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EXTREME VACUA: ACHIEVEMENTS AND EXPECTATIONS

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ABSTRACT

The obtention of pressures between 10^{-12} and 10^{-14} Torr inside vacuum systems operating at room temperature imposes severe limitations on the choice of materials and pumps. If the proper choice is made and the proper procedures are followed, the main obstacle to achieving such low pressure results from the hydrogen outgassing of the metal walls of the vacuum system. However, at the lower end of this range and for pumping systems based on getter pumps (both titanium sublimation and non-evaporable getter pumps), methane may become the main component of the residual gas pressure.

Although a large effort has been devoted to developing suitable gauges, only a few of them have actually been tested at the extreme vacuum for which they were designed. Furthermore, none of the commercially available instruments is adequate for pressures below 10^{-12} Torr.

The basic physical phenomena which contribute to defining the vacuum condition inside a system operating in this pressure range are reviewed. Guidelines to the selection of materials and pumps are given and discussed with the help of some examples.

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1. INTRODUCTION

As many other disciplines, vacuum technology underwent a spectacular progress in the last 50 years. Most of the new developments and inventions were achieved during the first half of this period. The last 20 years have been mainly devoted to consolidation of the progress achieved and the application to a variety of vacuum related disciplines such as surface studies, thin film deposition, space simulation, particle accelerators, vacuum metallurgy etc. Although all these disciplines require ultra-high vacuum (UHV) conditions, the most stringent demands of low pressure arose from space simulation and particle accelerators of the storage ring type.

Fairly complete reviews of the evolution of vacuum technology have been given in some recent papers (1)(2). The aim of the present paper is somewhat less ambitious and more specific. The discussion will be limited to the obtention of extreme vacua (EV), defined here as the pressure domain below 10^{-11} Torr.

After the evacuation of the initial air content, the pressure P inside a vacuum system is determined by the equation

$$P = Q/S + P_0 \quad (1)$$

in which Q represents the amount of gas entering the gas phase per unit time due to leaks, permeation, degassing, and where S is the effective pumping speed and P_0 the limit pressure of the pump, i.e. that pressure the pump would achieve when pumping on itself. Designing a vacuum system implies choosing the proper materials, pumps and, equally important although not apparent from eq. 1, the instruments to measure the resulting pressure. Materials, pumps and pressure gauges are reviewed in three separate sections of this paper. In an additional section the results which have been or could be obtained are discussed with the help of a few examples. Throughout this paper we will try to illustrate the basic physical phenomena which participate in determining the ultimate pressure in a vacuum system as well as to identify the practical difficulties which may be encountered when a particular solution is adopted.

2. MATERIALS

The most widely used material for vacuum applications is stainless steel. Since the pioneering work carried out in the 1950's by Alpert who developed

metal valves and demountable, bakeable joints (3), glass has been gradually and at present completely replaced for the construction of UHV systems. Stainless steel presents many advantages for vacuum applications. It has good mechanical properties, it is oxidation and corrosion resistant, and it is suitable for welding by argon arc. It is hard enough to be used for flanges which may provide vacuum-tight couplings by squeezing gaskets of softer metals like gold, aluminium and copper. Finally, it is bakeable at high temperatures, resulting in clean surfaces with low outgassing rates.

More recently, aluminium alloys have been extensively studied and used for the construction of vacuum chambers. These alloys present two important advantages with respect to stainless steel for some particular applications, i.e. a higher thermal conductivity and extrudability which permits the production of chambers of a multi-channel section without internal welds. Both features are very important for application to electron storage rings of large size, and for this reason aluminium alloys were used for constructing the vacuum chambers of all machines of this type so far built or designed (PEP (4), PETRA (5), TRISTAN (6), LEP (7)). For this particular application aluminium alloys present the further advantage of low induced radioactivity. Beside these advantages, Al alloys also present some inconveniences which make them less suitable for the construction of small laboratory vacuum systems. Welding by argon arc is more difficult and may result in the formation of virtual leaks. The limited hardness does not make them very suitable for the construction of flanges which, in addition, must often be coupled to the stainless steel flanges of standard vacuum components like pumps, pressure gauges, valves etc. To circumvent this obstacle many solutions were developed like the special methods to join on stainless steel flanges (PETRA and PEP), special Al or Cu gaskets for coupling aluminium and stainless steel flanges (LEP) and coating with chromium nitride to increase the surface hardness so as to render the construction of ConFlat type flanges of aluminium alloy feasible (8).

