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THE OPTIMIZATION OF A TUBULAR CONDENSATION CRYOPUMP FOR PRESSURES BELOW 10^{-13} TORR*

by

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Abstract

Over the last few years a condensation cryopump was developed at CERN and successfully applied to one crossing region of the Intersecting Storage Rings for protons. Pressures in the 10^{-13} torr range were achieved. The major limitation of this pump is that the H_2 degassing from the 300 K walls of the pump prevents the achievement of pressures below 10^{-13} torr, even though the degassing rate of the stainless steel is 2×10^{-13} torr ℓ/cm^{2}sec. Herein a cryopump design of tubular geometry is presented, which incorporates in its vacuum system only a very small fraction of ambient temperature walls, greatly reducing the previous limitation. Furthermore, the total amount of the 300 K radiation reaching the cold baffles is reduced by about two orders of magnitude. This has the double advantage that the baffles can be cooled at lower temperatures and can be allowed to be more "transparent" to radiation and hence to molecules. The new model has been entirely optimised both for molecular and radiation transmission by a Monte Carlo method. It is designed to have a pumping speed of 3000 ℓ s^{-1} for H_2 at the two entrances, an axial conductance providing a pressure drop across the pump of a factor of ten and a limit pressure in the 10^{-14} torr range.

Geneva, 25th January 1974

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*Paper submitted to the 6th International Vacuum Congress to be held in Kyoto, Japan, 24-29 March 1974.

1. INTRODUCTION

Extremely low pressures are required in the intersection regions of the ISR at CERN in order to reduce the spurious events due to the interaction of the proton beams with residual gas molecules. Although the initially desired pressure was 10^{-11} torr or below, a pressure in the 10^{-13} torr range has been achieved in a particular intersection by means of liquid helium cooled cryopumps1). However, lower pressures could be desired for particular physics experiments. We have therefore designed a cryopump model which is able to produce and maintain pressures below 10^{-13} torr.

2. DESIGN AND LIMITATION OF THE EXISTING CRYOPUMP

Figure 1 shows the design of the cryopump that has already been applied to an intersection region1)2). It consists basically of a liquid He container, surrounded by a liquid nitrogen tank to which a baffle of chevron type is connected.

The limit pressure of a cryopump is defined here as the hydrogen pressure in the pump after its saturation with H_2. It is given by the sum of the hydrogen pressure Q/S due to the degassing from the walls of the pump and of the H_2 saturated vapour pressure p_{sat}:

$$p_{lim} = \frac{Q}{S} + p_{sat}, \qquad (1)$$

where Q is the degassing rate and S the pumping speed. The latter term, which in principle only depends on the temperature of the condensing surface, was found to be a function of the intensity and of the spectral distribution of the thermal radiation reaching the condensing surface and of the nature of the condensing surface itself1)2)3).

The condensing surface at T = 2.3 K is constituted of a few monolayers of N_2, condensed on a silver plated surface, because this is the combination yielding the lowest hydrogen saturated vapour pressure for a given radiation load among all the combinations which have so far been tested. In this case, hydrogen saturation pressures of about 10^{-13} torr have been measured if the 300 K radiation transmission probability through the cold baffles is lower than 10^{-3} and the baffle temperature is about 80 K.*) Lower pressures can be achieved by reducing the temperature of the baffles to below 80 K; pressures of 3×10^{-14} torr and 1×10^{-14} torr can be achieved for instance for baffle temperatures of 63 K and 50 K respectively.

However, these features are useless if the degassing term Q/S is not sufficiently low. When the pump is operating, the dominant source of hydrogen is its outer wall which remains at ambient temperature. For the cryopump model as shown in Figure 1 and for a stainless steel of a given degassing rate Q, the degassing term in Eqn. (1) is scarcely influenced by the choice of the pump's dimensions; it is equal to about 10^{-13} torr for a steel with $Q = 2 \times 10^{-13}$ torr ℓ/cm^2sec which as far as we know characterizes the best steel that is available in industrial quantities. The existing cryopump therefore suffers from an intrinsic limitation which depends on the steel used, preventing us so far from reaching limit pressures of below 10^{-13} torr.

