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Bakeable Molecular Pumps*

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THE principle of molecular pumping was first utilized for producing vacua by Gaede in 1912. Since that time, Gaede,[1] Holweck,[2] Siegbahn,[3] von Friesen,[4] and others[5] have improved the technique of molecular pumping until the lowest pressure attainable is determined only by the vapor pressure of the lubricants in the bearings of the pump or by the fact that the parts of the pump exposed to the high vacuum cannot be baked out. For example, von Friesen[4] reports a pumping speed of 73 l./sec at 10^{-3} mm Hg. Also, with the same pump he obtained a limiting vacuum of 6×10^{-7} mm Hg.

The purpose of this paper is to report some experiments with molecular pumps which may be baked out and when used with the proper fore pumps will produce high vacua.[6] The bakeable molecular pumps when used with a fore pumping system consisting of the standard rotary and diffusion pumps in series, is particularly effective for several reasons. First, they pump all kinds of gases and vapors. They are especially effective in removing the heavier molecules which usually are present because of the unavoidable back streaming of the diffusion pump. Second, they require no cold traps or baffles; third, it has been shown by theory[5, 7] that when the molecular mean free path is somewhat greater than the depth of the grooves in the stator the ratio of the pressure on the high vacuum side to that on the fore pressure side of the pump is constant and independent of the absolute pressure on the fore pressure side; and fourth, no high speed ions or hot emitting surfaces in the vacuum chamber are present to release contamination.

To illustrate the principle of molecular pumping, consider a stationary surface with a second surface moving, along with a velocity v shown schematically in cross section in Fig. 1. Molecules striking the moving surface are given momentum in the direction of its velocity which in turn produces an increase in pressure from A to B. In practice, the moving surface usually is a cylindrical surface of a spinning tube or rod or the flat surface of a spinning disk. The stationary surface contains grooves which are cut in such a way as to direct the molecules along the axial direction if the rotor is a cylinder or in a radial direction if the rotor surface is a disk. The depth and width of the grooves are much larger than the clearance between the moving and stationary surface. The exact dimensions of the grooves and the pitch of the spiral depends upon the speed of the moving surface, the fore pressure, the desired ratios of the pressure p_A at A to the pressure p_B at B, and the required pumping speed. The clearance between the two surfaces is usually made as small as conveniently possible.

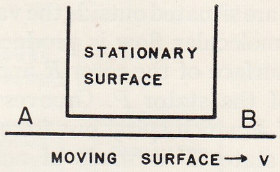

FIG. 1. Principle of molecular pump.

Figure 2 shows a schematic diagram of a disk type

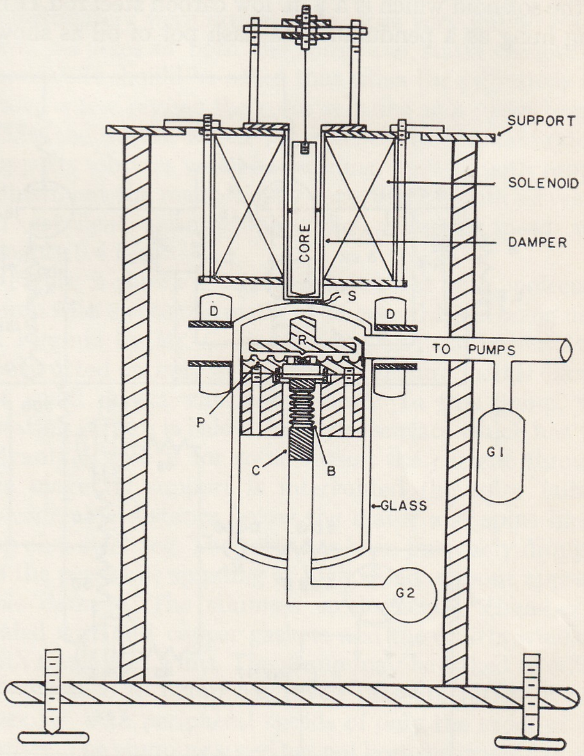

FIG. 2. Disk type metal-glass molecular pump.