Besides these two materials, copper is extensively used for the production of gaskets and for specific applications in which a high electrical conductivity is mandatory, such as electrical feedthroughs and accelerating cavities.

Because of their very limited use, other metals will not be discussed here.

2.1 Vacuum performance and treatments

In the absence of gases inleaking from the outside, the rate of gas entering a vacuum system (Q in eq. 1) is determined by the release of molecules adsorbed on the surfaces and/or outgassing by diffusion from the bulk of the vacuum chamber walls. The surface contribution must be minimised by carefully cleaning all components prior to assembly and by baking in situ at a temperature higher than about 100°C . Baking in situ results in a fast release of water vapour physisorbed on surfaces, which otherwise would degas very slowly at room temperature and inhibit the obtention of EV, whatever the applied pumping speed would be.

After these treatments have been properly applied, bulk outgassing of H_2 is the major gas source, and therefore represents the major obstacle to the obtention of very low pressures.

Industrially produced stainless steel contains H_2 at an atomic level of a few ppm and giving rise to a degassing rate of H_2 of the order of 10^{-12} Torr $\text{ls}^{-1} \text{ cm}^{-2}$ at the best. This rate may be reduced by vacuum firing at 950°C , under vacuum, for a time of the order of 1 h (9). During the vacuum firing H_2 outgassing is accelerated by the temperature enhanced diffusion (of H_1) and the final hydrogen content is determined by the competing effects of recombinative H_2 release and surface uptake (via dissociative solution) of H_2 present in the furnace atmosphere. Therefore, the lower the H_2 pressure during the treatment, the lower the final hydrogen content as well as the subsequent H_2 degassing at room temperature. A systematic experimental study of the dependence of the H_2 degassing rate on pressure during the thermal treatment has not been carried out yet. This is probably due to the small number of furnaces available for this treatment as well as to the difficulty of obtaining information on their H_2 pressure during operation. However, simple physical considerations indicate that for a given stainless steel the obtainable H_2 outgassing after vacuum firing should be, at least in first approximation, proportional to the H_2 pressure during the treatment. This was qualitatively confirmed by measurements carried out on the ISR austenitic stainless steel which presented an H_2 degassing rate of 2×10^{-13} Torr $\text{ls}^{-1} \text{ cm}^{-2}$ after firing at a nominal 10^{-5} Torr in a large scale industrial furnace and about 10^{-14} Torr $\text{ls}^{-1} \text{ cm}^{-2}$ on samples following a second firing in a better performing laboratory furnace (10^{-6} Torr). It is worth mentioning, however, that according to theory (9)

a vacuum firing at 10^{-4} Torr should already result in a degassing rate of 10^{-16} Torr $\text{ls}^{-1} \text{cm}^{-2}$. The reasons for this apparent contradiction are not clear but for practical purposes it may be assumed that degassing rates at least as low as 10^{-14} Torr $\text{ls}^{-1} \text{cm}^{-2}$ may be obtained in this way.

Aluminium alloys cannot be vacuum-fired at high temperature, and material softening limits the maximum baking temperature to about 200°C . However, the initial degassing rates after in situ bakeout at $100\text{--}200^{\circ}\text{C}$ are much lower than those reported for stainless steel. Typically, a value of about 10^{-13} Torr $\text{ls}^{-1} \text{cm}^{-2}$ was reported by many authors (12)(13)(14)(15). Also in this case, as for stainless steel, pre-baking in air at about 100°C resulted in a degassing rate decrease down to the low 10^{-14} Torr $\text{ls}^{-1} \text{cm}^{-2}$ range (12). A similarly low degassing rate was also achieved by carrying out the extrusion under a controlled, oxygen-argon atmosphere (16).