3. THE NEW CRYOPUMP MODEL

In order to overcome this limitation, we have designed the cryopump shown in Figure 2. Whilst the old design could be defined as an "appendix" cryopump, the new one surrounds a part of the vacuum completely. This feature implies as the main consequence that the major part of the walls at ambient temperature are separated from the main vacuum system by means of two bellows (see Figure 2), thus reducing the above discussed limitation by an order of magnitude. Furthermore, the tubular geometry greatly reduces the amount of room temperature radiation reaching the cold baffles and increases the transparency for molecules; at the same time, the cooling power needed for the radiation screens is reduced. Finally, the two tubular screens, blackened inside with a special paint that provides

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*) All the pressures which are reported here are intended to be measured at 300 K and in terms of nitrogen equivalent.

a reflectivity of less than 10% for thermal radiation, and directly cooled by liquid nitrogen, absorbs more than 90% of the radiation that enters from both apertures[4)]. Consequently the thermal contact between the chevron baffle and the liquid nitrogen container becomes much less problematic.

We have preserved a double wall geometry for the liquid helium container, in order to avoid desorption of pumped gases caused by the decreasing liquid helium level. The enclosed volume is filled with neon and sealed off. The neon gas provides the thermal contact between the two walls during the precooling down to approximately 15 K, as well as the required thermal insulation at the operation temperature of 2.3 K. We have also introduced a screen between the liquid helium tank and the liquid nitrogen container; its function is to reduce the radiation exchange between them.

In order to optimize the geometry of the pump with respect to molecular and thermal radiation transmission, we have written a Monte Carlo computer program, since the Monte Carlo method has already been successfully applied to similar problems[5)]. Subsequently, the capacity of the liquid helium container has been calculated in order to provide the required autonomy for the operation in the ISR, which is about four weeks at the operation temperature of 2.3 K, corresponding to some 40 days at 4.2 K.

4. THE MONTE CARLO OPTIMIZATION

It has been assumed for the optimization that both molecules and photons enter the cryopump with uniform density starting from the cross-section plane at the end of the baffle, see Figure 2. Furthermore, we have presupposed that the molecules enter the pump with cosine angular distribution and that they are reflected diffusely when interacting with the chevron, whereas photons are assumed to enter with isotropic angular distribution, and to be specularly reflected. These assumptions are not entirely justified due to the beaming effect of the tubular screen[6)]; however, since we have fixed its diameter at 160 mm and its length at 300 mm for practical reasons, the error caused by these suppositions is negligible.

The trajectories of each single molecule or photon are then calculated one by one until it impinges either onto the cryosurface, is transmitted to one of the apertures or is absorbed by the chevron surface. We consider the cryosurface to be the only pumping surface, thus the sticking coefficient of all other walls is assumed to be zero. In order to achieve reasonable small statistical errors, the trajectories for at least 4000 molecules and at least 15000 photons have been calculated for each single set of pump parameters.

Besides the dimensions of the tubular screens, the diameter of the cryosurface $D_c = 300$ mm has been fixed prior to optimization. All other parameters, i.e. the length of the cryosurface cylinder L_c, the length of the chevron legs ℓ, the chevron's inclination angle α, the chevron fold angle β and the number of chevrons in the baffle n, have been varied in order to find the best design, see Figure 3. At the end of the optimization, i.e. after the design with the highest molecular transmission and a minimum of transparency for light has been found, the latter were calculated as a function of the baffle's reflectivity R in order to find the maximum reflectivity that can be afforded.

Obviously, the optimization of the new design with all parameters as given above is very complex, hence our procedure was somewhat arbitrary. We started with a set of parameters which would have been chosen without using the Monte Carlo method: $L_c = 700$ mm, $n = 36$, $R = 0.1$ and with equilateral chevrons. With these parameters, the molecular and light transmissivities have been calculated as a function of the chevron's inclination angle, see Figures 4 and 5. The highest baffle efficiency was obtained for $\alpha = 55^{o}$. With this value the optimization was continued with respect to all other parameters and so forth until the optimal design was found. As the result, we found a baffle composed of 32 isosceles chevrons with $\alpha = 55^{o}$, $\beta = 70^{o}$ and $\ell = 36$ mm, as well as $L_c = 700$ mm for the cryosurface cylinder, together with the transmission probabilities for molecules $T_m = 0.65 \pm 0.015$, and for thermal radiation $T_p = (4 \pm 1.5) \times 10^{-4}$ for a baffle reflectivity of $R = 0.1$, provided by a special paint. Taking into account the effect of the tubular screens and the small entrance apertures, this figure yields a 300 K radiation load which is negligible compared with the radiation emitted by the cold baffle.

For these parameters, we obtain a pumping speed of S = 3000 ± 100 ℓ/sec at each of the two entrance apertures for hydrogen and a molecular conductance across the entire pump of 320 ± 20 ℓ/sec. This latter value is considerably lower than is expected for a plain cylindrical tube of the same dimensions which is about 1300 ℓ/sec. It gives rise to a pressure drop across the pump of about one order of magnitude, which is another important advantage of the circular design, besides a pressure limit in the 10^{-14} torr range.

