Room-temperature pumping characteristics of a Zr–Al nonevaporable getter for individual gases

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(Received 16 November 1987; accepted 24 January 1988)

The main pumping for the vacuum system of the Large Electron Positron (LEP) collider, at present under construction in the Geneva area, will be achieved by a linear getter pump. In contrast to the usual operating conditions of nonevaporable getter (NEG) pumps, which consist of maintaining the pump hot to continuously diffuse into the getter bulk the gases adsorbed on its surface, the LEP pump will be kept at ambient temperature and heated only intermittently. This difference has required a study on the behavior of a NEG pump under these unusual operating conditions, which result in a progressive reduction of pumping speed with increasing quantity of the gas adsorbed. It was found that the pumping speed reduction may be described in terms of a progressive saturation of the NEG surface inside the cracks and porosities which are present in the getter film thickness.

I. INTRODUCTION

A nonevaporable getter (NEG) strip subtended along the inside of a vacuum chamber may provide an economic linear pump of large pumping speed and capacity, particularly suitable for use in the conductance limited vacuum systems of particle accelerators.¹ A NEG linear pump has been adopted for the Large Electron Positron (LEP) collider which is at present under construction at CERN in the Geneva area.^{2,3}

Use of such a pump for a particle accelerator implies, however, abandoning its traditional operating mode where the getter is kept hot while pumping.⁴ Heating is required to diffuse into the getter bulk the molecules which are continuously adsorbed on its surface and which would otherwise progressively reduce its pumping speed. In the case of LEP, the NEG strip is electrically insulated with respect to the 11-m-long vacuum chamber, and it is accessible for heating by Joule effect via electrical feedthroughs installed at both ends of each chamber. Continuous heating, however, would not be feasible, because the electric–magnetic effects of a current flowing in the getter would upset the circulating electron beams, and also because it would yield an excessive H_2 pressure⁴ and require excessive power. NEG surface cleaning, therefore, may be achieved only by intermittent heating to be supplied, in the absence of beam, whenever the NEG pumping speed decreases to below the minimum acceptable value for the considered application.

Because of the lack of experience in this operating mode, the room-temperature behavior of the chosen NEG in the presence of various gases and gas mixtures was studied in detail. The purpose of the study was to ascertain how frequently the NEG should be heated in LEP operating conditions and, possibly, to optimize the relevant NEG production parameters.

Only the pumping of individual gases is the object of this note; the pumping of gas mixtures will be discussed in a separate paper.

II. CHOSEN NEG AND THE MEASURING PROCEDURE

The chosen NEG is a Zr–Al (16%) alloy bonded in a powder form by cold pressing on a Constantan ribbon 30 mm wide and 0.2 mm thick. The alloy is known by the trademark of St 101 and it is produced by SAES Getters (Milano, Italy).^{5,6} The manufacturer recommends heating under vacuum at $\sim 700^\circ\text{C}$ (1 h) for full activation, and continuous heating at $\sim 400^\circ\text{C}$ during operation. The strip is coated on both sides and presents a narrow uncoated band on the edges, such that the active area is $\sim 540\text{ cm}^2/\text{m}$ length. Pumping speed measurements were carried out on samples 25 cm long by means of a Fischer dome⁷ (equipped with a residual gas analyzer), inside which the NEG sample may be heated by Ohmic dissipation at any desired temperature. To reduce the risk of systematic errors produced by the measuring apparatus, measurements were initially carried out using three distinct but identical systems.

The measuring procedure is as follows. After extraction from the transport can inside which the NEG is sealed under dry nitrogen atmosphere by the manufacturer, the sample is installed in the measuring dome which is pumped by a turbomolecular pumping station and baked at 300°C for $\sim 24\text{ h}$. Then the NEG is activated and the bakeout stopped. Activation is carried out at $740 \pm 10^\circ\text{C}$ for 45 min, a choice which represents the best compromise between achieved pumping speed and mechanical deterioration of the NEG strip. Excessive heating may result in powder peeloff. Laboratory testing showed that this NEG may withstand 50 such activation cycles without any noticeable deterioration.