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1 W. GAEDE, *Ann. Physik* **41**, 337 (1913).
2 F. HOLWECK, *C.R. Acad. Sci. Paris* **117**, 43 (1923).
3 M. SIEGBAHN, *Arch. Math. Astr. Fys.* **30B**, No. 2 (1943).
4 S. VON FRIESEN, *Rev. Sci. Instrum.* **11**, 362 (1940).
5 S. DUSHMAN, *Vacuum Technique.* Wiley, New York, 1948, p. 151.
6 J. W. BEAMS, *Science* **130**, 1406 (1959); *ibid.* **120**, 619 (1954).
7 R. B. JACOBS, *J. Appl. Phys.* **22**, 217 (1951).

molecular pump which may be baked out at as high temperature as the glass parts will stand. The steel or magnetic stainless steel rotor R is freely suspended inside of a vacuum tight glass chamber by the axial magnetic field of the solenoid which is mounted above the chamber. A small sensing coil S is used to regulate the current in the solenoid in such a way as to maintain the rotor at the desired height or clearance above the stator P. The rotor is spun by a rotating magnetic field in a manner similar to that of the armature of an induction motor. The drive coils D are situated outside the vacuum chamber.

The induced molecular flow is produced between the spinning lower surface of the rotor R and the stationary upper surface of the stator P. Grooves are cut in the upper surface of P which spiral out from the axis to the periphery. The stator P is made of non-magnetic low vapor pressure metal such as Duralumin or stainless steel. The loosely fitting stator is positioned in the glass chamber by three stainless steel springs not shown in the figure. The stainless steel tube is sealed to the stator P with a copper gasket and then welded to the stainless steel Sylphon B. The Kovar to glass seal at C is located at least 20 cm below the plate and is concentric with the axis of the rotor because the Kovar is magnetic. The remainder of the pump is glass. The rotor is usually spun in the proper direction to give the low pressure at the axis and the high pressure at the periphery, although these pressures may be reversed if the direction of the rotor spin is reversed.

The solenoid contains 35,000 turns of No. 22 copper wire and is mounted on an adjustable support. The core of the solenoid which is a $\frac{5}{8}$ in. low carbon steel rod 11 in. long hung as a pendulum in a dash pot of oil as shown in Fig. 2. The sensing coil and electronic circuits give great vertical stability to the rotor but it is usually advisable to provide horizontal damping of the solenoid or its core to prevent the building up of oscillations. The rotor may have any convenient diameter. The one shown in Fig. 2 is 5 cm diameter and is operated from 3000 to 3500 rev/sec. The strength of the rotor material is the only limiting factor to the speed which may be used. Because of the very low friction on the rotor, when the pressure at the axis is below 10^{-7} mm Hg, the rotor is allowed to "coast" without the drive during a few days at a time.

The magnetic suspension system has been described in detail previously[6] so only a brief description will be given. Figure 3 shows a typical support circuit. The sensing coil L_2 is in the grid circuit of a partially neutralized tuned-grid tuned-plate oscillator that operates at a frequency between 3 and 10 Mc/sec. A variation in the height of the rotor R changes the Q value of the oscillator circuit and hence the amplitude of the oscillations. The output of the oscillator is applied to the grid of a 6J5 tube used as a cathode follower. The d.c. voltage appearing across the cathode resistor is an electrical measure of the distance between the rotor and the sensing coil. A part of this error signal and its derivative are amplified, mixed, and applied to the grid of a second cathode follower stage. The combined signal is then applied to the grids of the 5881 output stage and hence regulates the current through the support solenoid, L_1. In Figs. 2 the solenoid current was the order of 120 mA. Several different types of support circuits have been used successfully including the frequency modulated control as well as the above amplitude modulated control.