Both for stainless steel and Al alloys the reported degassing rates for other gases are much lower. Usually they do not exceed 10% of the H_2 value, and therefore these gases have a minor influence on the ultimate pressure achieved in a vacuum system. An exception may be found in the case of CH_4 , which, although characterized by degassing rates 100 to 1000 times lower than those of H_2 , may substantially contribute to the ultimate pressure in a system mainly pumped by getter pumps. This point will be discussed in more detail in section 4 of this paper.

A much smaller effort has been devoted to measuring the outgassing properties of copper. Measurements carried out in our laboratories indicate that Q values in the low 10^{-12} Torr $\text{ls}^{-1} \text{cm}^{-2}$ range may be obtained.

3. PUMPS

As eq. 1 indicates, pumps with large S and low P_0 are needed for achieving very low pressures. Each pump type presents characteristic pumping speeds for the various gases depending on molecular conductances, sticking factors and chemical selectivity. Equally, each pump type presents a limit pressure (resulting at lower pressure in a net gas flow backstreaming from the pump into the vacuum system), which may be determined by wall degassing, vapour pressure, chemical dissociation pressure, limited compression ratio.

The EV domain is very sensitive to pump limitations: eq. 1 shows that only pumps or pump combinations which are capable of P_0 lower than 10^{-12} Torr may be used. For this reason some pump types which are very useful in the UHV range must be disregarded for EV applications. In this category are all pumps which are not bakeable (like the '20 K' cryopumps, in which adsorbing materials are glued to cold surfaces by organic binders) or which make use of organic fluids either for lubrication (turbomolecular pumps) or for pumping (oil diffusion pumps). Sputter-ion pumps, getter pumps and bakeable cryopumps are suitable for EV applications.

3.1 Sputter-ion (SP) pumps

In this pump, ions are produced in the gas(es) to be pumped via a Penning discharge confined by a magnetic field inside (usually) cylindrical cells. An electrostatic potential of a few kV drives these ions towards a cathode, where they are implanted while simultaneously sputtering off cathode atoms. The sputtered atoms (usually titanium) deposited on the surrounding surfaces create a clean metal film which on the one hand may adsorb further gas molecules ('getter' pumping) and, on the other hand, definitively covers the implanted ions. Based on this principle, the SP pump exists in two different configurations, diode and triode.

Although not all details of the functioning of the SP pump are understood, a satisfactory description of the main physical phenomena taking place during pumping has been formulated (17)(18)(19).

The SP pump may be operated at relatively high pressures (10^{-4} Torr), works without need of external intervention over a wide pressure range and pumps all gases, although some of them with lower pumping speed (rare gases). At present triode SP pumps are available on the market which give a pumping speed for argon equal to about a half of the nominal pumping speed. The SP pump is unique in so far as its discharge current may provide a useful indication of the operating pressure.

For the reason of these good characteristics the SP pump became the work horse of UHV pumping. However, it also presents some inconveniences. It is relatively heavy and bulky with respect to its pumping speed, which furthermore tends to decrease at low pressure and even to vanish if the Penning discharge gets extinguished. To overcome this problem, additional electron sources were

sometimes introduced into the pump, as resulting from electron multipactoring produced by an RF field (20) or from radio-active materials (21). These developments, however, are not industrially available.