Measurements are started $\sim 24\text{ h}$ after the end of the bakeout, when the pressure is in the 10^{-11} Torr range and the NEG is at ambient temperature. The gases are injected at a constant rate and the pumping speed S is periodically measured. The measuring range extends from a few hundred to a few liters per second. The measuring uncertainty above $S = 10\text{ l s}^{-1}$ is $\pm 10\%$. In order to provide some pumping

for gases which are not pumped by NEG (CH_4 , A) and avoid pressure buildup, the turbomolecular pump is kept pumping through a known conductance ($\sim 2 \text{ l s}^{-1}$ for N_2).

The gases present inside the LEP vacuum system during machine operation will mainly be H_2 ($\sim 70\%$), CO, and CO_2 . These gases will be desorbed from the walls of the vacuum chamber by the synchrotron light produced by the circulating electron beams.^{8,9} Methane, which is also produced at lower percentage ($\sim 1\%$), is not pumped by NEG and in the LEP vacuum system it will be pumped by 30 l s^{-1} sputter ion pumps installed at $\sim 20\text{-m}$ distance from each other. In addition to these gases, air may enter through leaks. Measurements showed that NEG pumping for CO_2 and air closely corresponds to that for CO and N_2 , respectively, therefore our study was focused only on H_2 , N_2 , and CO.

Usually, individual gases are injected in the sequence N_2 , H_2 , and CO. Nitrogen is injected first because its pumping speed was found to be very sensitive to the initial NEG conditions. After measuring each gas the NEG is heated at $\sim 450^\circ\text{C}$ for 10 min. This heating, which we name "conditioning," is mild compared to that of initial activation, but sufficient in this situation to restore the initial pumping speed.

In addition to vacuum measurements, also direct porosity measurements were carried out. These measurements consisted in weighing NEG samples before and after prolonged immersion in demineralized water. The weight variation is representative of the volume filled by water, provided that the immersion time is long enough to ensure complete displacement of the gases initially present in the NEG porosities.

This study was initiated in 1979 and is still in progress for the acceptance tests of the $\sim 23 \text{ km}$ of strip which are required for LEP. The samples used for the measurements here reported will be singled out by indicating the year of production, or year and month when many deliveries per year were received.

III. RESULTS

The $S(Q)$ curves obtained from samples belonging to two different deliveries (1979 and 1981) are shown in Fig. 1. The pumping curves for N_2 and CO were found to be independent of the gas injection rate, as it should be expected because of the absence of diffusion of these gases at room temperature.

In contrast, diffusion is known to take place for H_2 even at room temperature.¹⁰ For this reason, the decrease of pumping speed with increasing pumped quantity is both much smaller and dependent on the injection rate. For H_2 , the pumping speed at any given moment is defined by the competing action of molecular adsorption and atomic diffusion into the getter bulk. This subject has already been studied¹⁰ and will not be discussed in this paper.

The effect of impurities present in the injected gas is not very relevant. A level of 1% is tolerable for obtaining reproducible results with N_2 and CO. For H_2 , a level of 0.1% is desirable because of the larger H_2 quantities injected.

Measurements not shown here indicated that at complete saturation the NEG may absorb 7 ± 1 times more CO than

FIG. 1. Pumping speed (S) variation vs pumped quantity (Q) for CO, N_2 , and H_2 of NEG's delivered in 1979 and 1981. The rates of injection for H_2 (1979) are curve 1, $8 \times 10^{-6} \text{ Torr l s}^{-1} \text{ m}^{-1}$; curve 2, $5 \times 10^{-5} \text{ Torr l s}^{-1} \text{ m}^{-1}$; curve 3, $5 \times 10^{-4} \text{ Torr l s}^{-1} \text{ m}^{-1}$. The rate of injection for H_2 (1981) is $5 \times 10^{-4} \text{ Torr l s}^{-1} \text{ m}^{-1}$.

N_2 , a result which is in agreement with data obtained from the manufacturer.¹¹

The reproducibility of the measurements on the same sample or on different samples belonging to the same batch for these two different deliveries is within 10%. Therefore the differences shown by Fig. 1 distinctly indicate a real difference of NEG quality as will be discussed in the next section.

