Vacuum

Gauges for ultrahigh vacuum

Modifications of the early triode ionization gauge have greatly extended its low-pressure limit and have also increased the complexity of operation and interpretation.

W. J. Lange

The basis for essentially all gauges used for total or partial-pressure measurement in ultrahigh vacuum is the ionization produced by electrons traversing the space between two electrodes. The ratio of ion current to ionizing current is measured and assumed to be proportional to the gas density or pressure. This principle has been used for over fifty years, spurred and nurtured by the vacuum-tube industry, so it was natural that early gauges resembled simple triode receiving tubes (see figure 1 on the facing page).

The production and measurement of vacuum has always been a prime concern of those scientists studying surface conditions—in particular thermionic, field and photoelectric emission. Early workers in these fields encountered a barrier of sorts at about 10^{-8} torr. We now know that this was not because lower pressures were never reached but rather because this was the low-pressure limit of their gauges. On some occasions these workers noted that surface conditions continued to change while their gauge readings remained steady in the region of 10^{-8} torr. The best indication of the state of the vacuum seemed to be that obtained from flash-filament data.

The development of the Bayard-Alpert gauge[1] some twenty years ago penetrated this barrier by permitting the measurement of pressures below 10^{-8} torr and gave great impetus to the study of surface phenomena and to vacuum technology generally. In this article we will take this pressure region, below 10^{-8} torr, as our definition of what we mean by "ultrahigh vacuum," and will concentrate on the gauges that are useful at those pressures. The emphasis will be on popular gauges, the interpretation of their pressure indications, their limitations and the precautions one must take while using them. Frequently the pressure indication is not simple to interpret, and the gauge may itself alter the pressure being measured. Phenomena that can lead to misinterpretation include the soft x-ray effect, surface-generated ions, ion pumping, adsorption, chemical change in gaseous species, high-frequency oscillations and nonlinearity.

The total-pressure gauges available in the range include the Bayard-Alpert gauge itself, some improved hot-cathode gauges and magnetic-field gauges. We will also discuss briefly the partial-pressure gauges (with which the residual gases may be identified or measured separately) that can be used in ultrahigh vacuum.

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The Bayard-Alpert gauge

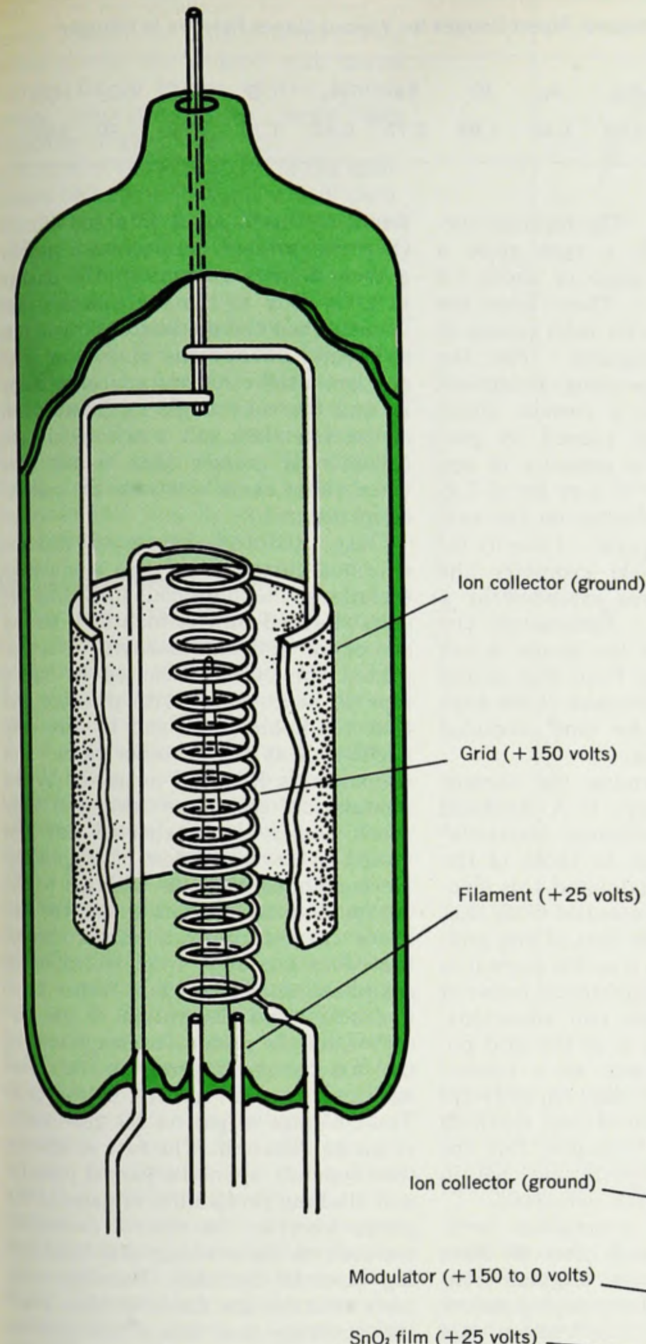
We can best understand the gauges in the ultrahigh-vacuum region by describing the most widely used—the Bayard-Alpert gauge (BAG). As shown in figure 2, it resembles the early triode gauges of figure 1 except that the geometry has been inverted so that the ion collector is on the axis of the tube. R. T. Bayard and D. Alpert introduced this new geometry[1] to reduce the spurious current in the ion collector.

