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CHARACTERISTICS, ADVANTAGES AND POSSIBLE APPLICATIONS  
OF CONDENSATION CRYOPUMPING

by

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ABSTRACT

A few years ago, serious doubts were raised about the possibility of obtaining very low pressures by means of condensation cryopumping. In fact, the equilibrium pressure of condensed H<sub>2</sub> was found, in various laboratories, to deviate from the Clausius-Clapeyron law below about 3 K and to reach a temperature independent value ranging from 10<sup>-11</sup> to 10<sup>-9</sup> torr.

This phenomenon has since been investigated and clarified such that H<sub>2</sub> saturation pressures as low as 10<sup>-14</sup> torr have been obtained in our laboratories. In parallel, a drastic improvement of the cryogenic aspect of cryopumping has made it possible to achieve the very high pumping speeds characterising this pumping technique while still keeping the operating cost very low.

The performance of a few cryopumps made at CERN will be presented and critically compared to those of pumps of different types.

Although developed for extremely low pressures (below 10<sup>-11</sup> torr), we will show that these cryopumps could be advantageously used for higher pressure applications.

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## 1. INTRODUCTION

In spite of the obvious practical complications introduced by the use of low temperature technology, an impressive number of investigations have been carried out during the last few years concerning the possibility of obtaining ultrahigh vacua by cryopumping.

In fact, cryopumping offers practically all the advantages that anyone can hope from a pumping technique, namely extreme cleanliness, high pumping speed, very low ultimate pressure, easy and complete regeneration; to these advantages a practically infinite pumping capacity and a non-selective pumping (except for He, generally absent from all-metal vacuum systems) must be added when working at liquid helium temperatures (condensation cryopumping). However, although it was undoubtedly easy to obtain a pressure decrease in a vacuum system by cooling down a part of it, it was also clear from the beginning that not all the advantages of condensation cryopumping were immediately realisable. More particularly, two major obstacles considerably reduced the initial optimism; these were the H<sub>2</sub> problem (A) and what could be called "the fight against cold" (B).

### A. The "anomalous" behaviour of H<sub>2</sub>

In a vacuum system pumped by a cryosurface at a temperature T<sub>0</sub>, the situation can be described by the following equation :

$$P = P^* + \frac{Q}{S} \quad \text{with } 0 < P^* \leq P_{\text{sat}}(T_0) \quad (1)$$

in which Q is the load of a given gas, pumped with a pumping speed S, and P\* represents the contribution to the pressure due to desorption from the cryosurface. This contribution, which ideally equals zero for zero coverage, increases with the time and is expected to reach a final value (P<sub>sat</sub>) corresponding to the saturated vapour pressure of the considered gas at the temperature T<sub>0</sub>. From this moment the surface should condense a practically infinite quantity of this gas without any further pressure increase.

The characteristic parameters of a condensation cryopump should therefore be the temperature of the pumping surface and vapour pressure (V.P.) curves of the gases to be pumped. In this respect we can observe that in an all-metal ultrahigh vacuum system hydrogen is generally the main component of the residual gas pressure, and it is also the only gas (apart from He) presenting an appreciable vapour pressure at 4.2 K (boiling temperature of He at atmospheric pressure). Nevertheless, extrapolating the available H<sub>2</sub> vapour pressure data<sup>1)2)3)</sup>, an equilibrium pressure in the 10<sup>-15</sup> torr is expected at a temperature (2.3 K) which can easily be obtained by using liquid He refrigeration.

However, experimental investigations on the equilibrium pressure of condensed H<sub>2</sub> have shown<sup>4)5)</sup> a systematic departure, at low temperatures, from the Clausius-Clapeyron equation

$$\log P = A - B/T$$

P = H<sub>2</sub> saturated vapour pressure  
T = Temperature of the condensed H<sub>2</sub>  
A,B = Constants.

This deviation, resulting in an unexpected pressure limitation which is independent of the temperature of the condensing surface but strongly dependent on the characteristics of the experimental apparatus, could destroy one of the major attractions of condensation cryopumping, i.e. the possibility of pumping large quantities of H<sub>2</sub> gas at pressures below 10<sup>-10</sup> torr.

#### B. The cryogenic problems

Although the running cost of a commercially available cryopump of average size was generally not catastrophic as far as the liquid helium consumption was concerned, the life times of a helium filling for "bath" cryopumps were of the order of a few days only (two to four, typically). This implies a continuous manual intervention and exposes a laboratory, not having good liquid He provisioning facilities, to big dangers; in fact, frequent liquid helium manipulations increase the probability of

unexpected losses and can upset the provisioning programme. Similar considerations apply to the use of "circulation" cryopumps.

On the other hand, the capital investment for buying a helium liquifier or a refrigerator can not be easily justified when a small pump is involved.

## 2. THE EXPERIENCE GAINED AT CERN AND A FEW PRACTICAL REALISATIONS

In our particular case (ISR at CERN) cryopumping had to offer the possibility of reaching the extremely low pressures (below  $10^{-11}$  torr) required in the intersection regions for the high energy physics experiments<sup>6)</sup>. We have therefore investigated the behaviour of condensed hydrogen at temperatures below 3 K, with the following results<sup>6)7)</sup>:

- the deviation of the  $H_2$  vapour pressure from the Clausius-Clapeyron law was found to be due to desorption of  $H_2$  by thermal radiation originating in warmer parts of the vacuum system and reaching the condensing surface;
- different surfaces yield different  $H_2$  saturation pressures under the same radiation load: in particular, precondensed layers of better condensable gases (Ne, Ar,  $N_2$ , for example) can strongly reduce the  $H_2$  desorption rate;
- the  $H_2$  desorption rate is proportional to the quantity of radiation impinging on a given surface if the spectrum of the radiation, i.e. the temperature of the radiation source is kept constant. When decreasing this temperature the desorption efficiency of the radiation decreases considerably below about 100 K: 1 mW from 78 K, for example, is about 2 times less effective than 1 mW from 300 K.