A more serious limitation of the SP pump is its high P_0 (10^{-11} Torr range), which renders this pump inadequate for EV applications if used alone. Gas analysis shows that P_0 is mainly determined by H_2 , a fact which may simply be a consequence of the degassing of the pump walls. If we consider a commercial pump of 30 ls^{-1} nominal pumping speed, the surface area of the pump envelope is typically about 1500 cm^2 . Assuming a degassing rate of $10^{-12} \text{ Torr ls}^{-1} \text{ cm}^{-2}$, one would expect a $P_0 = Q/S = 5 \times 10^{-11} \text{ Torr}$, a value which agrees with the P_0 actually measured. Using a stainless steel of a lower degassing rate may not result in a proportional decrease of P_0 because of the decreasing pumping speed at lower pressures. Measurements carried out in our laboratories show that even at pressure as low as 10^{-12} Torr the SP pumps keep about a half of their pumping speeds for A and CH_4 . However, this decrease may be larger for H_2 . For this gas the low mass results in a particularly low sputtering yield (22). This reduces the gettering mechanism in the SP pump and renders the desorption of pumped gas molecules easier (22). It is therefore convenient to combine the action of the SP pump with that of a getter pump to increase the pumping speed for H_2 at very low pressures. According to this principle many solutions have been proposed. In some cases the two pumping principles are coupled inside the same pump body like in the binion pump (23) in which additional Ti sublimation from a central rod is achieved by electron bombardment, or in an 'integrated' pump for particle accelerators (24) in which Ti is sublimated by ohmic heating from filaments which hold the cathodes. More recently, Varian has produced a 'combined' pump in which a getter module is added to a standard SP pump (25), resulting in a P_0 in the low 10^{-12} Torr range. This additional getter is activated during the normal in-situ bakeout of the pump and does not require any additional power supply. This combined pump is the only one of this type available on the market at present. Obviously, independent getter pumps may also be added on the same vacuum system; this possibility is discussed in more detail in section 4 of this paper.

3.2 Getter pumps

Gas molecules reaching a chemically active surface may be trapped in the form of stable chemical compounds. Gas adsorption results in increasing surface coverage and progressively decreasing pumping speed, which would vanish at

complete surface saturation. The initial value of the pumping speed may be restored by the deposition of a new reactive layer (sublimation pump). Alternatively, the adsorbed molecules may be diffused away from the surface and into the getter bulk by heating (non evaporable getter). In this case heating may be applied continuously (to cope with high gas loads, i.e. at high pressures) or intermittently. Neither of these getter pump types pump rare gases or methane, but both present very low P_0 and high pumping speeds for all reactive gases.

3.2.1 Sublimation pumps (SU) Although many different metals may be and have been used, the adsorbing film is most frequently obtained by sublimation from an ohmically heated Ti filament. The P_0 of this pump only depends on H_2 concentration in the film and film temperature. At room temperature P_0 may be reduced below any desired value by carefully degassing the Ti filament at sufficiently low pressure. This operation also reduces the possible CH_4 production during sublimation (26)(27). The pumping speed for the various gases is proportional to a 'sticking factor' and to the surface area of the reactive layer. Very large S values may be obtained by sublimating directly onto a large part of the vacuum system walls. This also suppresses the need of a pump envelope and its inherent degassing. Typical values of the specific pumping speed (in $ls^{-1} cm^{-2}$) of a freshly sublimated Ti layer at room temperature are 2.2 for H_2 , 1.2 for N_2 , 4.8 for CO (28). Cooling the Ti film to liquid N_2 temperature enhances these values to 10 for H_2 , 10 for N_2 and 11 for CO (28). Cooling also provides some pumping for CH_4 and A, which must otherwise be pumped by a different type of pump, such as the SP pump.

3.2.2 Non-evaporable getter (NEG) pump During the last 10 years NEG pumps have entered the UHV field for different applications, namely particle storage rings (29)(30)(7)(31), fusion reactors (32)(33) and the combined SP pump (25). All NEG's used for these applications are produced by SAES Getters (Milano, Italy). The most widely used NEG is the so-called ST 101, an 84 Zr/16 Al alloy (34)(35) which, after activation under vacuum at about 740°C for 45 minutes results in pumping speeds at room temperature (in $ls^{-1} cm^{-2}$) of about 3 for H_2 , 2 for N_2 and 5 for CO and CO_2 (36). More recently, a new getter has been produced (37) which requires for activation heating at about 500°C for only 10 minutes. This new getter, designated ST 707, is a 70 Zr/24.6 V/5.4 Fe alloy. Both NEG's are produced in the form of a ribbon of various widths and may be also supplied as pre-assembled units of various sizes and shapes (cartridges, modules). The ST 707 getter provides appreciable pumping speeds even if activated at only 400°C, a temperature which may be achieved during the bakeout of a stainless steel

vacuum system. As with the SU pumps, the NEG pumps may present a very low P_0 if properly activated at sufficiently low pressure and then operated at room temperature. Again, as with the SU pump, NEG pumps must be combined with pumps able to pump CH_4 and rare gases.