The Bayard-Alpert gauge, like all other ionization gauges, measures the ratio of ion current to ionizing current, i^+/i^-. Clearly the number of ions produced by an electron as it moves from one electrode to another depends on the density or pressure of the residual gas:

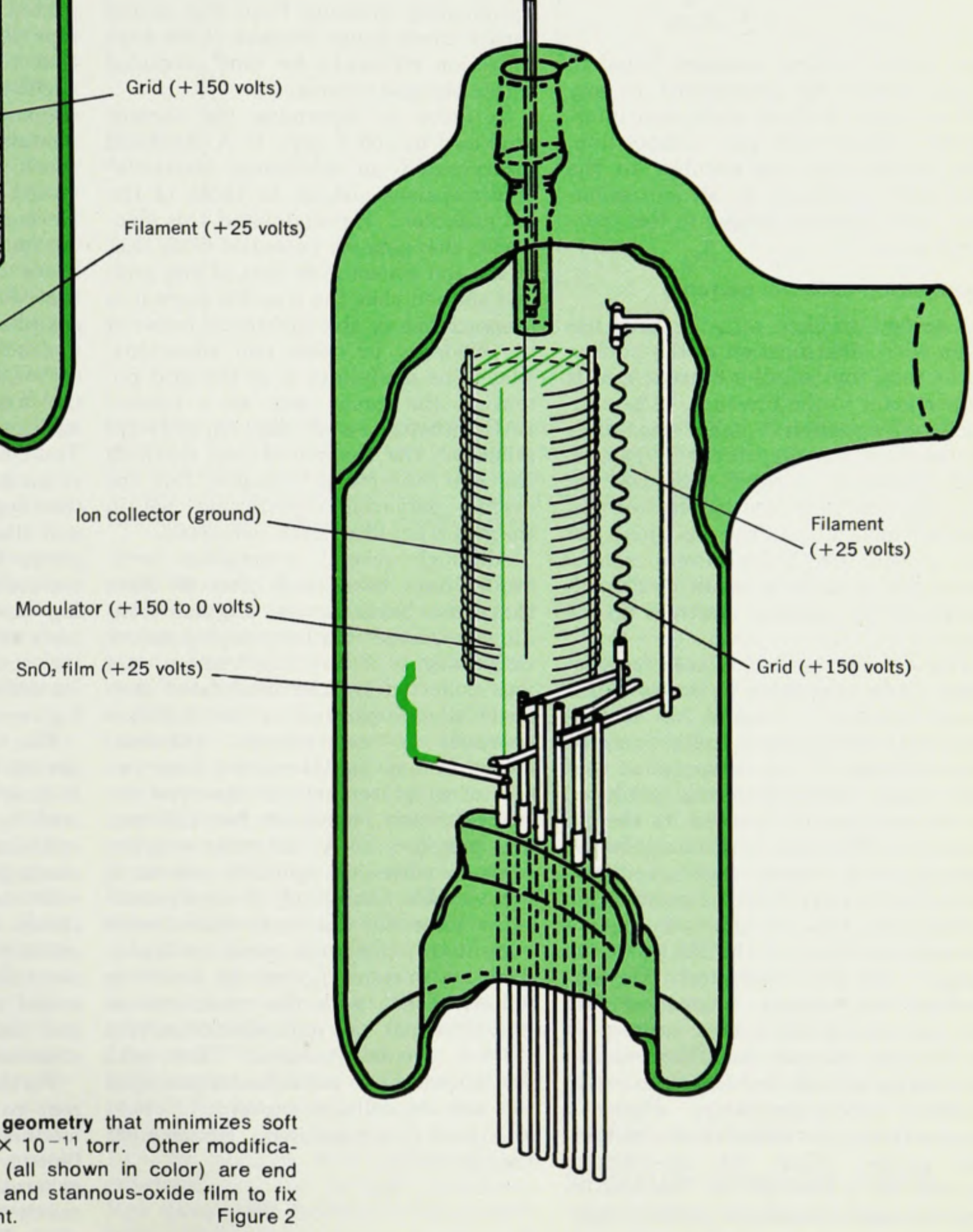
$$i^+/i^- = Kp \qquad (1)$$

However the number of ions also depends on the actual path length of the electron between the electrodes, the kinetic energy of the electron, and the gas species. The factor K in equation 1, commonly called the gauge sensitivity, includes all these factors as well as the probability of collecting an ion once it is produced. K cannot be calculated with any reliability; it must be determined experimentally by calibration. A typical value of K for nitrogen is 12 torr^{-1} for gauges without grid caps (for example, WL-5966). Sensitivities for various gases relative to nitrogen are listed in the table. The values represent a composite of the results of a number of authors and are in reasonably good agreement with total-ionization cross sections. The absolute values for nominally identical gauges may vary by as much as 20%.

In the Bayard-Alpert gauge the electron path length turns out to be about 2 cm on the average. Most electrons do not go directly to the wires of the spiral grid but make at least one trip through the grid. Because the potential inside the grid falls off logarithmically toward the centrally located, negatively biased ion collector, the electron energy over most of the grid volume is reasonably uniform. The ioni-



Triode ionization gauge was originally limited to pressures greater than 10^{-8} torr by interference from soft x rays. Typical potentials for the various components are shown. Figure 1