On the basis of these experimental observations it is obvious that the best cryopump is that having radiation screens offering the maximum ratio of molecular to radiation transmission, and a pumping surface yielding the lowest  $H_2$  pressure under a given radiation load. Both these directions have been followed in our investigations, and the results obtained, only partially published, guided us in the building of the cryopumps here described.

A. The basic characteristics of the existing pumps

Figure 1<sup>6)</sup> represents schematically the cryopump model that we have developed. Basically, it consists of a stainless steel liquid helium container (the bottom of which provides the pumping surface) surrounded by a liquid nitrogen container holding the cold baffles.

i) The pumping surface

The pumping surface is silver plated because silver is the material (among about 20 tested so far, excluding the precondensed gases which cannot always be used) yielding the lowest H<sub>2</sub> saturation pressure. When such Ag plated surface faces directly onto room temperature walls the vapour pressure of H<sub>2</sub> condensed on it at 2.3 K is  $7 \pm 2 \times 10^{-10}$  torr (all the quoted pressures are measured at room temperature and nitrogen equivalent, i.e. three times lower than the real H<sub>2</sub> pressure). Upon reducing the quantity of the room temperature radiation reaching the condensing surface by means of baffles cooled at 78 K, the H<sub>2</sub> vapour pressure decreases proportionally at the beginning, approaching finally an asymptotic value of about  $1 \times 10^{-12}$  torr (due to the radiation coming from the screens) at which point the radiation from 300 K approaches zero. Lower pressures can be achieved by further decreasing the temperature of the baffles; for example, a pressure in the low  $10^{-13}$  torr range is obtainable at a baffle temperature of 64 K. Another way of obtaining H<sub>2</sub> V.P. below  $10^{-12}$  torr is to precondense on the silver plated surface a gas layer, in which case values in the low  $10^{-13}$  and  $10^{-14}$  torr ranges were measured for baffles temperatures of 78 K and 64 K respectively.

ii) The cold baffles

The cold baffles we have used are of the chevron type. This geometry has been chosen because it is very compact and efficient. The effect of the chevrons is twofold: on the one hand they reduce the quantity of room temperature radiation reaching the helium container (reducing therefore both the H<sub>2</sub> vapour pressure and the liquid helium consumption) but on the other hand they reduce the pumping speed of the

cryopump. Many geometries and materials have been tested in order to maximise the first and minimise the second reduction. A discussion of the parameters involved and a complete review of the results obtained will be published soon; we simply report here than in the best case ( $45^\circ$  or  $60^\circ$  chevron coated with a special paint suitable for ultrahigh vacuum and of about 0.93 emissivity at 300 K) a room temperature radiation transmission of  $7 \pm 2$  parts in  $10^4$  has been measured together with a pumping speed for  $H_2$  of  $9 \pm 1$  litres per second and per  $cm^2$  of pumping surface. The addition of another half of a chevron reduces the pumping speed to  $6 \pm 1$   $\ell/\text{sec}^{-1} \text{cm}^{-2}$  for  $H_2$  and the room temperature radiation level to below our detection limit (one part in  $10^4$ ). These values of the radiation transmission imply that a simple chevron yields a  $H_2$  vapour pressure of about  $2 \times 10^{-12}$  torr, whilst one and half chevrons yield a pressure of about  $1 \times 10^{-12}$  torr (due only to the cold radiation emitted by the chevrons) when the chevron temperature is 78 K and the pumping surface is bare silver. A  $H_2$  V.P. below  $10^{-12}$  torr can therefore be obtained, on bare silver, only by using one and a half chevrons at a temperature below 78 K. When using a layer of precondensed gas however,  $10^{-13}$  and  $10^{-14}$  torr pressures were measured in both the mentioned screening situations at chevron temperatures of 78 and 64 K respectively.

iii) The helium container

The helium container has a double wall with vacuum independent of the main vacuum system. This construction protects the latter from disturbing adsorption-desorption effects due to change of liquid level or local variations in cooling power when pumping over the liquid helium (the operating temperature, of 2.3 K, corresponds to a pressure, over the helium bath, of 50 torr).

Since Ag is also the best infra-red reflector among the tested materials, not only the pumping surface but also the complete liquid helium container are usually silver plated. The ratio of the absorbed to the total impinging radiation, measured for seven different silver coated surfaces and various radiation loads was  $1.15 \pm 0.15 \times 10^{-2}$  (maximum error for all measurements). Such a surface immersed in a closed cavity at 78 K will therefore absorb  $2.6 \pm 0.3 \times 10^{-3} \text{ mW cm}^{-2}$  (i.e. six times less than electropolished stainless steel).

B. Dimensions and performances of the existing pumps<sup>6)8)</sup>

Four pumps, of two different dimensions, have been built so far at CERN. Table I describes their construction characteristics.

Their performances are discussed below.

i) Pumping speed

It depends (see section 2, A ii) on the screening situation and the results already presented (measured<sup>6)</sup> or simply estimated<sup>8)</sup>) are based on anodised aluminium chevrons, about ten times less efficient from the radiation point of view than the chevrons now available. The new chevrons have only been used so far on the E pumps, and the performances of the D pumps reported here are estimated on the basis of the results obtained with the E's.