5. CRYOGENIC CONSIDERATIONS

With the optimal value L_c for the cryosurface length (see Figure 2), the lifetime of a liquid helium filling varies with the geometry and the dimensions of the cross section of the He container. The geometry as shown in Figure 2 has been chosen for practical reasons: the width of the pump has to be as small as possible. The lifetime becomes thus a function of the helium tank height h for a given screen temperature.

Since we do not yet have any experience about the use of an intermediate screen, we have chosen the tank height h to provide the required lifetime of 40 days at 4.2 K even without the application of this screen for a baffle temperature of 78 K.

In this situation, the liquid helium consumption can be calculated from:

$$q = \varepsilon A, \tag{2}$$

where A is the total surface area of the silver plated helium container in cm^2 and $\varepsilon = 8.6 \times 10^{-2}$ cm/day[2]. When the baffle temperature is reduced to 63 K or 50 K, ε will become 2.3 or 5.9 times smaller, respectively, according to Stefan-Boltzmann's law. We have assumed for any one of these situations that the effect of the intermediate screen is to halve the amount of thermal radiation absorbed by the surfaces that it protects. Figure 6 shows this dependence for three different temperatures as the parameters: 78 K, 63 K and 50 K.

We have chosen h = 700 mm, thus the helium capacity is about 100 ℓ. Since the calculated total power absorbed by the liquid nitrogen container, which is also silver plated at its outside, is about 50 W, the liquid nitrogen must be refilled every five days at an operation temperature of the baffles of 78 K.

6. CONCLUSIONS

The new cryopump design, which is presented in this paper, is characterized by a limit pressure in the 10^{-14} torr range. Its geometrical features provide a pumping speed of about 3000 ℓ/sec at each of the two entrance apertures, and a high trapping efficiency for the entering molecules. It is designed for those applications where the part of the vacuum system, in which low pressures must be achieved, is conductance limited or where a good differential pumping is essential. However, in order to profit from its extremely low limit pressure, the degassing rate of the materials constituting the vacuum chamber has to be extremely low. This imposes appropriate treatments and choice of special materials. In particular, the application of the new pump is advantageous where the vacuum chamber is cold, as could be, for instance, the case in storage rings which operate with superconducting magnets.

References

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Figure captions

Figure 1	The cryopump developed at CERN as it was applied to the Intersecting Storage Rings.
Figure 2	The design of the new cryopump.
Figure 3	Cross section of the baffle with the parameters that have been optimized by the Monte Carlo method.
Figure 4	Photon transmission through the baffle to the cryosurface as a function of the chevron's inclination angle α with the parameters $n = 36$, $L_c = 700$ mm, $R = 0.1$ and for equilateral chevrons.
Figure 5	Molecular transmission for the parameters as given in Figure 4. Curve a represents the transmission to the cryosurface, b and c denote the probabilities that a molecule is returning to the entrance aperture and going to the opposite aperture, respectively.
Figure 6	The lifetime of the tubular cryopump as a function of the height h of the liquid helium container, see Figure 2. The dashed line represents the minimum value required for the Intersecting Storage Rings. The dot represents the lifetime as calculated without the intermediate screen; this result has been used to fix the tank height indicated by the arrow.