Bayard–Alpert gauge has inverted geometry that minimizes soft x-ray effect and extends range to 4×10^{-11} torr. Other modifications from triode ionization gauge (all shown in color) are end caps on grid, modulator electrodes and stannous-oxide film to fix the wall at the potential of the filament. Figure 2 zation probability as a function of electron energy rises steeply from onset to a broad maximum lying between 50 and 150 volts. Consequently the filament-to-grid bias is selected at, say, 125 volts. The ion collector is biased some 25 volts below filament potential so that it is the most negative element. Even so, not all ions produced in the gauge reach the ion collector; many ions are created outside the grid and are not recorded. Of those created within the grid structure some orbit the collector and escape axially because of initial velocity and conservation of angular momentum. This effect is reduced in some designs by including mesh end caps on the grid (as in figure 2).

The problem of change in sensitivity with gas species imposes an ultimate limit of accuracy, because the BAG is a total-pressure gauge and in general the gas composition is not known. For a mixture of gases equation 1 becomes

$$\sum_n (i^+/i^-)_n = \sum_n K_n p_n$$

and clearly the true pressure, equal to $\sum_n p_n$, cannot be determined to any real accuracy without additional information about the gas composition. This problem is not peculiar to the BAG but is common to all ionization-type, total-pressure gauges in this pressure region.

Sensitivities of Bayard–Alpert Gauges for Various Gases Relative to Nitrogen

Gas	He	Ne	Ar	Kr	Xe	H_2	CO	O_2	CO_2	H_2O
K/K_{N_2}	0.16	0.30	1.45	1.95	2.75	0.42	1.15	0.90	1.40	0.90

Spurious ion-collector currents

A second problem with the BAG has to do with identification of the portion of the total ion-collector current that is proportional to the pressure. The simplicity of equation 1 belies the many phenomena that may occur in gauges. The measured current includes not only the ions produced by electron impact on molecules in the gas phase but also at least two other current components that arise as a result of the collection of the ionizing electrons on the grid.