When using a single chevron the pumping speeds for H<sub>2</sub> are about 30000 and 4500  $\ell/\text{sec}^{-1}$  for the pumps D and E respectively, whilst when adding another half chevron they become about 18000 and 3000  $\ell/\text{sec}^{-1}$  respectively. The pumping speeds for the other gases are lower (and conductance dependent), except if the considered gas can be condensed at very low pressure at the temperature of the baffles; in this case the pumping speed is much higher and independent of the number of chevrons. For water vapour, for example, the speeds are 68000 and 11300  $\ell/\text{sec}^{-1}$  for the pumps D and E respectively.

ii) Limit pressure

According to the formula (1), two terms contribute to the pressure of a condensation cryopump at saturation, i.e. the vapour pressure of the pumped gas and the ratio of the H<sub>2</sub> degassing rate to the corresponding pumping speed of the pump. We will define the limit pressure of a condensation cryopump as that H<sub>2</sub> pressure in the pump after its saturation with H<sub>2</sub>. When the pump is cold the dominant source of H<sub>2</sub> is its outer wall, which remains at ambient temperature. For a stainless steel of a given quality, or degassing rate, the degassing term of the formula (1) presents only minor variations when changing the dimension of the pump, being slightly

smaller for "flatter" pumps. In our case the degassing rate of the stainless steel is  $2 \times 10^{-13}$  torr  $\ell/\text{sec}^{-1} \text{cm}^{-2}$  and the degassing terms should therefore be  $7 \times 10^{-14}$  and  $1 \times 10^{-13}$  torr for the pumps D and E respectively in the situation where a single chevron is mounted. The corresponding measured values were about 1 and  $1.5 \times 10^{-13}$  torr, but in order to make the measurements possible a few other degassing parts of non negligible size were added. This cryopump model therefore suffers from an intrinsic limitation, fortunately not absolute but depending on the steel used. At present this prevents us from reaching pressures below  $10^{-13}$  torr. This effect could possibly be much more important when using a steel of less good quality. A degassing treatment in a vacuum furnace at a temperature around  $900^{\circ}\text{C}$  and at a pressure of  $10^{-6}$  torr might provide an improvement of a factor of ten, and even more if done at lower pressure<sup>9)</sup>. Limit pressures in the low  $10^{-13}$  torr range, according to the previous definition, can nevertheless be achieved with these pumps either by using a precondensed layer of gas (and in this case a simple chevron at 78 K is sufficient) or, without such a layer, by means of one and a half chevrons at about 64 K.

### iii) Operating pressure range

The operating pressures of the pumps considered here range from  $10^{-13}$  (see section 2 B ii) to  $10^{-3}$  torr. Although in practice the upper limit could be displaced up to atmospheric pressure<sup>10)</sup>, we do not recommend this operating method because it introduces important He losses, especially since cheap ways of obtaining  $10^{-3}/10^{-4}$  torr pressures exist. Furthermore, the important feature, more than the theoretical extension of the range of applicability of the pumps, is the pressure range covered during a single experiment. Pressures in the low  $10^{-12}$  torr range, for example, were repeatedly obtained in about 24 hours cycle time when activating the pump E at  $10^{-6}$  torr (during bakeout at  $300^{\circ}\text{C}$ ). No similar investigations were carried out for higher starting pressures, because the latter do not present an actual interest for the ISR. However, we have observed that these pumps can tolerate  $\text{H}_2$  and  $\text{N}_2$  pressures in the  $10^{-3}$  range for a few minutes without complications.



iv) Liquid He Consumption

In order to reduce the He losses during the filling of the pumps the He container is initially precooled with liquid nitrogen before the He transfer. Furthermore, He gas is introduced between the two walls of the He container and pumped out only when some liquid He is present in the pump; this has the advantage that the enthalpy of the gas instead of the vaporisation heat is used for cooling the outer wall. With these precautions the amounts of liquid He vaporised during the filling of the pumps D and E are 5 to 10 and 1 to 2 litres respectively. The complete operation, starting at ambient temperature until the end of the He transfer, takes about 6 hours.

When thermal equilibrium is reached, the measured He consumptions are about 0.25 and 1 litres of liquid per day for the pumps E and D respectively with one or more chevrons at 78 K. These consumptions provide a life time of about 40 and 75 days at 4.2 K corresponding to about 28 and 52 days at the working temperature of 2.3 K for the pumps E and D respectively.

Lower liquid He consumptions can be obtained by simply cooling the chevrons and the N<sub>2</sub> container at temperatures below 78 K; for instance, according to the Stefan-Boltzmann law, at 64 K the amount of the emitted radiation (and, practically, the He consumption) is about 2.5 times lower than at 78 K.

If the chevrons are removed, thus providing a pumping speed for H<sub>2</sub> after saturation of about 40 l/sec<sup>-1</sup> cm<sup>-2</sup>, the consumptions become 8 and 72 l per day, and the life time of a He filling (at 4.2 K) approximately one day for both pumps.

v) Liquid N<sub>2</sub> consumption

The N<sub>2</sub> consumption of the cryopumps of this model are quite important, because the chevrons, necessarily black, are immersed in a cavity at 300 K. Silver plating of the outer wall of the N<sub>2</sub> container (pump E) has reduced the consumption from 0.5 to 0.3 litres of liquid per hour. For the pump D, not submitted to this treatment, the consumption is

2.5 litres per hour. For both the D and E pumps the  $N_2$  containers have been designed in such a way that one filling per day is sufficient. Temperatures lower than 78 K can be obtained in a simple way by pumping over liquid  $N_2$ ; this method is limited to about 63 K ( $N_2$  triple point, corresponding pressure 94 torr) due to the poor thermal conduction of the solid  $N_2$  so that when no liquid is present the temperature of the chevrons increases. If the  $N_2$  container is so designed that the thermal inertia provided by the presence of the solid  $N_2$  is sufficient, the temperature of the regions surrounding the He container can be kept constant during a normal  $N_2$  transfer at atmospheric pressure and the subsequent pumping to the triple point. The only disadvantages accompanying the important reduction of liquid He consumption (see section 2, B iv) are in this case the doubled liquid  $N_2$  consumption and the need of an extra rotary pump.

vi) Pumping capacity and regeneration

When increasing the thickness of the condensed gas layer the limit pressure of a cryopump is expected to increase, due to the thermal gradient established across the layer by the infra-red radiation absorbed in it or by the heat released by the condensing molecules. Additionally, the increased radiation absorption can considerably increase the liquid He consumption. When one or both of these effects are judged to be too important for a given application the cryopump must be regenerated, i.e. warmed up to remove the disturbing gas layers.