IV. DESCRIPTION OF THE NEG PUMPING MECHANISM

A. Basic assumptions and introduction of the pumping model

With the exception of H_2 , gas molecules are chemically adsorbed on the getter surface and do not diffuse at ambient temperature (localized chemisorption). It may be assumed, under these circumstances that

(a) Molecules are adsorbed as a whole onto defined adsorption sites.

(b) Each site may accommodate only one molecule ("single-site" adsorption).

(c) The adsorption on one site is independent of the presence of other molecules on neighboring sites.

(d) No desorption takes place.

Under these assumptions and for a flat surface, it follows from the Langmuir's adsorption isotherm that

$$S = S_0(1 - Q/Q_0), \quad (1)$$

where Q_0 is the initial quantity of adsorption sites and S_0 the initial pumping speed. If S is plotted linearly versus Q , $S(Q)$ is represented by a straight line starting at S_0 and ending at zero for $Q = Q_0$. This result was indeed obtained for CO adsorbed on flat Zr samples.¹² However, if the results shown in Fig. 1 are represented on a linear scale, only the initial part

FIG. 2. $S(Q)$ for CO (1979 NEG) plotted linearly against Q . The intercept on the Q axis of the extrapolated initial part of the curve is assumed to represent the density Q_0 of adsorption sites for CO on a getter surface without holes ($\sim 10^{15}$ sites cm^{-2}).

of the curve is straight, while the lower part bends and presents a long tail with a very slow decrease (Fig. 2).

Since the NEG surface is very rough, it is natural to suspect that the tail originates from surface roughness. A realistic quantitative description of this roughness is not easy. It is known that the very hard getter grains are practically incompressible at the sintering pressure and that the total surface area exposed to vacuum after sintering is practically the same as that of the unbonded powder.¹¹ Therefore it may be assumed that voids of various size and irregular geometry are evenly distributed in the volume of the getter film. A direct confirmation of this has been also obtained by electron microscopy.

In order to extend the mathematical description of the adsorption process to the inner surfaces of the irregular voids, some simplifying assumptions must be introduced. It will be assumed that

(e) On a flat NEG outer surface a multitude of circular holes of equal diameter is present.

(f) Each hole represents the end aperture of a cylindrical straight void the diameter of which is the same as that of the holes and the length of which is equal to the getter film thickness.

(g) For a given gas the density of the adsorption sites is the same on the inner surfaces of the voids as on the outer flat surface, and in first approximation it may be obtained (from Q_0) by extrapolating the initial straight part of the adsorption curve as shown in Fig. 2.

Under these assumptions, the following adsorption process may be considered.

Initially, the gas molecules impinging onto the NEG are absorbed either on the "flat" outer surface or inside the voids. After adsorbing a certain amount of gas, pumping persists essentially inside the voids only. Saturation progresses inside the voids to a depth which is proportional to the quantity of gas pumped.

The pumping speed therefore becomes limited by the conductance of the void length that the molecules must travel to reach a still active surface. Since the conductance is inversely proportional to this length, in this part of the $S(Q)$ curve one obtains

$$S \propto Q^{-1}. \quad (2)$$

This dependence in a logarithmic plot defines a straight line with slope -1 , a result which reasonably approaches the intermediate part of the curves shown by Fig. 1.

In the final part of these curves, the decrease of the pumping speed is enhanced by approaching complete NEG saturation.

B. Quantitative description

In order to arrive at a quantitative formulation of the presented pumping mechanism, the following quantities must be introduced:

A_f = area of the flat surface of 1 m of NEG strip,

A_v = area of the entrance orifice of the voids for 1 m of NEG strip,

$A = A_f + A_v = 540 \text{ cm}^2$ = NEG coated surface per meter of NEG strip,

n^2 = density of the voids per cm^2 of NEG coated surface,

L = thickness of the getter coating,

D = diameter of the voids,

Q_0 = gas quantity needed to saturate the surface of a meter of NEG strip with no holes in its surface,

Q_{sat} = gas quantity needed to saturate the surface of a meter of NEG strip,

α_f = sticking factor on flat clean surface,

α_v = sticking factor at the entrance of the voids,

S_f = pumping speed of the flat outer surface of 1 m of NEG strip,

S_v = pumping speed of the voids present on 1 m of NEG strip,

S_0 = initial pumping speed of 1 m of NEG, and

C = conductance of an orifice of unit area.