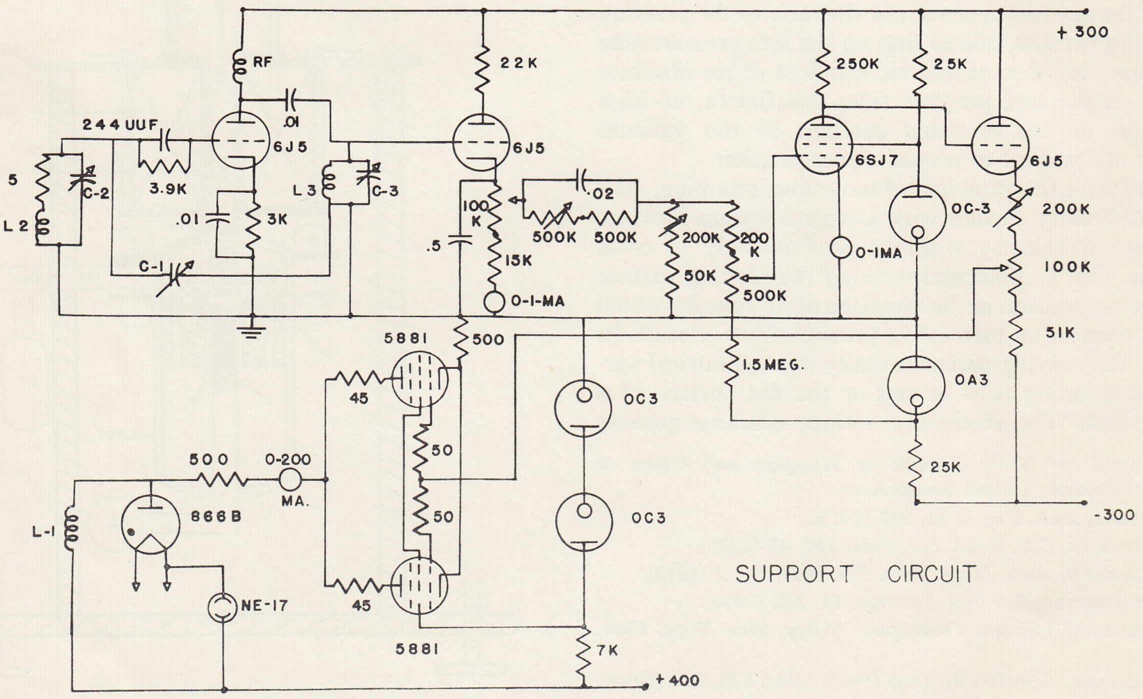

Fig. 3. Magnetic support circuit diagram.

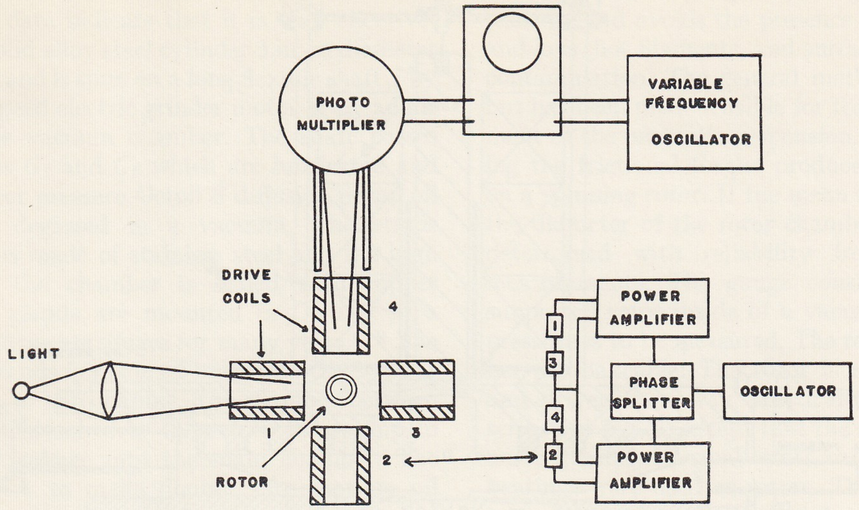

FIG. 4. Method of speed measurement and drive for the rotor.

Figure 4 shows a schematic diagram of the rotor drive together with the method of measuring the speed. Essentially the drive may be any kind of generator which will produce a rotating magnetic field. For the 5 cm rotor shown in Fig. 2 an electronic generator was used since the frequency required was of the order of 4000 c/sec. The power was one kilowatt but this is more than necessary unless very rapid acceleration is desired. However, for larger diameter rotors an a.c. motor generator set may be used. These are especially useful for rotor speeds below 1500 rev/sec and are commercially available. Either two or three phase drives may be used. The rotor speed is measured by reflecting or scattering light off of the rotor into a photomultiplier cell or other light detecting device. The output of the photomultiplier is periodic with a repetition rate equal to the speed of the rotor. This electrical signal is amplified and compared with that from a known frequency oscillator by means of a cathode ray oscilloscope.