The correlation between the thickness of the layer and the equilibrium pressure in the pump is a complex function of the gas composition of the layer, of the infra-red absorptivities, heats of condensation and vapour pressures of the components, of the radiation load and of the thermal conductivity of the mixture; it is therefore impossible (although a magic value of 1 mm often appears in the literature<sup>11)</sup>) to obtain an estimation of the critical thickness independently of the values of the above-mentioned parameters. As a matter of fact, among the three gases most commonly found in a vacuum system (i.e.  $H_2$ ,  $N_2$  and water vapour) only the last one, which is however

stopped on the baffle, presents an important infra-red absorption in the condensed phase.

Since this effect is completely negligible when working at pressures below  $10^{-9}$  torr, a systematic investigation on this subject is outside our present interest. Only sporadic information on thick  $H_2$  and  $N_2$  layers were therefore collected. The  $H_2$  case, in particular, deserves special comments. As the Figure 2 shows<sup>7)</sup>, the  $H_2$  adsorption isotherm on stainless steel, in this case at 2.3 K, presents a maximum around the completion of the first monolayer and becomes practically constant between two and ten monolayers. The  $H_2$  V.P. previously quoted (see 1A) are relative to this interval. When increasing the thickness the slight decrease of the pressure already present in this interval becomes more relevant: a reduction of a factor of ten was measured on the D pumps, in a situation yielding a  $H_2$  vapour pressure (two to ten monolayers definition) of about  $4 \times 10^{-12}$  torr, when reaching a condensed  $H_2$  thickness of about 0.1 mm.

In another experiment a film of about 0.3 mm thick of  $N_2$  was condensed on a few monolayers of  $H_2$  and Ne at 2.3 K. The injection was carried out at a pressure in the  $10^{-4}$  torr range. A pressure in the  $10^{-7}$  torr range was achieved during the hour following the end of the injection, and over-night the pressure descended to below  $10^{-8}$  torr. After having raised the temperature of the baffles by about 40 K above the working temperature (78 K), upon recooling them a pressure of about  $2 \times 10^{-11}$  torr was obtained in less than one hour. After completing the above operations the consumption of liquid He returned to its normal value as measured beforehand.

From this experimental evidence it is possible to conclude that this cryopump model might work for periods of time of the order of a year at least at a pressure of  $10^{-7}$  torr if the gas composition is that normally found in an unbaked vacuum system and if a chevron protects the pumping surface.

### 3. CONSIDERATIONS LEADING TO THE DESIGN OF A CRYOPUMP OF THIS TYPE FOR A PARTICULAR APPLICATION

According to the basic features of condensation cryopumping it is clear that to design a pump for application below  $10^{-11}$  torr is a three step process: first, the operating pressure range determines the number of chevron units and, as a consequence, the pumping speed per  $\text{cm}^2$  of condensing surface; second, the required speed determines the diameter of the pumping surface; third, the required life time of a helium filling determines the height of the helium container.

For higher pressure applications the process is somewhat less rigorous because from the vacuum point of view a lower screening efficiency is acceptable; this implies however a higher helium consumption and a shorter life time. For example, above  $10^{-8}$  torr the pump could be used without screens but the helium consumptions would be terrific (see section 2 B iv). On the other hand, the same gain in pumping speed (a factor of four, with the exception of the gases behaving like water vapour, see section 2 B i), for which there is no gain at all) can be much more cheaply achieved by simply expanding the linear dimensions by a factor of two. This situation also provides a higher pumping capacity (see 2 B vi). These cryopumps should be therefore employed with a simple chevron even for high pressure applications.

In order to put in evidence the influence of the room temperature radiation, filtering through the cold baffle, on the liquid helium consumption, let us consider the Figure 3 relative to the E cryopumps. In this figure the calculated helium consumption is plotted as a function of the height of the helium container, with a variable parameter being the radiation transmission of the baffle. Since each centimetre of height (see Figure 1) presents the same area of liquid He container surface to the liquid nitrogen temperature, the helium boil-off rate increases proportionally to  $h$ . The straight line does not cross the origin because when  $h = 0$  the conduction losses (a in Figure 3) and the 78 K radiation losses (b in Figure 3) on the top and bottom of the liquid helium container

are still present. Any radiation filtering through the screens introduces an additional constant, i.e. produces a translation of the line towards higher consumptions; for example, for a room temperature radiation transmission of 1/100, the additional constant (c in Figure 3) is equal to b (h = 0).

It is evident from this example that for radiation transmissions below  $10^{-3}$ , as in the situation provided by our simple chevron, the consumption curves practically overlap the zero transmission curve, with the practical consequence that the liquid helium losses can be calculated without taking this contribution into account. Another interesting observation is that the contribution of the thermal conduction in this case is not negligible if compared to the contribution of the radiation from the baffles, in this example maintained at 78 K. More precisely, the former is equal to about 10% of the latter when considering the chosen height of the He container (200 mm). The conduction term is due to the presence, around the He container, of the second wall, whose upper side is connected to the liquid N<sub>2</sub> vessel by means of a thin-walled bellow. The relative importance of this term tends to increase when reducing the dimensions of the pump, because the characteristics of the bellow cannot be easily varied to reduce it in the same proportion as the area of the He container (which determines the radiation losses). When considering for instance the D pumps the conduction term is negligible.