With this notation the pumping speed of the NEG outer surface may be written as

$$S_f = \alpha_f A_f C \left(1 - \frac{Q}{Q_0(1 - A_v/A)} \right), \quad (3)$$

while S_v , according to the Knudsen formula for molecular flow, may be expressed for N_2 as

$$S_v = \alpha_v n^2 A \frac{12.5 D^3}{l + 1.3 D}. \quad (4)$$

The gas quantity required to saturate A_f is

$$Q_f = Q_0 A_f / A, \quad (5)$$

and the quantity required to saturate A_v to the depth l is

$$Q_v = n^2 \pi l D Q_0. \quad (6)$$

TABLE I. Geometrical quantities.

Year of production	L (μm)	n^2 (voids/ cm^2)	D (μm)	A_v/A
1979	120	2.9×10^7	0.55	0.07
1981	90	2×10^7	0.85	0.113

Therefore

$$Q = Q_f + Q_v = (A_f/A + n^2\pi l D) Q_0, \quad (7)$$

$$Q_{\text{sat}} = (A_f/A + n^2\pi L D) Q_0, \quad (8)$$

and for $Q \gg Q_0$, combining Eqs. (7) and (8),

$$l \simeq L Q_0 / Q_{\text{sat}}. \quad (9)$$

Finally,

$$S_0 = (\alpha_f A_f + \alpha_v A_v) C. \quad (10)$$

Combining Eqs. (4) and (6) under the approximation $l \gg D$, gives

$$S \simeq S_v = 3.44 \times 10^4 \alpha_v (A_v/A)^2 Q_0 / Q_v. \quad (11)$$

As will be shown later, $D \simeq 1 \mu\text{m}$. On the other hand, $L \simeq 100 \mu\text{m}$ and $Q_{\text{sat}} \simeq 1 \text{ Torr l m}^{-1}$ for CO. Since [Eq. (9)] $l \simeq 10 \mu\text{m}$ at $Q \simeq 0.1 \text{ Torr l m}^{-1}$, it may be deduced that above this Q value and for CO, $S \propto Q^{-1}$ as anticipated by Eq. (2).

Equation (11) provides the additional important information that, under the above approximation, S is proportional to the square of A_v/A . This quantity represents the NEG porosity, i.e., that fraction of the NEG volume which is occupied by voids. The porosity is particularly important here because it appears to be the key quantity to define NEG performance and, furthermore, it is directly measurable, thus providing a powerful means to check the validity of the model developed in this work.

From Eqs. (4)–(11) it results that a NEG may be completely characterized by three geometrical quantities (n^2 , D , L) and three physical quantities, i.e., α_f , α_v , and Q_0 which vary for different gases. The value of L may be directly measured, while Q_0 may be obtained as described in Sec. IV A (g). Obtaining the other four quantities is not straightforward and it has been carried out by guesswork and iteration by differently combining and fitting to experimental data Eqs. (4)–(9). The six relevant quantities and the porosity (which, however, is contained in n^2 and D) for the 1979 and 1981 NEG are grouped in Table I (geometrical) and Table II (physical).

Direct porosity measurements carried out on the 1981 NEG as described in Sec. II gave 0.12 ± 0.01 , in good agree-

ment with the calculated value. Unfortunately, the 1979 sample was not available any more when the present pumping model was developed and its porosity could not be measured. This point is of great practical importance because it shows that the porosity, easily measurable, becomes a very useful indication of the NEG vacuum performance.

In order to extract the values of α_f and α_v , Eq. (10) was fitted to data obtained both from 1979 and 1981 NEG's. The implicit assumption is that a different NEG structure does not affect α_f or α_v . This may not be the case in reality, because the probability that a molecule be trapped in a cavity or on the outer surface strongly depends on their geometry. However, the assumption is perfectly justified in the framework of the model here adopted, in which all voids are cylinders with $L \gg D$ and the outer surface is assumed to be perfectly flat.

