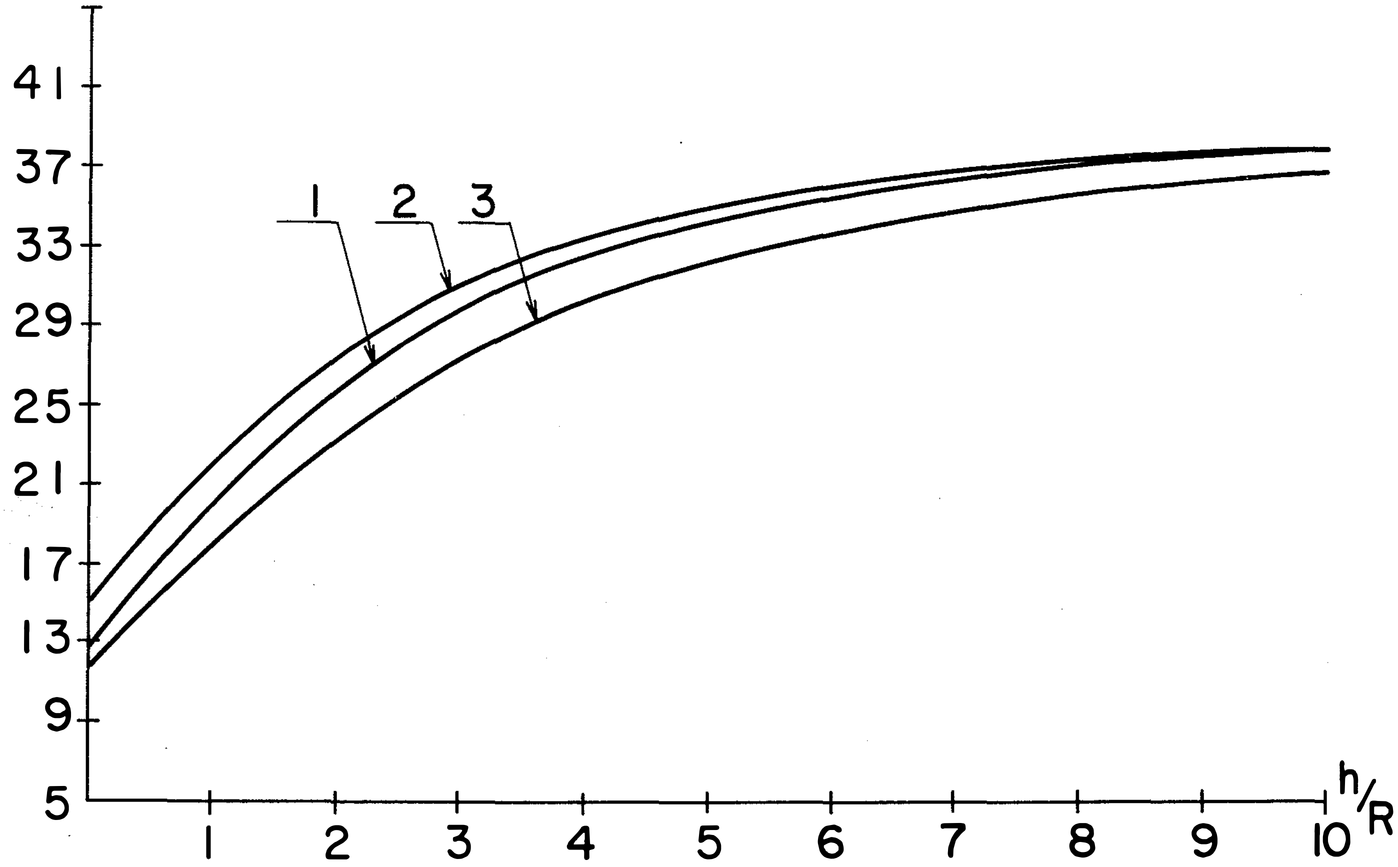
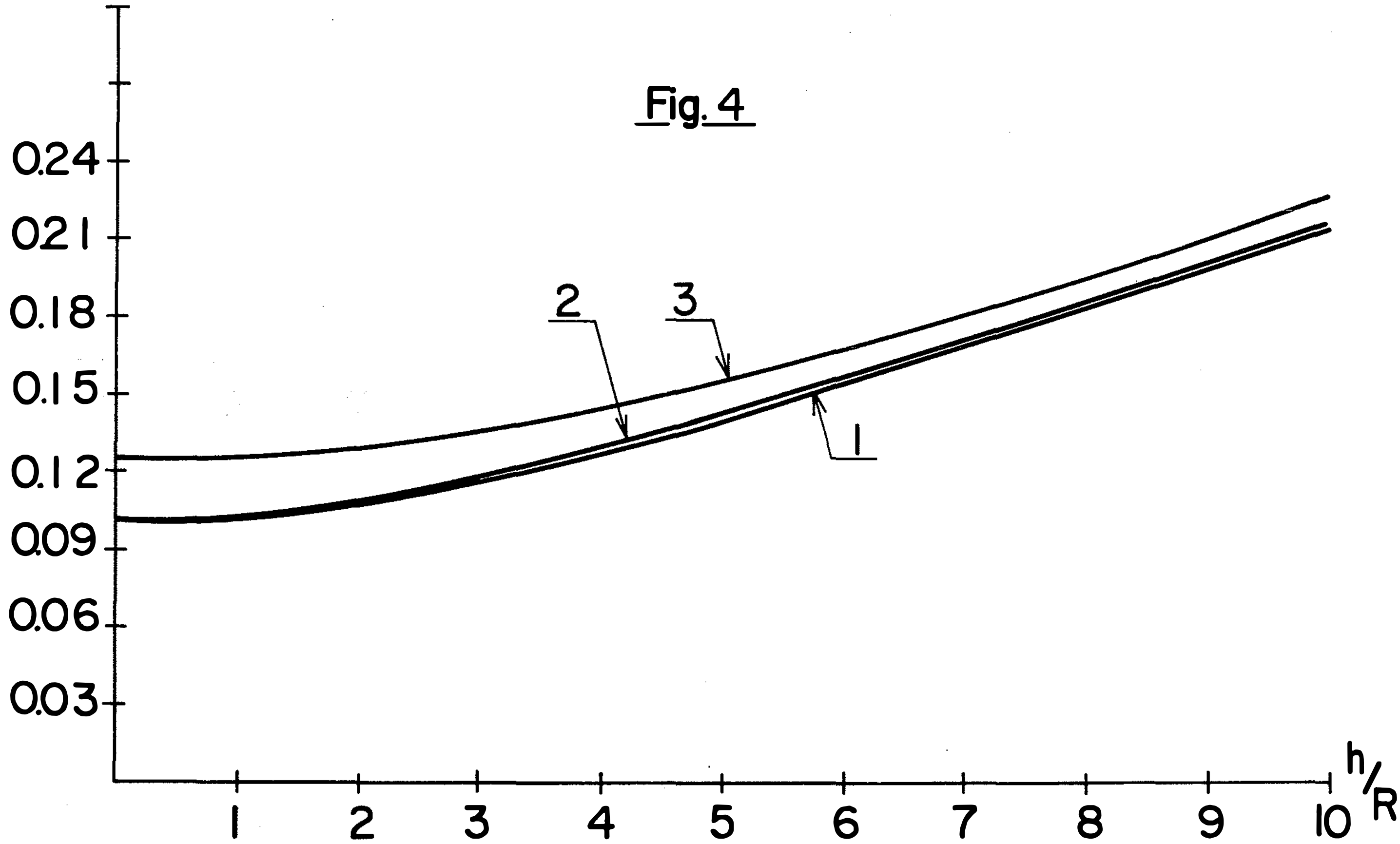
(Ag plated)
Liquid N_2
0,2 mm thick copper
layer
Shield (Ag plated
outside blackened
inside)
Neon filled
volume
H
R
h
liquid He
Pumping surface
(Ag plated)
baffle
Gap d
Connection flange

Fig. 3



Ts (K)
41
37
33
29
25
21
17
13
9
5
1
2
3
1
2
3
4
5
6
7
8
9
10
h/R

Fig. 4



Q / πR² (cm/day)
0.24
0.21
0.18
0.15
0.12
0.09
0.06
0.03
2
3
1
1
2
3
4
5
6
7
8
9
10
h/R

Fig. 5