The important consequence of these observations is that the He boil-off rate of a cryopump of this model can be calculated (in first approximation for small pumps and almost exactly for pumps of larger dimensions) by multiplying the area of the He container by the radiation losses per cm<sup>2</sup> (i.e.  $2.6 \pm 0.3 \times 10^{-3}$  mW, see section 2 A iii). This situation can be expressed by the formula

$$Q = \epsilon S \text{ cm}^3/\text{day} \quad (2)$$

where Q = liquid He consumption in cm<sup>3</sup> per day with baffles at 78 K

S = area of the He container in cm<sup>2</sup>

and  $\epsilon$  = liquid He consumption of the unit area ( $8.6 \times 10^{-2}$  cm day<sup>-1</sup>).

The uncertainty on the  $\epsilon$  value, and therefore on Q is  $\pm 11\%$ .

When applying this formula to the D and E pumps we obtain respectively  $940 \pm 100$  (measured values for the two pumps 910 and 970) and  $220 \pm 25$  (measured values 253 and 232)  $\text{cm}^3/\text{day}$ . The agreement between calculated and measured values for the E pumps is improved when taking the conduction into account: the estimated total consumption was  $250 \pm 30 \text{ cm}^3/\text{day}$ <sup>8)</sup>.

What is still more relevant in practice is another physical quantity, i.e. the life time L of a He filling, because it defines the available working time. By definition

$$L = V/Q \quad (3)$$

where V is the liquid He volume  
and Q the He consumption.

Since the value of r, for a given application, is determined by the required pumping speed, it is interesting to consider the dependence of L on h, for a given r. This dependence is shown, for the E pumps ( $r = 12.5 \text{ cm}$ ), by Figure 4 (L and h axis, full line)<sup>8)</sup>. In this figure, L is calculated on the basis of the Q values given by Figure 3. Observe that the slope of this curve (i.e. the L increase per unit of height increase) decreases with increasing h and becomes zero for h tending to infinity. This means that L approaches an asymptotic value ( $71 \pm 8 \text{ days}$ ) when the conduction losses and the radiation losses due to the top and bottom parts of the He container became negligible if compared to the radiation losses due to the lateral surface.

When neglecting the conduction term, from (2) and (3) follows

$$L = rh/2\epsilon(r+h) \quad (4)$$

where r and h are the radius and the height respectively of the liquid He container. L has the dimensions of time and is expressed in days, when r and h are in cm and  $\epsilon$  in  $\text{cm}/\text{day}$ . When varying now the parameter r we obtain a family of curves crossing the origin and approaching the asymptotic value

$$L_{\infty} = \lim_{h \rightarrow \infty} L = r/2\epsilon = 5.80 r \quad (5)$$

(L in days and r in cm)

By putting  $y = L/r$  and  $x = h/r$  the formula (4) becomes :

$$y = x/2\epsilon(x+1) \quad (6)$$

and represents a unique curve in the  $y$  and  $x$  axis. Figure 4 ( $L/r$  and  $h/r$  axis, dashed line) shows this more general behaviour: the most important indication is that  $h/r$  should generally not exceed 2. Only exceptionally, if the  $L$  value is very critical, should this ratio be higher than 2 but in any case never higher than 4. A similar result could be more efficiently obtained by increasing  $r$  (for a given  $h/r$  value  $L$  is proportional to  $r$ ). The simple correlations between  $L$  and  $r$  for two  $h/r$  ratios of practical interest are

$$L(h/r = 1) = 2.9r \quad (7)$$

and 
$$L(h/r = 2) = 3.9r \quad (8)$$

All these considerations permit us to estimate the characteristics of pumps of different sizes as shown in table II. It is worthwhile to recall that these calculations are carried out without taking into account the conduction losses; and that for this reason the two curves shown by Figure 4 do not overlap; this contribution is however negligible for the majority of the cases considered in table II. When calculating the  $L$  values by means of formula (6), for the pumps D and E we obtain :

pumps D ( $h/r = 0.806$ ,  $r = 31$  cm)  $79 \pm 8.5$  days (measured  $82 \pm 6$  and  $78 \pm 5$ )

pumps E ( $h/r = 1.6$ ,  $r = 12.5$  cm)  $45 \pm 5$  days ( $40 \pm 5$  including conduction losses; measured values  $43 \pm 2$  and  $39 \pm 0.5$ ).

It is also important to recall that the quoted life times are relative to a helium temperature of 4.2 K, and that the figures corresponding to 2.3 K are lower by about 30%.

4. POSSIBLE APPLICATIONS OF THESE CRYOPUMPS AND COMPARISON WITH OTHER PUMPING TECHNIQUES

The possible applications of cryopumping are practically as numerous as the applications of vacuum technology; we will not try here to review the whole subject (many papers of this type have been written recently, see for example reference 12) but simply to point out a few particular possibilities or consequences resulting from the development of the high performance cryopumps described above.

The first of the consequences that needs to be mentioned is that the arguments usually employed to justify the applications of cryopumping by physisorption at 4.2 or 20 K or by 20 K condensation have lost a large fraction of their validity: the former was in fact justified because of its greater pumping capacity and the second because of the smaller power consumption. Condensation pumps of the kind described above present a pumping capacity for all the gases except He which is many times higher than the most porous material (which furthermore is generally "black" in the infra-red radiation range and difficult to bind onto a metal surface), and on the other hand does not suffer from the inconvenience of circulating the refrigerant characterising the 20 K pumping (namely need of a refrigerator, possible faults in the cryogenic circuitry and heat losses in the transfer lines). Furthermore, the 20 K condensation pumping is practically ineffective as far as the H<sub>2</sub> is concerned, and for this reason must often be coupled with diffusion pumping.