Historically the first of these components to be identified is the so called "x-ray current." Legend has it that Wayne B. Nottingham,[2] after consulting with John C. Slater, suggested that soft x rays (bremsstrahlung) produced at the grid are intercepted by the ion collector. The photoelectrons released give rise to a current that is indistinguishable in sign from the positive ion current and that, in effect, imposes a low-pressure limit on the old triode ion gauge. Shortly thereafter, Bayard, working with Alpert, recognized that the fraction of soft x rays intercepted by the ion collector could be reduced by a factor of well over 100 by using an inverted triode geometry. Figure 3 demonstrates the effectiveness of their new gauge. Here, the ion-collector current as a function of filament-to-grid voltage (essentially electron energy) is compared for the original triode gauge and the BAG. The residual current caused by soft x rays gives a straight line with a slope of about 1.6 on the log-log plot. These lines are evident in the curves for both gauges at sufficiently low pressures. For the BAG at normal operating potentials the soft x rays give a current about equal to the current caused by gas-phase ionization at a pressure of approximately 4×10^{-11} torr for a 0.2-mm diameter ion collector on the axis of a 1.9-cm diameter grid. Thus by inverting the old triode geometry the low-pressure limit was extended by a factor of about 500. Fortunately the overall sensitivity of the gauge is not significantly different from that of the earlier triode gauge because of the high collection efficiency for ions produced within the grid volume.

In order to determine the current produced by soft x rays, P. A. Redhead incorporated an additional electrode[3] of dimensions similar to those of the ion collector. He modulated this electrode, changing its potential from that of the ion collector to that of the grid, and showed that the true ion current is proportional to the difference between the currents in these two situations. When the modulator is at the grid potential, the gauge acts as a normal BAG; when it is at the ion-collector potential, the fraction of ions reaching the ion collector is changed, but the overall potential distribution within the grid is not drastically perturbed.

Although several modulation techniques have been used, they all have the same basis as the original technique. In the relatively high-pressure range, say 10^{-6} torr, the fraction α of ions collected by the modulator electrode when operated at ion collector potential is determined. (Alternatively, it may be determined from two sets of measurements of the type described below, made at two different low pressures.) At an unknown low pressure where the spurious current i_s is a sizeable fraction of, or even constitutes most of, the total ion-collector current i^+, the true pressure-dependent ion current, i_0, can be found as follows: First, with the modulator at grid potential, the ion-collector current $i^+ = i_0 + i_s$ is measured. Then, with the modulator at ion-collector potential the new ion-collector current, $i^{+'} = (1 - \alpha)i_0 + i_s$ is measured. Subtraction then gives

$$i^+ - i^{+'} = \alpha i_0$$

from which the true pressure can be found by inserting i_0 into equation 1. (For the present purposes we neglect a second-order correction—the change in x-ray flux to the ion collector that results when the modulator potential is switched.[4] When the modulator is at grid potential electrons are collected by it, and the solid angle for interception of the attendant soft x rays by the ion collector is greater than is the case when those same electrons are collected by the grid.)

Once Redhead began to measure spurious currents with his modulation technique, he obtained surprising results that led him to identify a second source of spurious currents. He expected the currents caused by soft x rays to be constant with pressure and time for noble gases and to vary only slightly, if at all, for other gases. But the currents Redhead measured by the modulation technique were not only much larger than expected but also varied by several orders of magnitude. He concluded that, in addition to the current induced by soft x rays, the collector current contains an ion current that does not arise from ionization of gas-phase molecules but rather from ionization and desorption of gas adsorbed on the grid. The magnitude of this ion current depends on the coverage and species sorbed on the grid. The coverage of gas on the grid reaches an equilibrium: The rate of adsorption depends upon the partial pressure and sticking probability of gases in the gauge whereas the rate of desorption depends on the coverage and bombarding electron current. Because many more neutrals are desorbed than ions,[5] the coverage and hence the spurious ion current can be minimized by using high emission currents.

The effect of emission current on the size of error is illustrated by figure 4. A molybdenum grid was initially covered by a monolayer of oxygen. The emission current was set at 80 microamps, and the pressure of oxygen was measured. The true pressure, shown by the lower, colored curve, is initially high because of desorption of neutrals. A higher emission current would increase the rate of desorption and thus decrease both the time constant and the error.