It must be noted also that α_f and α_v are derived as if they were independent from each other as well as from Q . In reality, under the assumptions of the model here developed, α_v may be obtained from α_f by computing the trapping probability of a molecule which enters a tube having an infinite l/D ratio and a wall sticking probability α_f . According to this calculation, carried out using a Monte Carlo simulation program,¹³ the α_v values for CO, N₂, and H₂ should be, respectively, 0.7, 0.4, and 0.28, values which are lower than those contained in Table II. More particularly, $\alpha_v = 1$ is physically possible only if also $\alpha_f = 1$. For the time being, this discrepancy appears to be a weakness of the model here developed.

The simulation program¹³ also shows that α_v should increase with increasing Q . This results from the fact that a molecule which deeply penetrates in a void, as is the case for large Q values, has a lower chance of finding its way backwards to the surface and escape pumping. This correction may be neglected when the initial α_v value is close or equal to 1, as is the case here for CO. However, this refinement becomes necessary in other cases, as will be shown in a future paper where the pumping of gas mixtures will be discussed.

C. Computation of the $S(Q)$ curve for CO

By means of the information contained in Tables I and II, it is possible to reconstruct the pumping curve for a given gas, for instance CO (Fig. 3). In this figure are shown the calculated $S_f(Q)$ and $S_v(Q)$, their combination $S(Q)$, and the experimental points. To combine these two curves the injection of small CO quantities is simulated starting from zero coverage. Each injected quantity is subdivided in two parts, i.e., adsorbed on the outer surface and in the voids, proportionally to S_f and S_v at the coverages prior to injection. After each injection, two new points on the curves $S_f(Q)$ and $S_v(Q)$ are defined, the coordinates of which are added to provide those of the corresponding point on the $S(Q)$ curve.

This same procedure was also applied for the case of N₂, and in first approximation a similar agreement with the experimental data was obtained. However, some peculiar differences were noticed, which will be discussed in Sec. IV D.

Figure 3 shows that for CO the agreement between the calculated $S(Q)$ and the measured one is satisfactory in the

TABLE II. Physical quantities.

	CO	N ₂	H ₂
Q_0 (Torr l m ⁻¹)	1.6×10^{-2}	2.3×10^{-3}	...
α_f	0.32	6×10^{-2}	1.7×10^{-2}
α_v	1	0.78	0.32

FIG. 3. Comparison of the calculated (continuous line) and measured (+) $S(Q)$ curves for CO (1981 NEG). Also shown are the calculated $S_f(Q)$ and $S_v(Q)$ which represent the pumping speed of the outer surface and of the voids, respectively.

initial and central parts of the curve. In the final part, the curves diverge. While the calculated S is proportional to the inverse of Q , i.e., its slope is constant, the slope of the measured S progressively increases when approaching NEG saturation. This negative slope increase is linked to the finite thickness of the getter as clearly demonstrated by its earlier appearance for the 1981 NEG with respect to the 1979 one (see Fig. 1). As shown in Table I, the 1981 NEG coating is $\sim 30 \mu\text{m}$ thinner. A faster S decrease when the saturation approaches may be obtained also in terms of the pumping model by introducing a decrease of α_v consequent to the progressive shortening of the voids which takes place when approaching the end of the getter layer. However, this effect would affect $S(Q)$ in the last few μm of the NEG thickness, while the observed bending covers a region a few tens of μm thick. A possible reason for the discrepancy may be that the NEG film thickness is not rigorously constant and consequently the saturation of the voids takes place over a large Q range. This is due to the protrusion of the Constantan into the getter film under the effect of the sintering pressure. A direct confirmation of thickness variation was obtained by measuring the roughness of the Constantan strip after NEG peeloff and also by electron microscopy (see Fig. 4). Both methods indicate that the getter film thickness may vary over a few tens of μm .