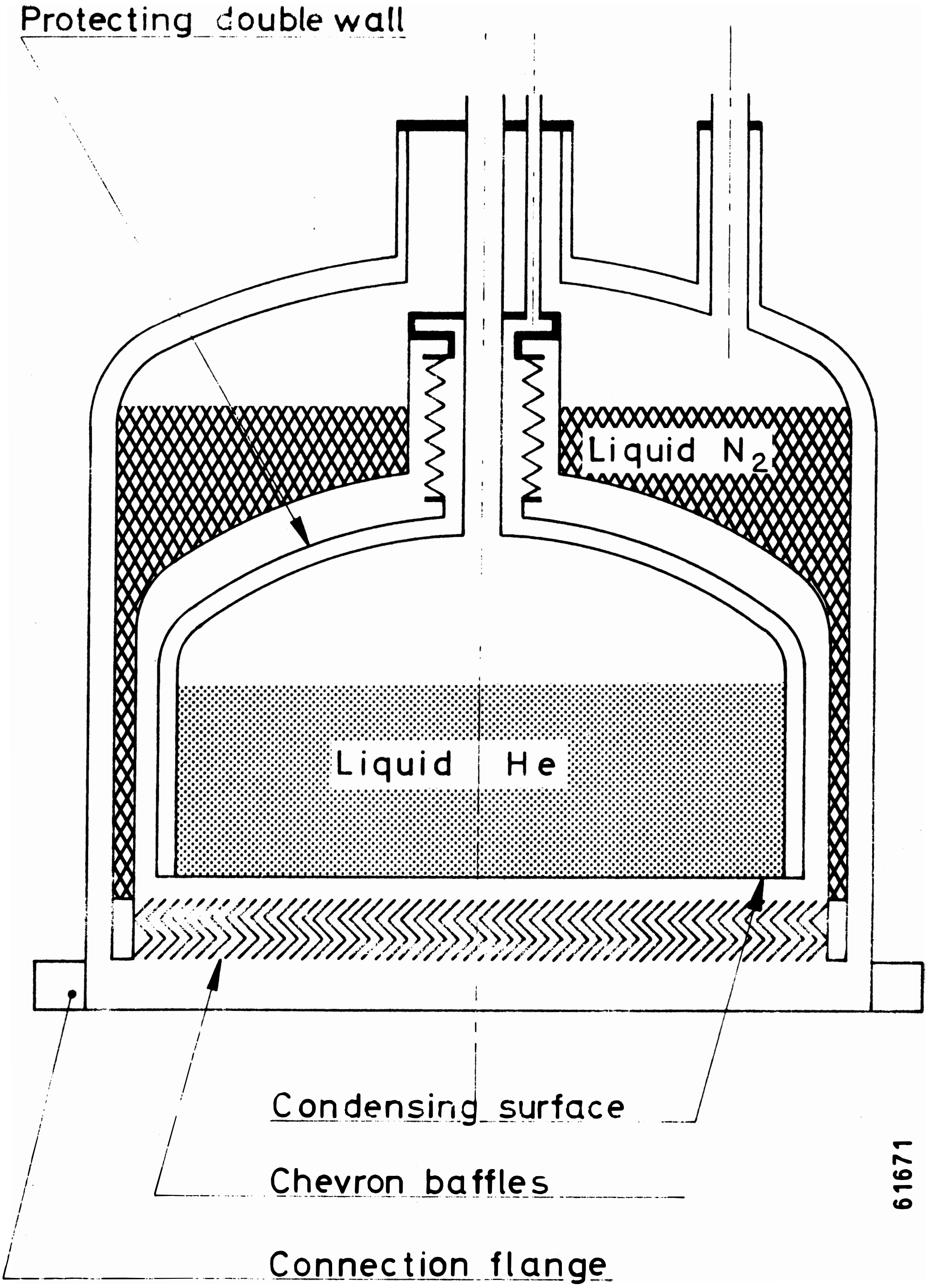

Protecting double wall
Liquid N_2
Liquid He
Condensing surface
Chevron baffles
Connection flange
61671