The very high pumping speed for H<sub>2</sub> and water vapour make condensation cryopumping the ideal pumping method for big, non bakeable vacuum systems, particularly when the pressures involved ( $10^{-4}$  to  $10^{-8}$  torr) discourage the use of sublimation pumping. This application at present is the typical field for diffusion pumping: cryopumping could become competitive from the points of view of both cost and ease of operation and provide the further (and sometimes necessary) advantage of its extreme cleanliness.

The applications at extremely low pressures, which constitute our major interest have already been discussed elsewhere<sup>6)8)</sup>. It is



sufficient to state an advantage which can be obtained when using a cryopump in a particular way. There are two possibilities when baking a vacuum system on which a cryopump is mounted: first, to keep the cryopump at the same temperature as the system and activate it (i.e. cool it with liquid N<sub>2</sub> and He) only when the system is at ambient temperature; second, to activate it during the bakeout. In other words, during the bakeout the cryopump is passive in the first and active in the second case. Although the ultimate pressures achieved in the two cases in a system reproducing a standard ISR unit were practically the same, the second method provides a pressure 100 to 1000 times lower when the system is at 300°C, and therefore a lower concentration of molecules on the system walls after baking<sup>13)</sup>. This result is particularly interesting for Storage Rings, where the walls of the vacuum system are submitted to ion bombardment producing desorption of molecules there adsorbed<sup>14)</sup>.

Amongst the calibration procedures of pressure gauges for UHV the most widely used is probably the dynamic expansion method<sup>15)</sup>. The ideal pump for this application should have a very low ultimate pressure and a very high pumping speed; furthermore, the pumping speed should be independent of the pressure and of the quantity and nature of the pumped gases. Our cryopumps provide all these advantages, and one of the D pumps is used at present in our laboratories as a part of a system where 20 gauges can be calibrated simultaneously (dynamic expansion coupled with porous plug) in the pressure range 10<sup>-5</sup> to 10<sup>-12</sup> torr. In order to avoid ultimate pressure and pumping speed variations due to the progressive coverage of the pumping surface with H<sub>2</sub> (about 1 × 10<sup>-12</sup> torr and 10 to 20% respectively) a Neon layer and about 10 monolayers of H<sub>2</sub> are condensed on the pumping surface before starting the calibration procedure. These injections of gas are made when the system is hot (at 200°C, during the bakeout) in order to avoid contamination. After injection a pressure in the 10<sup>-10</sup> torr range is usually obtained at 200°C, the temperature at which the gauges are degassed. After bakeout, a pressure around 1 × 10<sup>-12</sup> torr (depending on the number of the gauges in operation) is normally achieved.

In parallel we are investigating the possibility of using the H<sub>2</sub> isostere obtained by varying the temperature of the condensing surface after H<sub>2</sub> saturation between 2.3 and 4.2 K for calibration with H<sub>2</sub> in the range 10<sup>-12</sup> to 10<sup>-6</sup> torr.

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#### 6. CONCLUSION

Although our improvement programme on cryopumping is still in progress, we think that already at the present stage, represented by the model described here, this pumping technique overcame its two major limitations, i.e. the short operational life time and the difficulty to pump big quantities of H<sub>2</sub> at very low pressure. We therefore foresee an increasing interest for condensation cryopumping on the part of the vacuum technology users. The increasing utilisation of liquid He can only speed up the process.

Table I

Characteristics of the existing cryopumps

	Pump D	Pump E
number of pumps	2	2
outer diameter (mm)	800	320
height	1200	580
diameter of the He container	620	250
height of the He container	250	200
total weight (kg)	200	30
weight of the He container	32	4
liquid helium capacity (litres)	75	10

Table II

Estimated characteristics of cryopumps of various dimensions

S $\ell/\text{sec}^{-1}$	r cm	a		b	
		Volume litres	Life time days	Volume Litres	Life time days
5000	13.3	7.4	39	14.8	52
10000	18.8	20.8	54.5	41.7	73
20000	26.6	59	77	118	104
50000	42	233	122	466	164
100000	59.5	660	173	1321	232
200000	84	1865	244	3730	328

S is the pumping speed for  $\text{H}_2$  obtained when one chevron protects the pumping surface ( $9 \ell/\text{sec}^{-1} \text{ cm}^{-2}$ ). a and b represent the cases of  $h/r = 1$  and 2 respectively.

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### Figure Captions

- Figure 1 : The cryopump model developed at CERN, shown here with one and a half chevron baffles.
- Figure 2 : Adsorption isotherm of  $H_2$  on stainless steel at 2.3 K.
- Figure 3 : Liquid He boil off rates relative to the E pumps as a function of the height of the He container. The curves 1, 2 and 3 correspond to different transmissions (zero,  $10^{-3}$ , and  $10^{-2}$  transmission respectively) of room temperature radiation through the cold baffles here at 78 K. The letters a, b, c indicate the contributions to the consumption due to thermal conduction, 78 K radiation absorbed by the top and the bottom of the He container and 300 K radiation absorbed by the pumping surface respectively.
- Figure 4 : Operational life time L as a function of the height h of the liquid He container for the pumps E (L and h axis, full line). The dashed line represents, more generally, this dependence for a pump of radius r (L/r and h/r axis). The two curves do not overlap because the lower curve has been obtained taking into account the conduction term, which has been neglected in the upper.