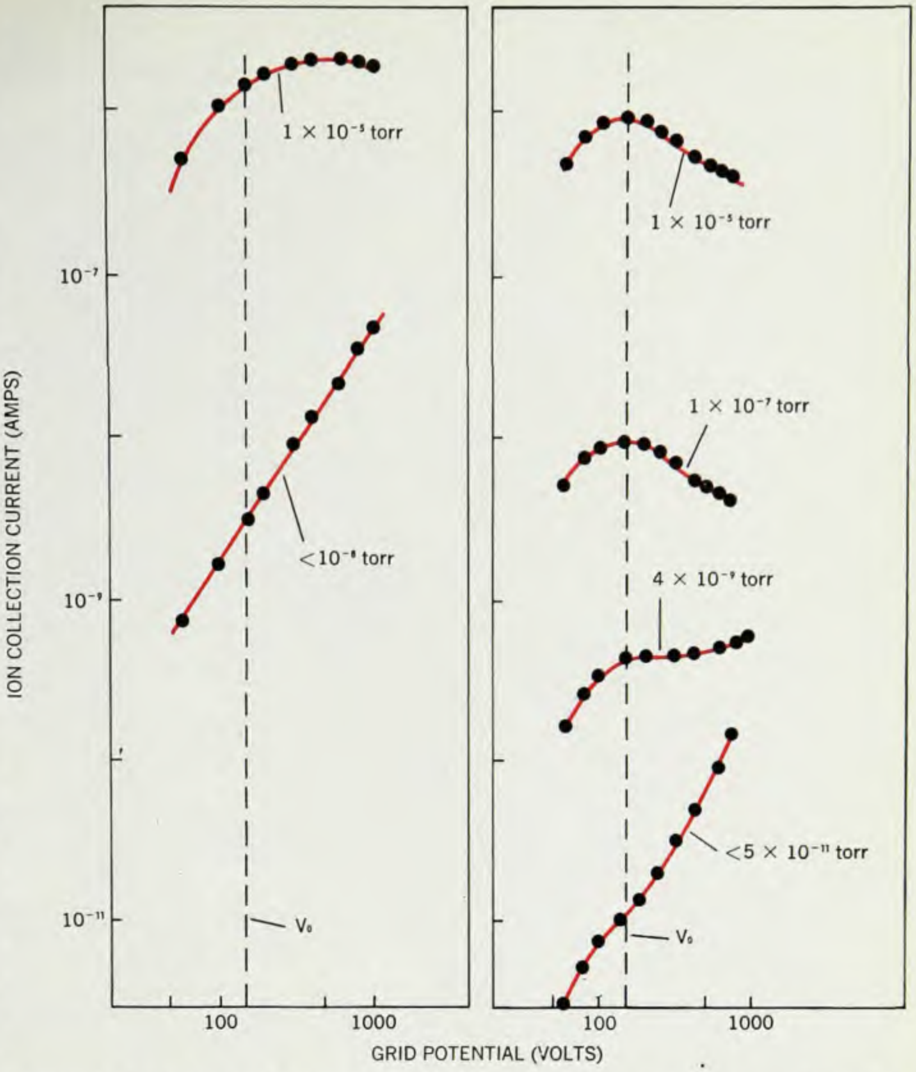
Fortunately, the *total* spurious current can still be determined with the modulation technique, because the efficiency for collection of the surface-generated ions is low and not significantly different for the two electrostatic-field conditions used in modulation. The low efficiency for collection results because the ions generated from sorbed species are created with initial energies far in excess of the kinetic energy associated with most ions formed in the gas phase.

In spite of the simplicity of the modulation technique it is not widely used. Yet the errors that may be undetected without it are enormous. For example, with a 10-mA ionizing current and a true oxygen pressure of 1×10^{-9} torr, the pressure indicated by a normal BAG will be five times too large; for lower ionizing currents, often used for other reasons discussed below, the gauge indication may be in error by two orders of magnitude. The data of figure 4 dramatize the magnitude of the errors that may be encountered because of desorption.