Fig. 1

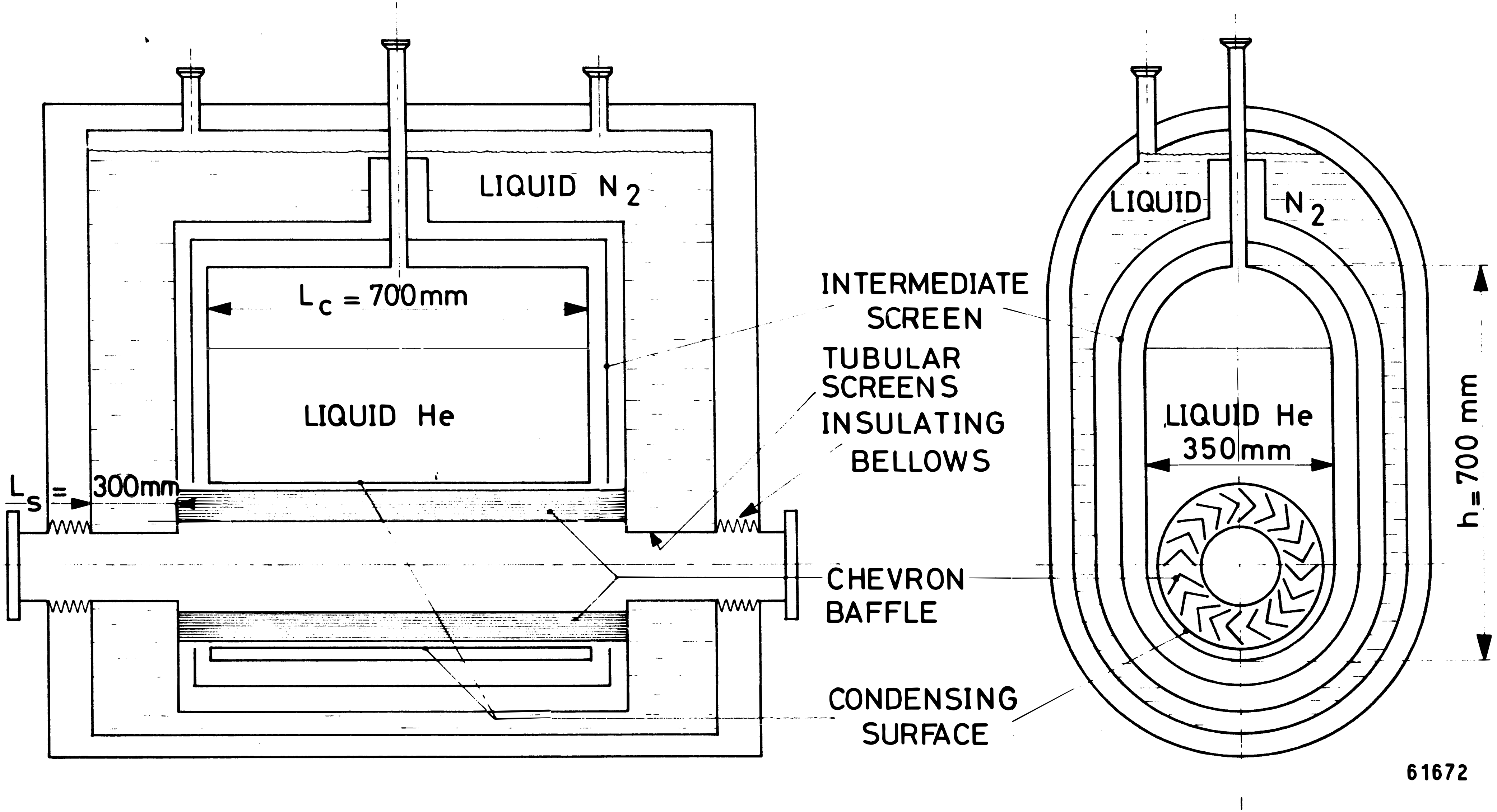

LIQUID N_2
$L_c = 700$ mm
LIQUID He
$L_s = 300$ mm
LIQUID N_2
INTERMEDIATE SCREEN
TUBULAR SCREENS
INSULATING BELLOWS
CHEVRON BAFFLE
CONDENSING SURFACE
LIQUID He
350 mm
$h = 700$ mm
61672