Figure 1

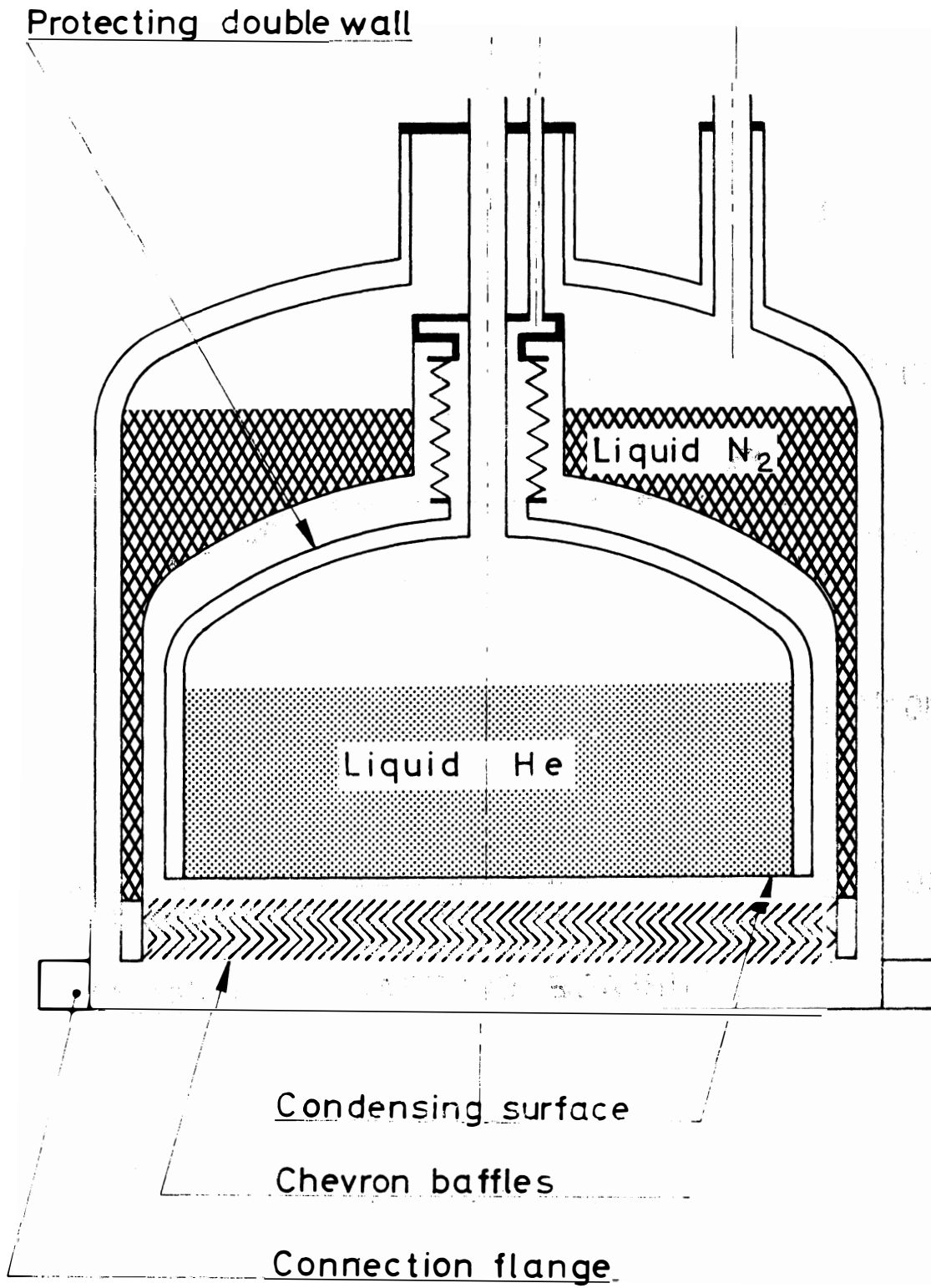


Figure 2

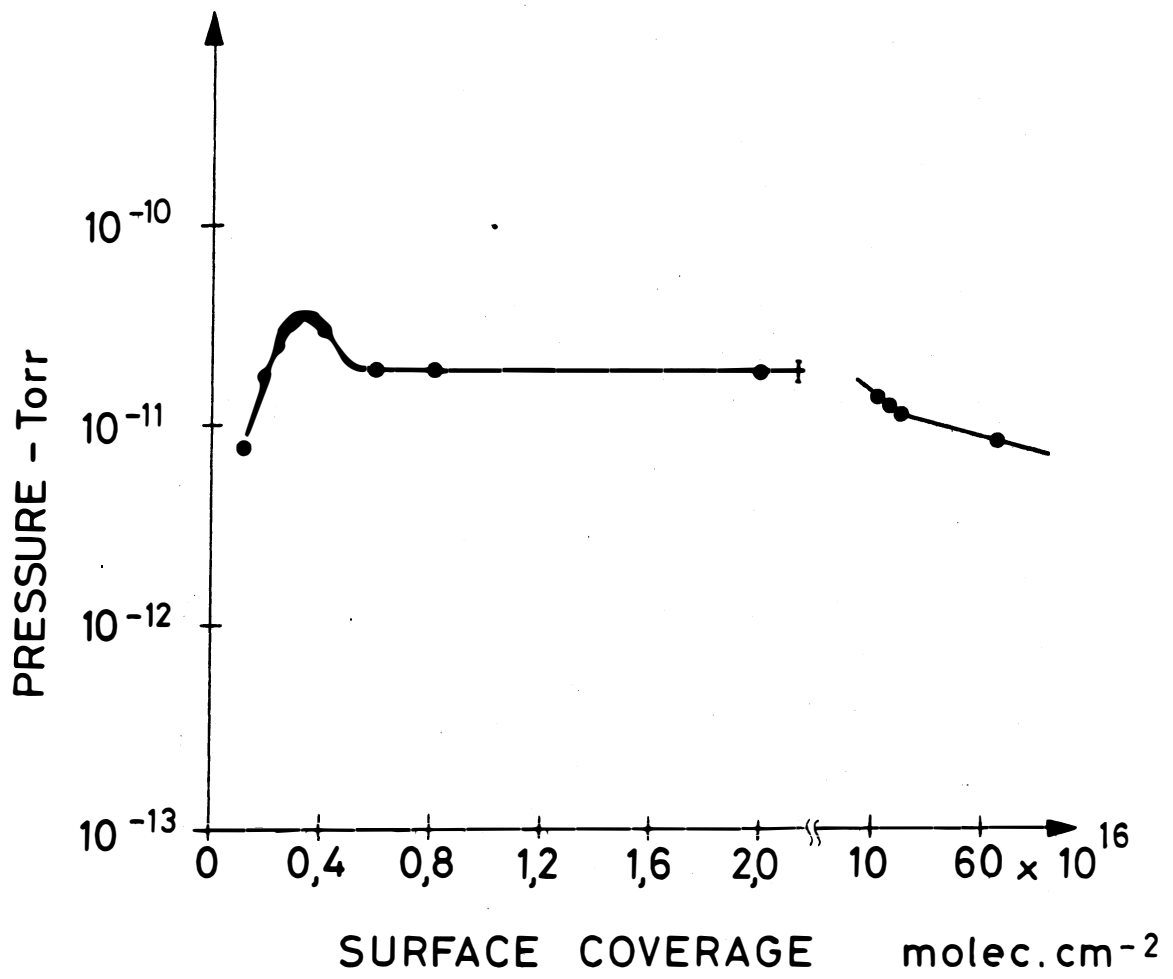