D. Case of N_2

The values of n^2 and D may also be extracted from data obtained from N_2 adsorption. These values are in good agreement with those obtained from CO. However, for N_2 the agreement of the calculated $S(Q)$ with the experimental curve is not as good as for CO. At the transition from the initial to the linear part, the calculated $S(Q)$ presents a "shoulder" which is absent in the smooth experimental curve. This bump could not be removed by varying the various parameters within their uncertainty range; therefore a different approach was followed.

FIG. 4. Electron microscope picture of a NEG section. The lighter central part is the Constantan substrate, $\sim 200 \mu\text{m}$ thick before NEG sintering.

It may be considered that CO is quite exceptional because it undergoes single-site adsorption¹² although it is a diatomic molecule. Usually, polyatomic molecules undergo dissociation when chemisorbed and occupy a number of adsorption sites at least equal to the number of atoms present in the molecule. If p represents the number of the sites which participate in the adsorption of a molecule, Eq. (1) becomes

$$S = S_0(1 - Q/Q_0)^p, \quad (12)$$

in which the power p accounts for the decreased probability of finding p free adsorption sites close to each other such as to render the adsorption of a molecule possible. Since N_2 is a diatomic molecule and it is known to dissociate when chemically adsorbed¹² the obvious choice is to take $p = 2$. This choice improves the agreement between the calculated and measured $S(Q)$, but the best agreement is obtained for $p = 6$. The $S(Q)$ curves obtained for $p = 2, 4$, and 6 , and the experimental curve are shown in Fig. 5. Since $S(Q)$ is not very sensitive to varying p above 4 , p cannot be defined very precisely but it may be assumed that $p = 6 \pm 2$.

The adsorption features of N_2 deserve the following comments:

(i) The faster decrease of the $S(Q)$ curve for N_2 , compared to that of CO, is a consequence of the smaller Q_0 . This results in a faster progression of the saturation inside the voids, i.e., a faster reduction of conductance.

(ii) The different slope of the $S(Q)$ curves for N_2 and CO is the consequence of the larger initial contribution for CO of S_f . For N_2 this contribution is small because of the low α_f value and the slope of the $S(Q)$ curve approaches quite well the value predicted by Eq. (2).

(iii) The lower Q_0 for N_2 could, *a priori*, be due either to a lower density of adsorption sites for this gas or to a larger number of sites required for the absorption of a single N_2 molecule. The developed adsorption model gives a direct

FIG. 5. Comparison of the calculated and measured $S(Q)$ for N_2 . The four $S_f(Q)$ curves here shown are obtained for $p = 1, 2, 4$, and 6 , resulting in the four different calculated $S(Q)$ curves. Experimental points are represented by $+$.

physical insight on this point, showing that the latter hypothesis is the correct one. Figure 5 suggests that about six adsorption sites might be occupied by a single N_2 molecule. Since the N_2 molecule is diatomic, it seems reasonable to assume that such a number be even, i.e., $p = 6$, although the fit to the experimental data is not sensitive enough to prove this definitely.

(iv) The value $p = 6$ accounts very well for the different surface saturation quantities measured for N_2 and CO (see Sec. III). In fact, p represents the lower limit to this ratio. Due to the random arrival of the molecules on the surface, adsorption sites may be left between adsorbed N_2 molecules in numbers lower than six, therefore being lost for adsorption and resulting in a larger surface capacity ratio.

(v) The multiplicity of the N_2 adsorption process also accounts for the higher sensitivity to the initial NEG cleanliness conditions which were experienced during the measurements with this gas (see Sec. II).

(vi) According to the Monte Carlo simulation program,¹³ the value of α_v should increase and reach unity approximately at $Q = 10^{-2}$ Torr l m⁻¹, while in the calculated $S(Q)$ curve for N_2 it remains lower than 1. For the time being the reason for this discrepancy is not clear.

V. "IDEAL" NEG

On the base of the model developed here it is possible to calculate the variation of the initial pumping speed S_0 of the Zr-Al NEG as a function of the surface porosity A_v/A . The results of this calculation are shown in Fig. 6. For each gas a straight line is obtained, the slope of which is larger for H_2 . At very large A_v/A (too large to be realistic!) the pumping speed for H_2 even exceeds that for CO.