3.3 Cryopumps

It may be assumed that a molecule is pumped when its sojourn time on the pumping surface is long with respect to the duration of the experiment for which vacuum is required. The sojourn time, t , binding energy, E , and surface temperature, T , are linked together by the Frenkel equation (38)

$$t = e^{E/kT} \quad (2)$$

For large E values, as resulting from a strong chemical bond (getter pumps) very large t values may be obtained at room temperature. If pumping should rely on the weaker van der Waals forces (physisorption), T must be reduced accordingly (cryopumping). After adsorbing on a cold surface a quantity of gas resulting in the formation of a few molecular layers an equilibrium pressure is established which, in the absence of a gas load, corresponds to the vapour pressure of the adsorbed gas at the temperature of the cold surface. Vapour pressures below 10^{-12} Torr for all gases except He may be produced at a temperature of 2.3 K (39), which may be produced by means of a liquid He bath at reduced pressure (about 50 Torr). Many models of liquid He cryopumps have been designed and some are available on the market. In the cryopumps built at CERN for the experimental regions of the ISR (40)(41), the pumping surface, protected against the ambient room temperature radiation by a liquid N_2 cooled chevron (42), provides pumping speeds (in $\text{ls}^{-1} \text{cm}^{-2}$) of about 9 for H_2 and 3 for N_2 and CO. The resulting total pumping speeds for H_2 are about 4500 and 30000 ls^{-1} for pumps of 32 cm and 80 cm outer diameter respectively.

In the absence of adsorbed gases (a reasonable approximation for EV application) the measured P_0 of these pumps is of the order of 10^{-13} Torr, due to the H_2 degassing from the steel used for the fabrication of the pump outer wall (about $2 \times 10^{-13} \text{ Torr ls}^{-1} \text{cm}^{-2}$). A P_0 value a factor 10 lower may be obtained by using a better steel (see section 2). The autonomy with respect to He filling is of the order of 200 days at pressures below 10^{-8} Torr.

4. CHOICE OF THE PUMPING SYSTEM

Getter pumps provide the easiest and most economical way to achieving large pumping speeds (larger than 1000 ls^{-1}) for reactive gases which represent the main gas load in the EV domain. They require auxiliary pumping, both for inert gases and for properly degassing the getter during bakeout. Auxiliary pumping is best performed by turbomolecular pumps during bakeout to evacuate the released gases from the vacuum system. After bakeout the turbomolecular pump must be valved off to avoid H_2 and oil vapour backstreaming and auxiliary inert gas pumping may be insured by SP pumps.

When dimensioning the SP pump a compromise must be found between the need of large pumping speed at low pressure for inert gases, and H_2 degassing and cost of the pump which both increase with pump size. A precise size dimensioning of the SP pump can be carried out upon knowing quantities which, unfortunately, are usually not well defined, like the low pressure pumping speed of the SP pump and the degassing rate of inert gases. Degassing of CH_4 may vary depending on surface cleanliness, while argon may be released from virtual leaks in the welds in an unpredictable manner. For these reasons it is wise to overdimension the SP pump and minimise the H_2 degassing by properly treating all components. The same result may be achieved by adding large getter pumping in, or very close to the SP pump to prevent as far as possible the released H_2 from reaching the EV region of the vacuum system. For achieving pressures below 10^{-13} Torr with an SU based pumping system, cooling the SU pump to liquid N_2 temperature is essential. Alternatively, bakeable cryopumps may be added. Cryopumps may in principle achieve EV alone, but it is convenient to add also in this case some SP pumping to hold the vacuum before the cryopump is cooled and also to pump He which may enter through small leaks. These considerations are illustrated by the following examples.