In order to test the operation of the pump in Fig. 2, the system was first evacuated with the diffusion pump through two cold traps with the one next to the molecular pump containing copper foil. Alpert type ionization gauges G_1 and G_2 were placed on the fore pump and on the high vacuum side of the molecular pump respectively. The system containing the cold trap with the copper foil, the ionization gauges and the molecular pump were baked at between 300°C and 400°C for one day. Liquid nitrogen was placed in the first cold trap, the furnace was removed and liquid nitrogen placed in the copper foil trap. The rotor was next magnetically supported at the desired clearance above the stator and the rotor accelerated to running speed (3000 rev/sec) which gave a peripheral velocity of about 6×10^4 cm/sec. The ratio of the pressure at the fore pump side p_B to that on the high vacuum side p_A was measured by the two ionization gauges. It soon became apparent that with small clearances it was necessary to adjust the fore pressure p_B to values the order of 10^{-5} mm Hg and higher if reliable readings of the ionization gauges on the high vacuum side at the highest rotor speeds were to be obtained since the pressure ratios at full speed reached values of over 10^4 with clearances of as large as 0.3 mm. The clearance could be held with a precision of at least 0.1 mm. Actually, the limiting factor of the clearance was due to vibrations of the building and mounting which unfortunately were rather large. It is very important to keep the axes of both the rotor and stator accurately vertical. It should be noted that when the vibrations are above a few rev/sec the rotor remains at a given height while the stator which is attached to the laboratory supports vibrates with the building. In fact, with proper adjustment the magnetically supported system serves as an excellent seismograph. The pumping speed was roughly 0.4 l./sec.

Figure 5 shows a schematic diagram of a molecular pump with a rotor diameter of 24 cm, which is being used at Virginia by Mr. C. E. Williams and the writer. It is constructed entirely of low vapor pressure metals except for small quartz viewing windows. In this pump, the rotating surface is below the stator surface which has the advantage that if for some reason the current through the magnetic support is interrupted the rotor falls a considerable distance below the stator and spins like a top on a steel peg. The rotor has been purposely dropped on the peg while spinning at high speed without appreciable damage. The stainless steel vacuum chamber is sealed with soft copper gaskets and the quartz windows with small gold wires. The pump may be baked to 400°C if desired. The pump has given pressure ratios of well over 10^3 with peripheral speeds of only the order of 10^4 cm/sec. The pumping speed has not been measured but it is considerably larger than for the pump in Fig. 2. The rotor is driven by a standard commercial a.c. motor generator.