Fig. 2

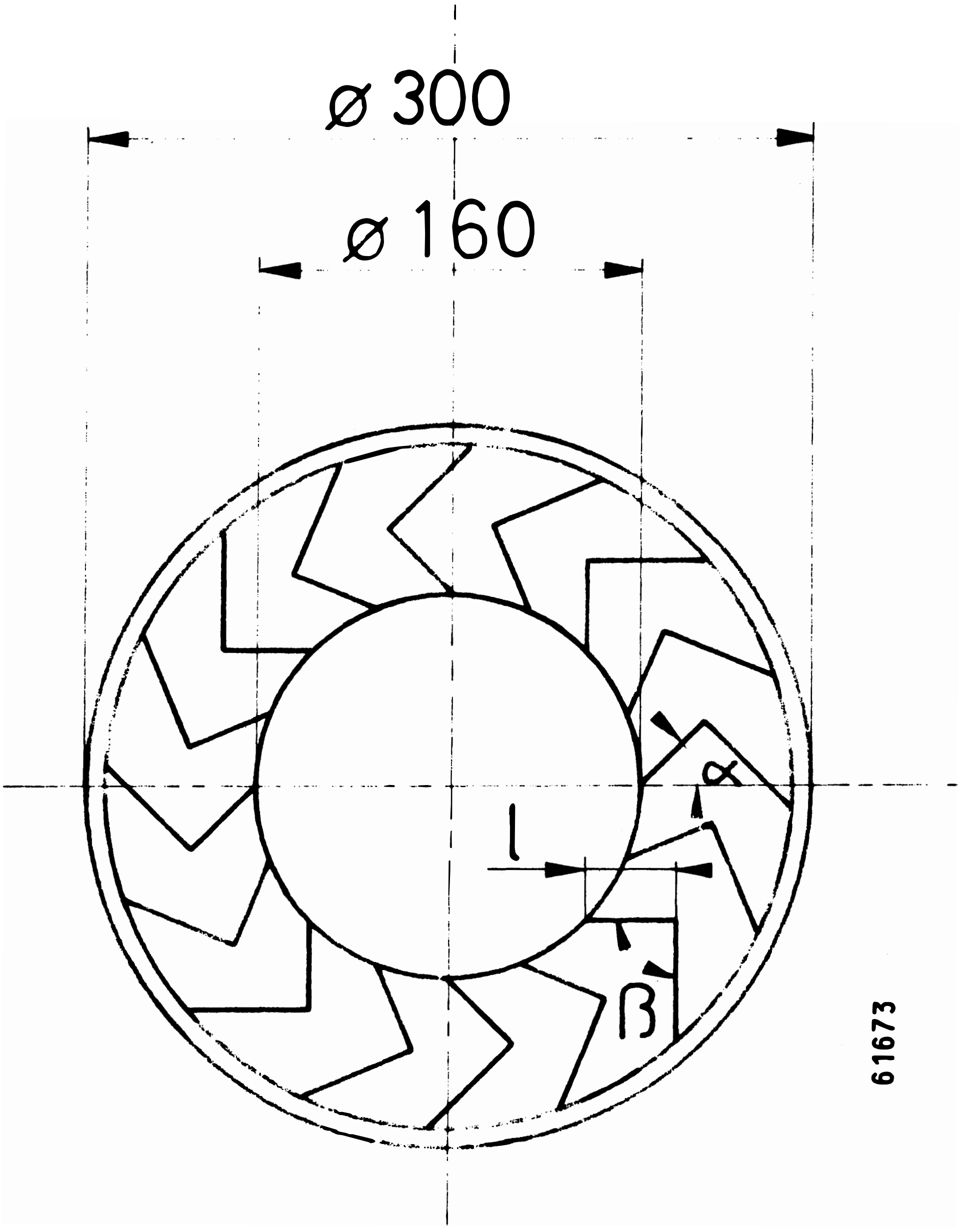
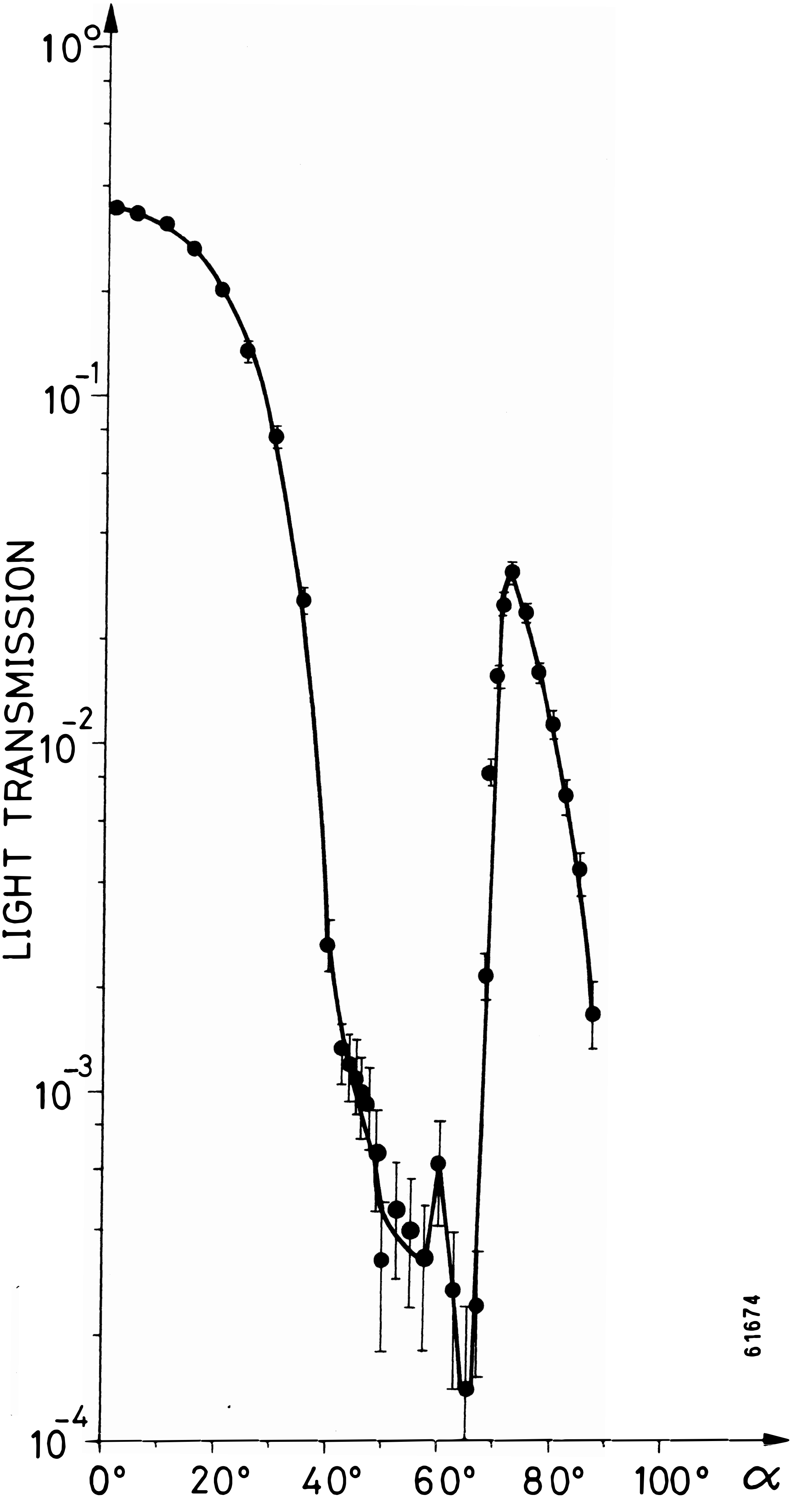