4.1 The ISR vacuum system

The 2 km long vacuum system of the Intersecting Storage Rings (ISR) at CERN was operated at an average pressure in the low 10^{-12} Torr range (43). The main residual gas was H_2 degassing from the vacuum chamber walls at a rate of 2×10^{-13} Torr $\text{ls}^{-1} \text{ cm}^{-2}$. Pumping was insured by about 600 SU pumps of about 1000 ls^{-1} pumping speed and 400 SP pumps of 350 ls^{-1} nominal pumping speed. The effective pumping speed was limited in most cases by the conductance of the elliptical vacuum chamber (44). The SP pumps were overdimensioned in the ISR because the use of the SU pumps was not foreseen in the initial design (45).

For this reason the partial pressures of inert gases were completely negligible except in some intersecting points where SP pumps could not be installed because of the presence of particle detectors. For example, in one of these intersections a CH_4 pressure in the 10^{-13} Torr range was measured even with only a few ls^{-1} of SP pumping speed showing that elsewhere smaller SP pumps could have been used. Taking a conservative view, it may be assumed that an inert gas pressure lower than 10^{-12} Torr may be achieved by installing an SP pumping speed of the order of 10 ls^{-1} per m^2 of vacuum system surface area.

4.2 A laboratory system for EV

The EV behaviour of pressure gauges was studied in our laboratories by means of a small vacuum system pumped by a 350 ls^{-1} SP and 3 SU pumps, one of which was cooled at liquid N_2 temperature (46). All the room temperature walls of the vacuum system (measuring dome, outer walls of the pumps and SP pump electrodes) had been vacuum fired (950°C , 10^{-6} Torr). The whole system has been baked dozens of times at 400°C . The extremely low degassing rate of the system resulted in a pressure of about 2×10^{-8} Torr already at 400°C while baking and pumping with the SP pump only. At this temperature, the degassing of stainless steel is about 4 orders of magnitude higher than at ambient temperature. About 2 days after bakeout a pressure of 10^{-13} Torr was routinely obtained, which decreased to 10^{-14} Torr (or lower, this was the limit of our best pressure gauge) when cooling the SU pump to liquid N_2 temperature. The residual gas before cooling was probably CH_4 , but it could not be measured directly because the addition of a residual gas analyser resulted in a pressure limit of 3×10^{-13} Torr. Unfortunately, commercial gas analysers usually present a large surface area and degassing rates of the order of 10^{-9} Torr ls^{-1} .

4.3 NEG pumping

The Large Electron Positron collider (LEP) under construction at CERN (7) contains about 1950 vacuum chambers, most of which are about 12 m long, made of an Al alloy (ISO AlMgSi, or AA 6060) and pumped by a NEG strip (ST101). This strip is 30 mm wide and it is attached via insulating ceramics to a rigid stainless steel carriage inserted in a 'pumping' channel adjacent to the main (beam) channel of the chamber (30). The standard length of the NEG pump is about 11 m. At its extremities the NEG strip is connected to electric feedthroughs to permit NEG activation via ohmic heating. The pumping speeds of 1m of pump are about 1000 ls^{-1} for N, 1500 ls^{-1} for H_2 and 3000 ls^{-1} for CO and CO_2 (36). Pumping

of inert gases in LEP will be insured by appendage SP pumps of about 30 ls^{-1} nominal pumping speed located on average every 20 m.

The very large installed NEG pumping speed is a consequence of the need to pump the large quantities of gas released by synchrotron radiation from the walls of the vacuum chamber during machine operation (30)(47)(7). In the absence of this dynamic gas load, pressures much lower than the required 3×10^{-9} Torr are obtained.

Acceptance tests carried out so far on about 800 chambers indicate that pressures in the high 10^{-12} Torr range 24 h after bakeout (about 20 h at 150°C) and in the low 10^{-12} Torr range after a few days may be achieved. The ultimate pressure consists mainly of CH_4 (about 80%) and H_2 (about 15%). During acceptance tests an SP pump of 30 ls^{-1} nominal pumping speed is mounted on each chamber.

Independent measurements of the pressure gradient obtained while pumping the chamber at one extremity only (NEG pump inoperative) indicate that the degassing rate of H_2 is about $2 \times 10^{-13} \text{ Torr ls}^{-1} \text{ cm}^{-2}$ 24 h after the end of bakeout, and decreases to below $10^{-13} \text{ Torr ls}^{-1} \text{ cm}^{-2}$ after a few days. The degassing rate of CH_4 is about $3 \times 10^{-16} \text{ Torr ls}^{-1} \text{ cm}^{-2}$ and the pressure of this gas is the same irrespective of whether the NEG pump is operative or not. The measured pumping speed of the SP pumps for CH_4 at 10^{-12} Torr is about 20 ls^{-1} .