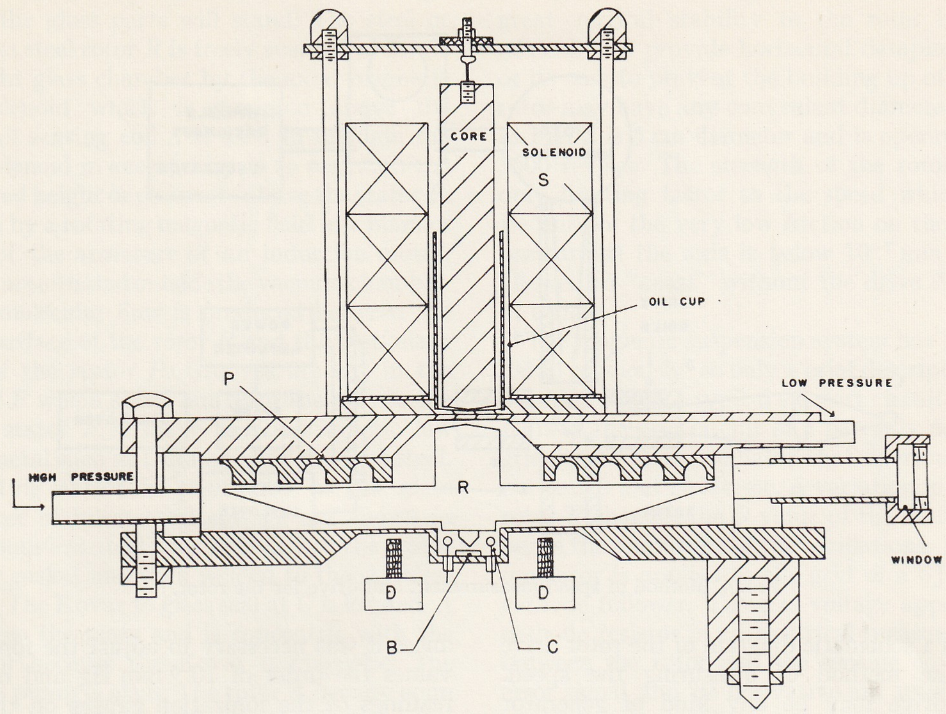

FIG. 5. All metal disk type molecular pump.

Figure 6 shows a magnetically supported cylindrical rotor pump. This operates in essentially the same manner as the pumps shown in Fig. 2 and Fig. 5 except the pumping takes place along spiral grooves in a cylindrical instead of a disk surface. This pump has been constructed but has not as yet been thoroughly tested out. The support solenoid is above the vacuum chamber and is not shown. Preliminary data indicate that greater care in adjustment is required than in the case of the disk type pumps especially if the clearance is small.

Figure 7 shows still another design of bakeable mole-

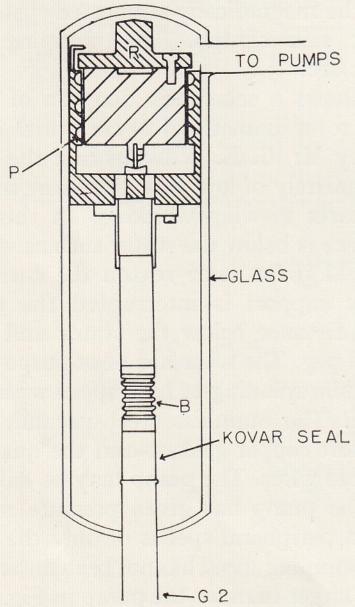

FIG. 6. Cylindrical type metal-glass molecular pump.

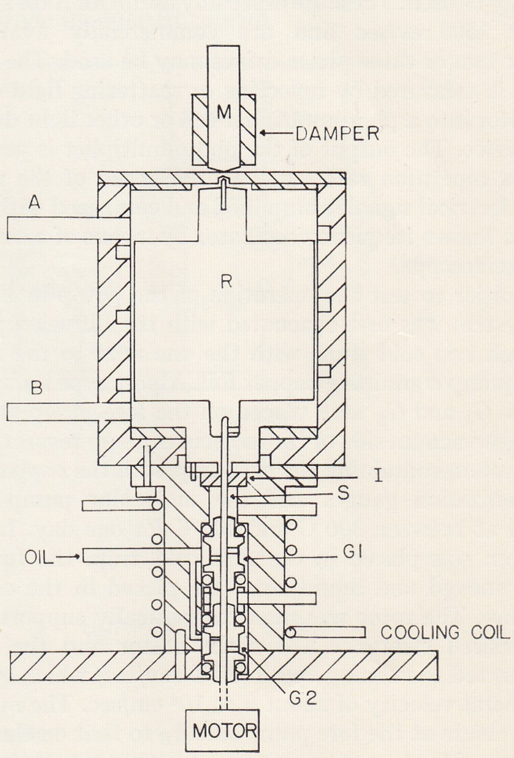

FIG. 7. Mechanically driven molecular pump.