Fig. 3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10^-4
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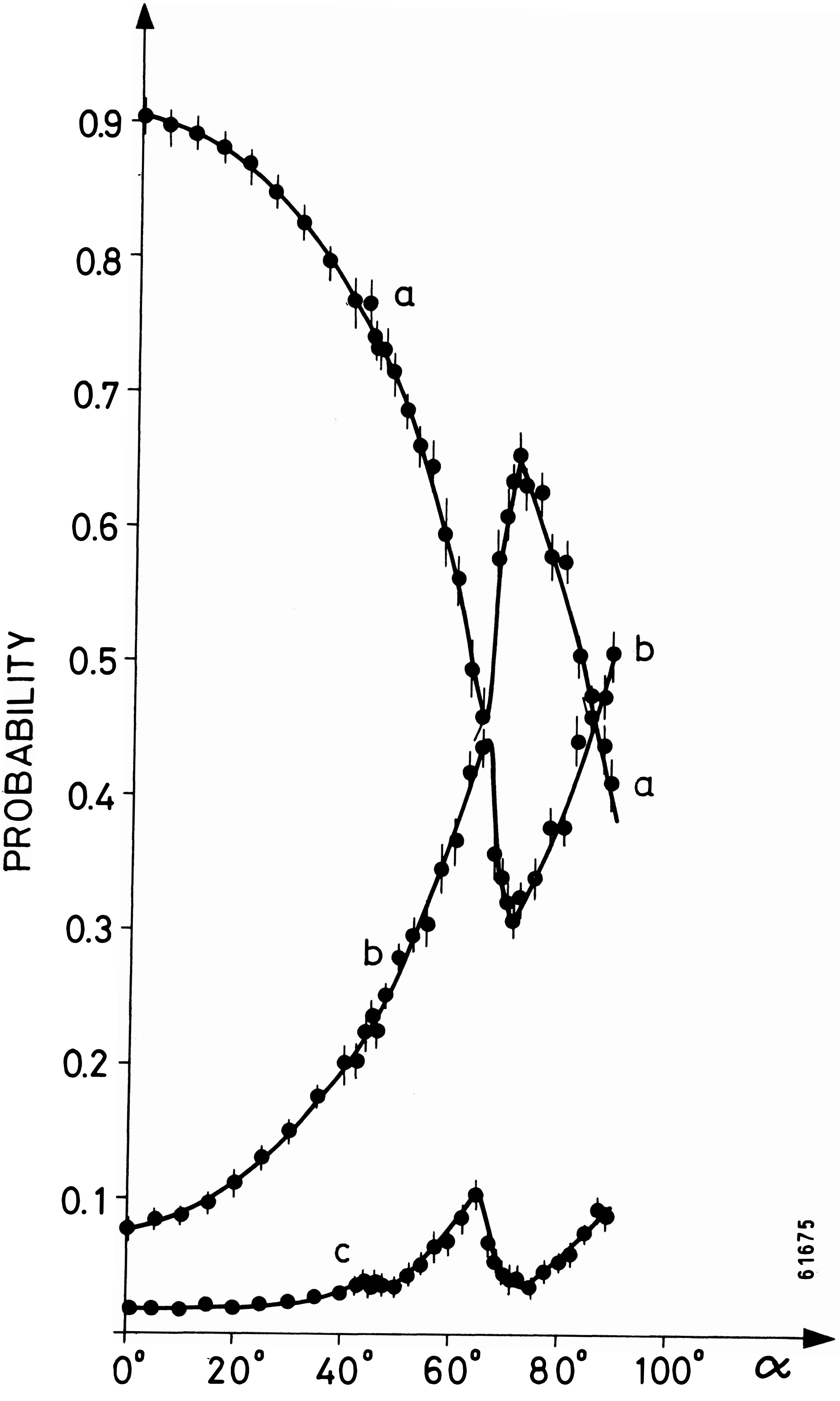
60°
80°
100°
α
61674