In the case of LEP vacuum chambers, the ratio of the chamber surface A_c to the NEG surface A_g is about 10. The installed SP pumping speed is of the order of 4 ls^{-1} per m^2 of chamber surface area and the resulting CH_4 pressure about 10^{-12} Torr.

By simple extrapolation of these measurements one obtains that total pressures in the low 10^{-13} Torr range could be achieved by increasing the SP pumping speed by a factor 10. This result was actually achieved inside a smaller stainless steel vacuum chamber pumped by a linear NEG pump and a 30 ls^{-1} SP pump (29).

If pressures even lower are required, also the NEG pumping speeds should be increased. The use of the ST707 NEG appears very promising in this respect. Since it may be activated at normal chamber bakeout temperatures, it does not require electrical insulation and it may be closely packed to cover, at the extreme case, the whole surface of the vacuum chamber, resulting in $A_c/A_g=1/2$.

Assuming that the ST707 NEG presents pumping speeds similar to those of the ST 101 NEG, H_2 pressures in the low 10^{-14} Torr range may be hoped for. Obviously, this benefit would be fully appreciable only by correspondingly increasing the SP pumping speed to the level of a few hundreds of litres per m^2 of vacuum chamber surface area.

However, more information on the low pressure behaviour of the ST707 NEG must be obtained before relying on this solution, particularly since some experiments have given poor results(48).

4.4 Cryopumping

Pressures as low as 10^{-13} and even 10^{-14} Torr may be achieved by cryopumping in small vacuum systems. Cryopumping, however, is not cost effective if used alone for pumping large vacuum systems. In this case the size of the cryopumps must be tailored on H_2 degassing, resulting in unnecessarily large pumping speed for the other gases.

A better approach consists in pumping active gases by getter pumping and adding cryopumping for inert gases when pressures down to or below 10^{-13} Torr are necessary.

According to this principle, pressures in the 10^{-13} Torr range have been obtained inside two different experimental regions of the ISR at CERN (49). Still lower pressures could have been achieved by using a stainless steel of lower H_2 degassing for the fabrication of the vacuum chamber and cryopumps. When getter pumps and cryopumps are combined, the cooling of the cryopump must be carried out after the activation of the getter pump is completed to avoid cryopumping the released gases.

5. PRESSURE MEASUREMENTS

5.1 Low pressure measuring limitations

The Bayard-Alpert gauge (B.A.) is the most widely used pressure gauge in UHV (50). In this instrument, electrons emitted by a hot filament are accelerated towards and into a cylindrical grid and ionise gas molecules inside the grid volume. The ions produced are collected on a straight metal wire installed at

the centre of the grid. The collector current I^+ is related to the electron emission current I^- , gauge sensitivity S and pressure P by the expression

$$I^+ = I^- SP + I_r \quad (3)$$

in which I_r (residual gauge current) represents the pressure independent part of the collector current. The residual current may be produced via various physical mechanisms, the most important and extensively studied of which is the photoemission of electrons from the collector by x-rays produced by the ionising electrons hitting the gauge grid.

Since the development of the BA gauge in 1950, most of the effort devoted to low pressure measurements has been aimed at decreasing I_r (2)(51)(52). To do so, the obvious approach consists in reducing the size of the collector, which has been made thinner (53)(54) and shorter (54) and finally placed outside the grid volume to be shielded as far as possible from x-rays (55)(56)(57)(58). Another (complementary) approach consists in increasing the gauge sensitivity by increasing the length of the electron path inside the grid volume. This may be achieved by optimising electron trajectories (59) and/or enlarging the grid diameter (60). A higher S value not only results in an effective reduction of I_r with respect to the true ion current, but also provides a higher collector current for a given pressure, a very desirable feature when measuring very low pressures. If $I^- = 10^{-2}$ A and $S = 60 \text{ Torr}^{-1}$ (60), eq. 3 gives $I^+ = 0.6 P(\text{A})$. This indicates that pressures in the 10^{-14} Torr range will result in currents which may be measured by good quality but otherwise standard electrometers. Since by means of special instruments (for instance vibrating reed electrometers) electric currents as low as 10^{-16} A may be measured, the measurement of the ion current does not represent a limiting factor.