cular pump which has been constructed and is now under test. Preliminary data indicate that it is very effective. The rotor R is a solid alloy steel cylinder 3 in. in diameter and 2.580 in. long and is spun on a long flexible shaft S by a standard high speed electric grinder motor or by an air turbine below the vacuum chamber. The shaft passes through oil glands G_1 and G_2 which are lubricated and sealed by low vapor pressure Octoil S diffusion pump oil which has been degassed in a vacuum. The stator (i.d. = 3.028 in.) is made of stainless steel and the high vacuum part of the chamber is sealed with copper gaskets. The oil glands are mounted in O-rings in a manner used in ultra-centrifuges for many years.[6, 8] The housing for the glands is made of brass and the bearing surfaces are made of hard babbit. The chamber between G_1 and G_2 is kept attached to the rotary fore pump to minimize the oil leakage into the main chamber. The Teflon baffles I are to make doubly sure that no oil droplets reach the rotor R. In order to center, to damp, and partially support the rotor R, a permanent magnet M or an electromagnet is placed above the chamber as shown in Fig. 7. This permits a small diameter lower shaft to be used. The small shaft at the top fits loosely into a dry journal and serves only to align the rotor during the start up period. With this arrangement, no oil can enter the high vacuum side of the pump. The upper chamber A to B is placed in a furnace with the part below B extending down below the furnace. Cold water is forced through the cooling coils during the baking process. This keeps the vapor pressure of the Octoil S oil below 10^{-8} mm Hg. The conduction of heat down the thin flexible shaft is so small that the temperature in the glands is not appreciably changed. With this type of cylindrical molecular pump both the pressure ratios and the pumping speed should be larger than in the disk type pumps described above.

Theories of molecular pumps have been proposed by several investigators.[7] The detailed application of these theories to the above types of pumps gives expressions for the pressure ratios p_B/p_A which are somewhat complicated. However, they show that this ratio p_B/p_A increases roughly as the peripheral velocity of the rotor and inversely of at least the square of the clearance. Our measured values so far are in fair agreement with theory, but it is hoped that it will be possible to obtain more precise data especially at the lower pressures which will subject the assumptions of the theory to a more rigid test.

With the above types of bakeable molecular pumps it is possible to reduce the pressure to values which are difficult to measure. This is especially true if precise values are required. In view of this, we have been experimenting with a gauge which gives reliable values of pressure and avoids the presence of high speed electrons and ions, hot filaments, and surfaces which may produce contamination. The general method is a very old one[5] but has been made feasible for this work by the development of the magnetic suspension.[8] It consists in measuring the frictional torque produced by the gas or vapor on a spinning rotor. If the mean free path is longer than the diameter of the rotor chamber, the pressure can be determined with reliability from the gas frictional measurements. The gauge consists of a magnetically supported rotor inside of a vacuum chamber where the pressure is to be measured. The rotor and vacuum chamber are bakeable. The rotor is magnetically suspended and driven in a way practically identical to that described in Fig. 2, except that the stator is not present. In our experiments, small steel balls such as used in ball bearings were used as rotors. These rotors can be spun to speeds which give a peripheral speed of almost 10^5 cm/sec. without exploding. The rotor is first driven to the speed desired and then allowed to coast. From its deceleration the pressure of the gas can be determined. If the friction in the magnetic support is comparatively small with respect to the gaseous friction and a spherical rotor is used, then it can be shown that

$$\log_e \frac{N}{N_0} = \frac{-5cp}{r\ d}\left(\frac{M}{2\pi RT}\right)^{\frac{1}{2}} \quad (t - t_0)$$

where N_0 is the number of rev/sec. at the time t_0, N is the number of rev/sec. at time t, p is the pressure in dyn/cm^2, d is the density of the rotor material, T is the absolute temperature, M, is the molecular weight of the gas, r is the radius of the spherical rotor, and c is a constant which turns out in practice to be approximately unity. It is clear from the above formula that for the lowest pressures small diameter rotors should be used. We have used rotors from about 5 mm to 0.2 mm in diameter. Much smaller rotors may be spun successfully but the above steel spheres can be obtained commercially and are quite accurately spherical. To illustrate the scope of the method with a 0.2 mm sphere spinning at say 1.5×10^6 rev/sec in a vacuum chamber at 10^{-10} mm Hg, the rotor would lose about 0.6 rev/sec per hour. This, of course, can be measured easily since frequencies can be determined with high precision. The very small friction which should be present in the magnetic support itself can be allowed for by measuring the deceleration at various low pressures and extrapolating the data to zero pressure. This type of measurement is now in progress in our laboratory for steel spheres of various sizes.

It is indeed a pleasure to record my indebtedness to Messrs. L. A. Dorrier, Jr., F. Linke, P. Sommer, and C. E. Williams for most valuable assistance with the above experiments.

[8] J. W. Beams, *J. Wash. Acad. Sci.* **37**, 221 (1947); *Physics Today* **12**, 20 (1959).