Underestimation of pressure

With two rather infrequent exceptions the spurious current leads to an overestimation of the pressure. The first of these cases occurs under certain circumstances when electrons reach the ion collector in large numbers. Usually this is evidenced by a relatively large negative current to the ion collector, several orders of magnitude greater than the positive ion current. At 10-mA electron current, the electron density within the grid structure is high, enabling spontaneous, coherent, rf oscillation of this space charge. Some electrons gain sufficient energy from the rf field to reach the ion collector. In general, these "Barkhausen–Kurz" oscillations only occur in a BAG at pressures below 10^{-9} torr. Two controllable factors contribute to their occurrence. One is the envelope potential: Oscillations are more likely when it is positive with respect to the filament. The second is the filament heating current: Although the oscillations occur with either direct or alternating currents, they appear more frequently with dc. Stray magnetic fields may also contribute to establishment of the oscillations.

When such oscillations occur they can usually be eliminated by changing a parameter that directly affects the space charge cloud. The most effective means are reduction of the electron emission or application of a magnetic field of about 50 gauss in an arbitrary direction. However, both these measures can lead to erroneous pressure indications; when the electron emission is reduced, the ratio of surface-generated ions to those from the gas phase increases, and when a magnetic field is used, the electron trajectories are altered and the gauge sensitivity or calibration changes. By contrast to the spurious currents, which give pressure indications that are clearly erroneous, the Barkhausen–Kurz oscillations for dc heating currents may give pressure indications that seem to be authentic but are in reality too low and are significantly altered when the direction of heater-current flow is reversed.



Difference in performance between old triode gauge (left) and Bayard–Alpert gauge is evident in these curves. At high pressures, both are in approximate agreement with ionization probability curves. At lower pressures, residual current caused by soft x rays gives straight lines for the triode gauge. Normal operating potential V_0 is a few hundred volts (see the vertical dashed lines in both curves). Figure 3

The second rare exception that can lead to an underestimation of the pressure occurs when the gauge envelope is at the same potential as the ion collector,[6] such as may be the case when the gauge is mounted "nude." Soft x rays from the grid can release photoelectrons from the envelope, and some of those electrons can then reach the ion collector. Even though the number of electrons reaching the ion collector is small it may well exceed the number of photoelectrons leaving the collector. Obviously the effect depends on the solid angles subtended. It can be prevented by proper biasing, so that the ion-collector potential is at least 5 to 10 volts negative with respect to the envelope. In the normal glass-envelope gauge this problem is eliminated, because the glass assumes a potential such that the net current to it is zero. Except for rare occasions this potential is very nearly equal to that of the filament, that is, some 25 volts above ion-collector potential. In this condition the net electron current to the envelope is equal to the positive ion current to the envelope. A second possible stable potential of the glass envelope is at or near the grid potential. Again the net current to the envelope is zero, in this case because the secondary-electron coefficient is unity. To prevent establishment of this infrequent condition the envelope may be coated with a conducting film (for example, stannous oxide), or an additional open grid or mesh electrode can be incorporated such that the gauge electrodes are enclosed by this additional electrode. In either case the shielding electrode is at filament potential.