The theoretical upper limit to NEG porosity may be expressed by the condition $nD = 1$. This is the case of a two-dimensional sequence of voids tangent to each other and filling up completely the NEG surface. Putting $n = 1/D$ in Eqs. (6) and (4) gives

FIG. 6. Estimated variation of the initial pumping speed (S_0) for CO, N_2 , and H_2 of the St 101 NEG as a function of its porosity.

$$Q_v = \pi l Q_0 / D, \quad (13)$$

$$S \approx 12.5 D / l, \quad (14)$$

for $\alpha_v = 1$ (case of CO), $A = 1$, $Q \gg Q_0$, and $l \gg D$.

Combining Eqs. (13) and (14) one obtains

$$S = 12.5 \pi Q_0 / Q_v, \quad (15)$$

which shows that for any n and D values such that $nD = 1$ all pumping curves may be described by a unique equation. Fur-

FIG. 7. Calculated $S(Q)$ curve for CO in the case of an ideal St 101 NEG ($\sim 80\%$ porosity), compared with measured curves for 1979 and 1981 samples.

FIG. 8. Spread of $S(Q)$ curves for CO, N_2 , and H_2 of the NEG delivered for LEP in 1986 (dashed lines), compared with those relative to the 1979 NEG sample. The rate of injection for H_2 is 5×10^{-4} Torr l s $^{-1}$ m $^{-1}$.

thermore, from Eq. (13) follows that for equal L/D ratio also the total gas capacity is the same.

Equation (15) coincides with Eq. (11) when considering 1 m of NEG strip and putting $A_v/A = \pi/4 = 0.785$. This reflects the fact that for $nD = 1$ the porosity is the same whatever values of n and D are chosen.

By means of these equations and of the values of α_f and α_v obtained from Fig. 6, it is possible to calculate for CO the $S(Q)$ curve for such an ideal NEG (Fig. 7). Although it is certainly not realistic to hope for such a level of performance, Fig. 7 also shows, as does Fig. 6, that there is room for further improvements with respect to the results so far presented.

VI. SERIES PRODUCTION FOR LEP

Before the series production was started a program was undertaken by the manufacturer to improve both on NEG quality and on reproducibility of its performance. During this study, which was continued also during the first phase of delivery, the production parameters were varied and carefully controlled in a way which, for obvious reasons, was not disclosed.

The results achieved are illustrated in Fig. 8. With respect to the 1979 quality, S has increased about a factor 4 for CO and N_2 and a factor 2 for H_2 at $Q = 0.1$ Torr l m $^{-1}$. This quantity is relevant for LEP because it was initially assumed that after pumping this amount of CO and CO_2 the NEG pump should be conditioned. The 1986 NEG may pump

three times more gas to reach the same pumping speed, therefore the conditioning frequency will be correspondingly lower.

This quality improvement will be beneficial even for the usual NEG operation at 400 °C. In this case the pumping takes place mainly on the outer surface of the NEG, which is kept clean by diffusion, and therefore S should present a dependence on porosity as described in Fig. 6.

The calculated average porosity for 1986 production is 0.13 and the best value 0.15. Direct porosity measurement on a sample gave 0.15 ± 0.02 . For this same sample the porosity calculated from the $S(Q)$ curve is 0.13.

VII. CONCLUSIONS

Some basic correlations were established between the geometrical characteristics and the vacuum performance of nonevaporable getters. Besides offering a satisfactory description of the experimental observations, the model developed is useful to provide NEG evaluation criteria and production guidelines as well as to indicate the best operating conditions.

NEG porosity measurements may provide a simple way of estimating the vacuum potentiality of a NEG.

Although increased by about a factor 2 since the measurements of the first samples in 1979, the porosity so far achieved is still low with respect to the maximum theoretical limit of about 80%, showing that further improvements may still be possible.

The model also describes remarkably well the NEG behavior when pumping mixtures of different gases and the variation of its performance consequent to pumping large gas quantities and/or ventings to atmospheric pressure. These arguments will be the subject of further publications.

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