Figure 3

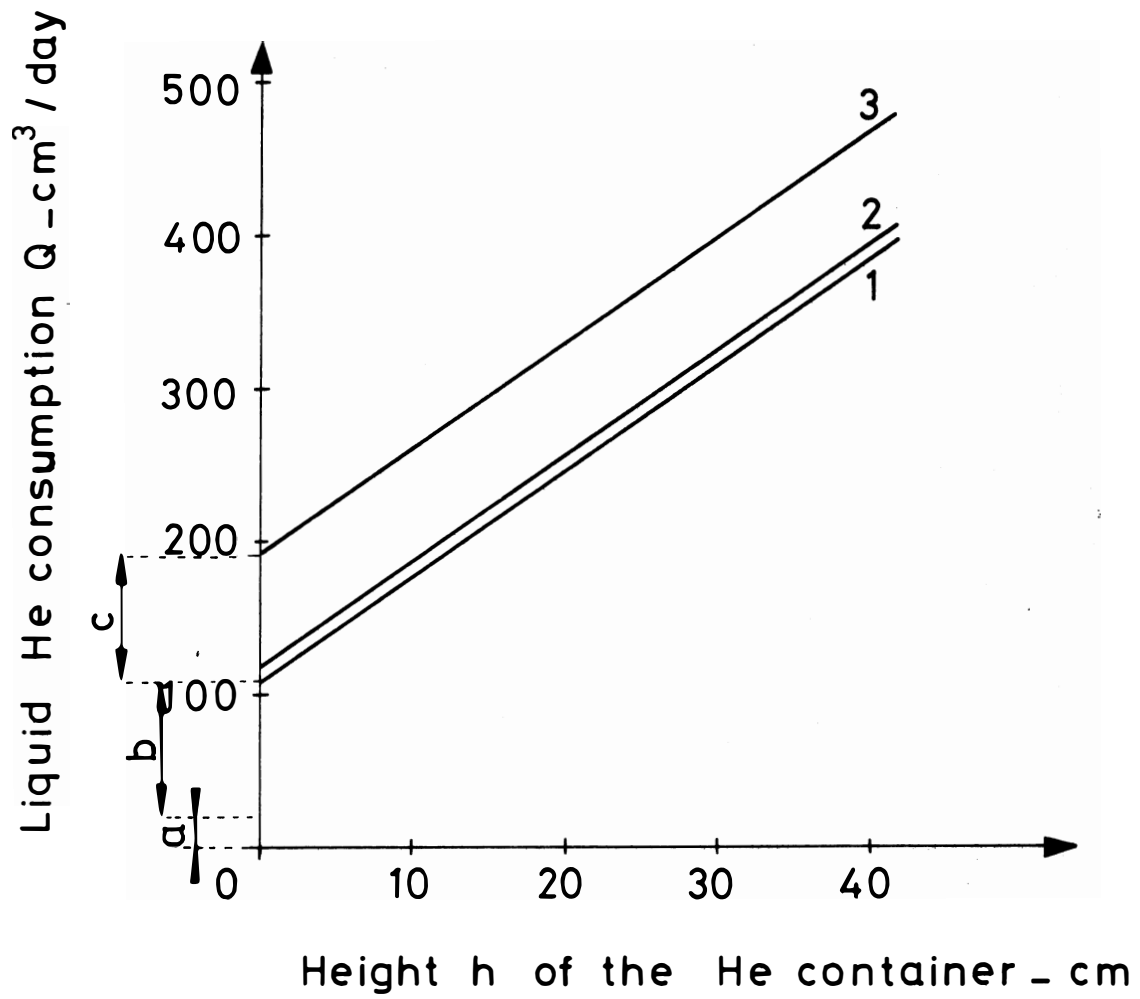




Figure 4