Effect of the gauge on the ambient

In a sense the Bayard–Alpert gauge is a destructive test device, because

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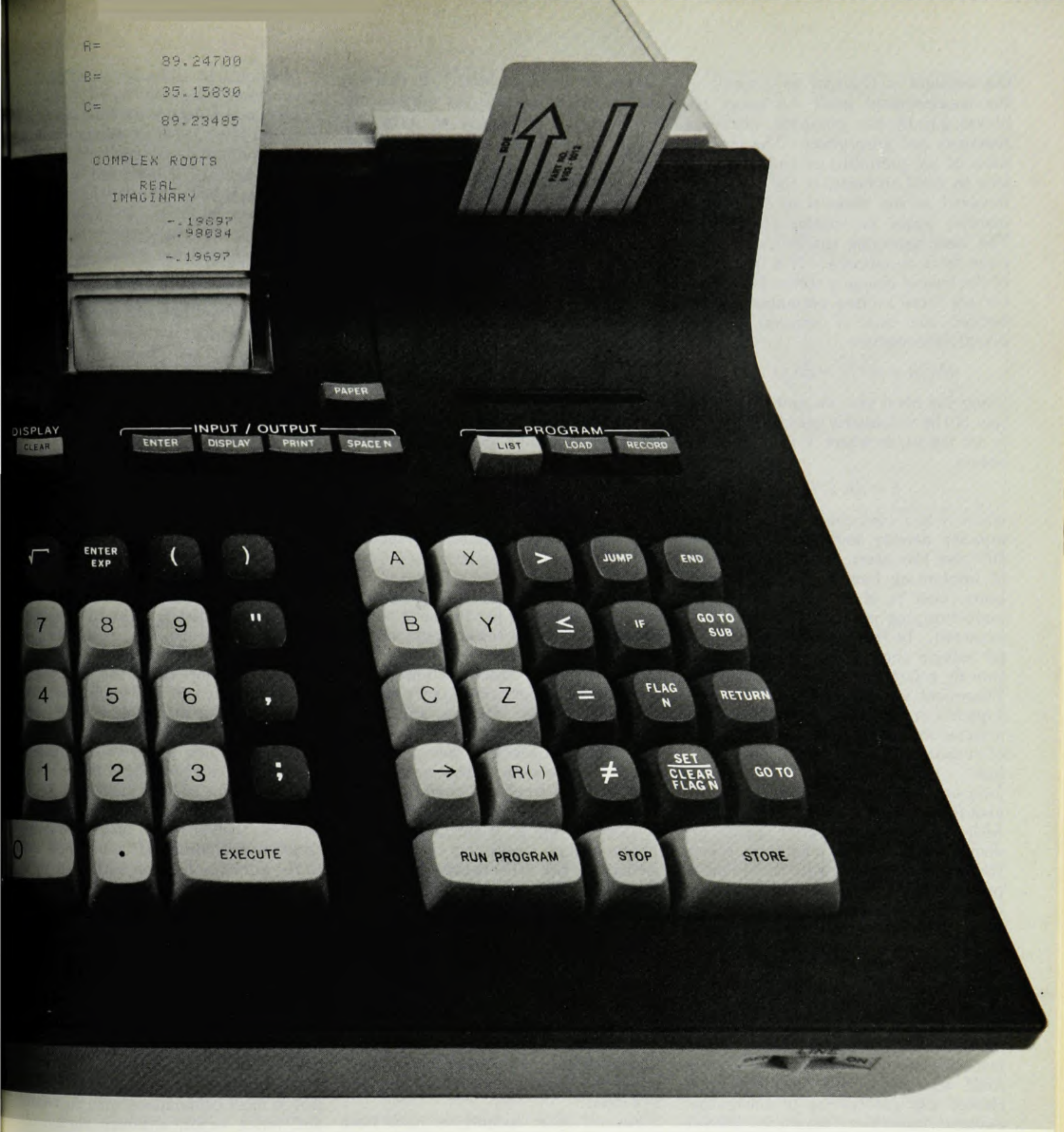

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CALCULATOR PRODUCTS

the ambient is changed as a result of the measurement itself. A gauge removes gas by ion pumping, chemical reactions and adsorption. The mechanism of ion pumping, or embedding of ions in solid surfaces, is the basic one involved in the removal of chemically inactive gases in sputter-ion pumps. The ionic pumping speeds can be derived from equation 1: If a fraction β of the ions of charge q to the ion collector are more or less permanently embedded the rate of removal of gas, dN/dt, is given by

$$dN/dt = \beta i^{+}/q = \beta K p i^{-}/q$$

Using the ideal gas law and the definition of the volumetric speed, namely, $S = Vd(\ln p)/dt$ where V is volume, we obtain

$$S = \beta K\, i^{-}/q\gamma$$

where γ is a conversion factor between number density and pressure (3.5×10^{19} per torr-liter). If the probability of implanting ions in the collector is unity, that is, if $\beta = 1$, a maximum ionic-pumping speed for the gauge is expected. In fact, more ions are created outside than inside the grid structure by a factor of approximately four. These ions are pumped at the filament supports or the envelope, whether it be a metal wall or the inevitable thin film of evaporated metal on the glass envelope. *Consequently, the maximum* ionic speed of a Bayard-Alpert gauge is about equal to Ki^{-} or 0.1 liter per sec. Although initial measured speeds are about equal to this maximum speed, the speed decreases with the quantity pumped until a dynamic equilibrium is established between the rate of entrapment of impinging ions and the rate of release of the gas that had previously been buried.