The efforts to reduce I_r may, however, considerably decrease the gauge sensitivity by rendering the ion collector less efficient. Furthermore, to reduce degassing it might be convenient to operate the gauge at lower I^- , resulting in a further ion current decrease. For these reasons high sensitivity gauges have been constructed both by increasing the electron path length by means of a magnetic field (61)(62)(63) and by amplifying the ion current by means of an electron multiplier (64)(65). This latter approach may result in sensitivity variations and adds some complexity to the instrument, but offers the advantage that varying the bias voltages on electrodes may permit the

discrimination, at least to a certain extent, of I_r from the true ion current (64). Many low pressure gauges are reported to exhibit a pressure limitation lower than 10^{-12} Torr, but only seldomly were such very low pressures actually measured (46). At present, the measuring range of commercially available gauges extends only to 10^{-12} Torr.

5.2 Pressure perturbations by measuring instruments

The pressure gauge should not only be adequate for measuring pressure, but also it should not influence the pressure to be measured. Unfortunately, this is usually not the case both because the heating produced by the hot cathode results in an increased H_2 degassing and because the accelerated electrons (and the X-rays they produce) desorb H_2 , CO and CO_2 from the surrounding walls. A BA gauge operating at $I^- = 4$ mA may produce an H_2 degassing rate of 10^{-9} Torr ls^{-1} , even if the stainless steel of the surrounding walls is of good quality. If the gauge is inserted in a tubular connection of 34 or even 60 mm inner diameter, such a degassing would result in a local pressure on the gauge higher than 10^{-12} Torr, whatever the low pressure capability of the vacuum system.

For this reason low temperature electron emitters, like thorium oxide or lanthanum hexaboride are mandatory as cathode material for EV, and even so the walls around the gauge must be made from carefully degassed stainless steel and baked in-situ at a temperature higher than $350^\circ C$.

A tungsten filament working at $2000^\circ C$ may dissociate polyatomic gases like O_2 and H_2 . This results in pumping (the highly reactive atomic species stick to any surfaces where they impinge) which, for H_2 , may reach the value of $2 ls^{-1}$. This disturbance is not very important per se, on systems where pumping speeds of many thousand litres per second are installed. However, if the gauge is exposed to high pressures of H_2 as may happen during Ti sublimation or NEG activation, a considerable amount of gas may be pumped which later results in prolonged degassing and prevents the attainment of the expected pressure.

Also in this case, a remedy may be found in the use of low temperature electron emitters, which operate at temperatures too low to produce molecular dissociation. If the cathode is made of pure W, the measuring instrument should be switched off at high pressures.

6. CONCLUSIONS

Both Al alloys and stainless steel, the latter degassed under vacuum at 950°C, offer degassing rates after an in-situ bakeout close to or below 10^{-13} Torr $\text{ls}^{-1} \text{cm}^{-2}$. Pumps (cryopumps) or pump combinations (getter and sputter-ion pumps) exist with pumping speeds higher than 10^3 ls^{-1} and with sufficiently low P_0 to produce pressures in the 10^{-12} Torr range in large vacuum systems and 10^{-13} Torr in small laboratory systems. At the price of a larger effort both these limits may be reduced by a factor 10 as shown by some examples.

Although an impressive amount of work has been devoted during the last 30 years to developing gauges capable of measuring pressures below 10^{-11} Torr, very few gauges have actually been tested down to their estimated measuring limit. Furthermore, no gauge exists on the market for measuring pressures in the 10^{-13} Torr range.

Residual gas analysers, not discussed in this paper, could be used to measure pressures down to 10^{-15} Torr, but their high degassing rates may represent a major obstacle to achieving pressures below 10^{-13} Torr.

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