Fig. 4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0.4
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b
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b
c
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40°
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80°
100°
α

Fig. 5

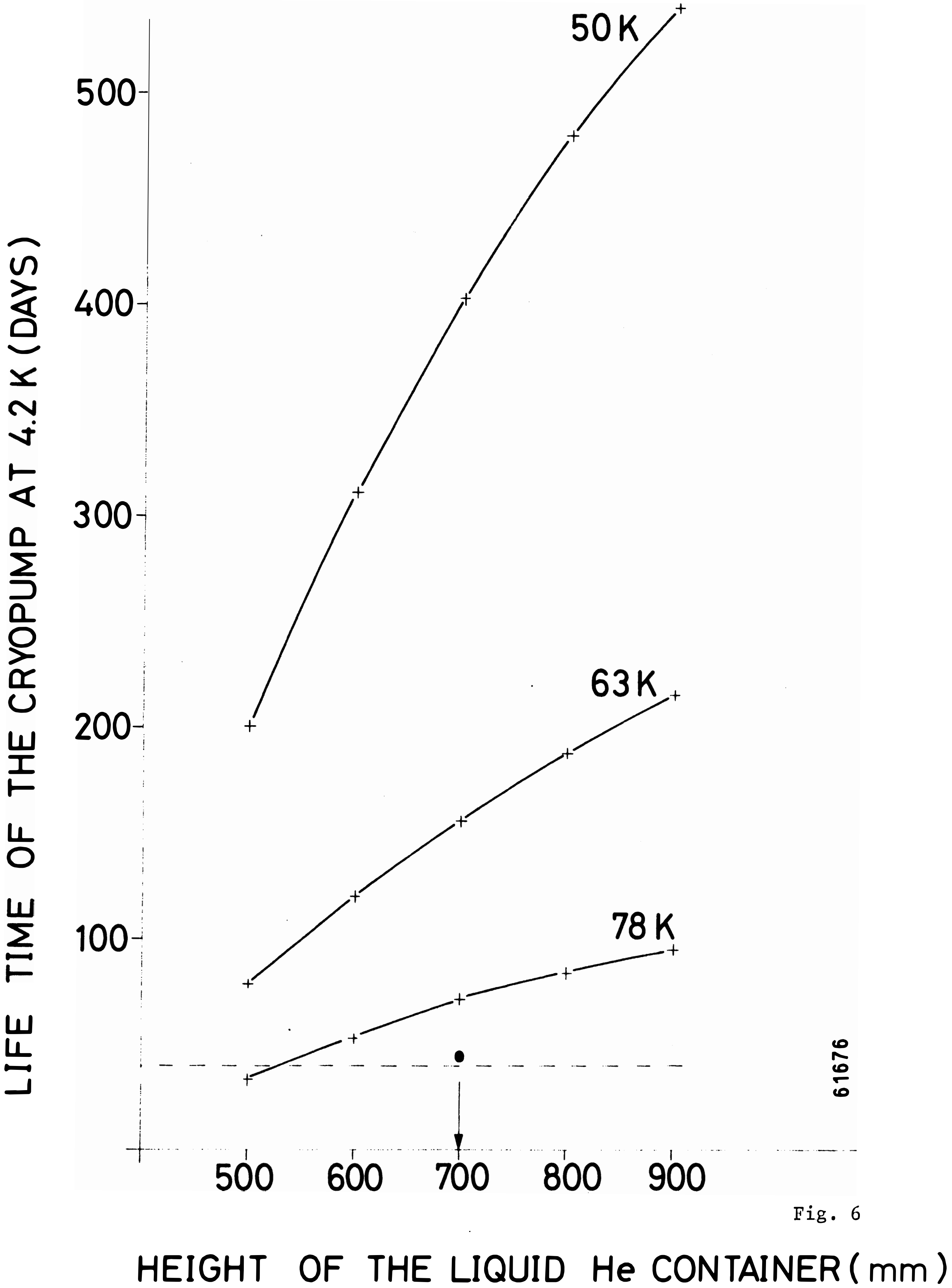
LIFE TIME OF THE CRYOPUMP AT 4.2 K (DAYS)
500
400
300
200
100
50 K
63 K
78 K
61676
500
600
700
800
900
HEIGHT OF THE LIQUID He CONTAINER (mm)

Fig. 6