The second mechanism leading to change of the ambient in the gauge involves chemical reactions of the gas molecules at the hot filament. These reactions not only remove molecules from the gas phase but may also change the gas species in the gauge. Several important reactions involve carbon impurities in the filaments employed. The introduction of gases such as hydrogen, oxygen and water frequently results in the generation of significant partial pressures of carbon monoxide, carbon dioxide and methane. *The actual pressure or density of* gas estimated on the basis of gauge output will then be in error because of the varying ionization probability with gas. Even worse the gauge may generate a relatively high partial pressure of *impurity.*

The carbon impurity in tungsten filaments, which provides a source for CO and CH_4, can be reduced significantly by first operating the filament at a temperature exceeding 2000 K in a dynamic pressure of about 10^{-6} torr oxygen for about an hour.[7] In this way the carbon diffuses to the surface and reacts with the oxygen to form CO, which is removed by the vacuum pump.

In addition to these reactions leading to impurities and change in the gas composition, other mechanisms lead to direct removal of gases from the gas phase. For example, oxygen reacts on the filament surface to form tungsten oxide, which has a high vapor pressure and condenses on the envelope or on the first cool surface it strikes. In addition, for filament temperatures greater than 1650 K, dissociation is significant, and the atomic oxygen adsorbs and chemically combines with atoms or molecules on the envelope or other surfaces to form stable adsorbed species.[8] In a typical BAG with a tungsten filament operated to give 10-mA emission, the pumping speed that is due to the dissociation of molecular oxygen may be as large as 0.5 liter per sec.

To reduce the effects arising from the presence of the hot filament, efforts have been directed toward reducing the emitter temperature. Emitting surfaces with work functions lower than that of tungsten are employed with considerable success. Barium and strontium oxide mixtures, such as those used in commercial electron tubes, are not *applicable because their emission is* drastically affected by chemically active gas and upon exposure to the atmosphere even at room temperature. Thoria-coated refractory-metal filaments, on the other hand, are widely used. For the same emission-current density, thoria-coated filaments operate at 500 deg C lower than tungsten emitters and have a reduced rate of evaporation from the emitting surface. Thoria-coated iridium offers the additional advantage that it is not damaged if it is exposed to air when hot. Thoria-coated tungsten or iridium filaments are particularly recommended for work in oxygen, water vapor and hydrogen.[8]

Several other techniques have been tried to eliminate the chemical pumping. Cold-electron emitters have not been developed to a state of usefulness, and certain problems may even decrease their potential for eventual use. Reverse-biased junctions at present *lack in total emission and emission* stability. Field emission is inconvenient at best, and photoemission leads to problems of desorption of adsorbed gas by the photons. Elec[illegible]ulti-pliers present problems [illegible]ess and convenience and, [illegible]il require a primary electr[illegible]

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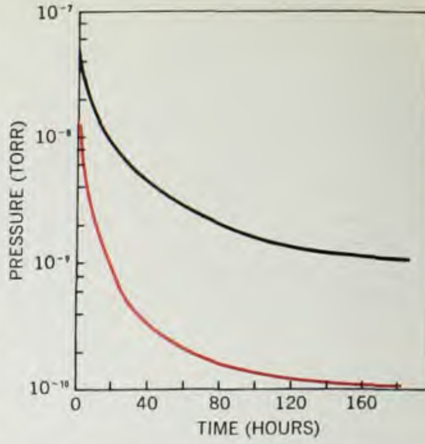


False readings. Desorption of ions causes measured pressure (black curve) to read higher than true pressure (color). High initial pressure comes from desorption of neutral species. Figure 4

by heating the gauge elements to high temperature. In this case the gauge indicates the lower pressure that exists in the gauge itself. Thus if the conductance between the gauge volume and the remainder of the vacuum system is smaller than the equivalent pumping speed of the gauge surfaces, the pressure in the gauge will be lower than the system pressure by the ratio of that pumping speed to the conductance. Errors exceeding a factor of ten can occur for a well degassed gauge connected to the system by a 1-cm tubulation that is 15 cm long. However, these errors drop to zero once the gauge surfaces become saturated by a monolayer coverage of gas, for then the adsorption no longer occurs.

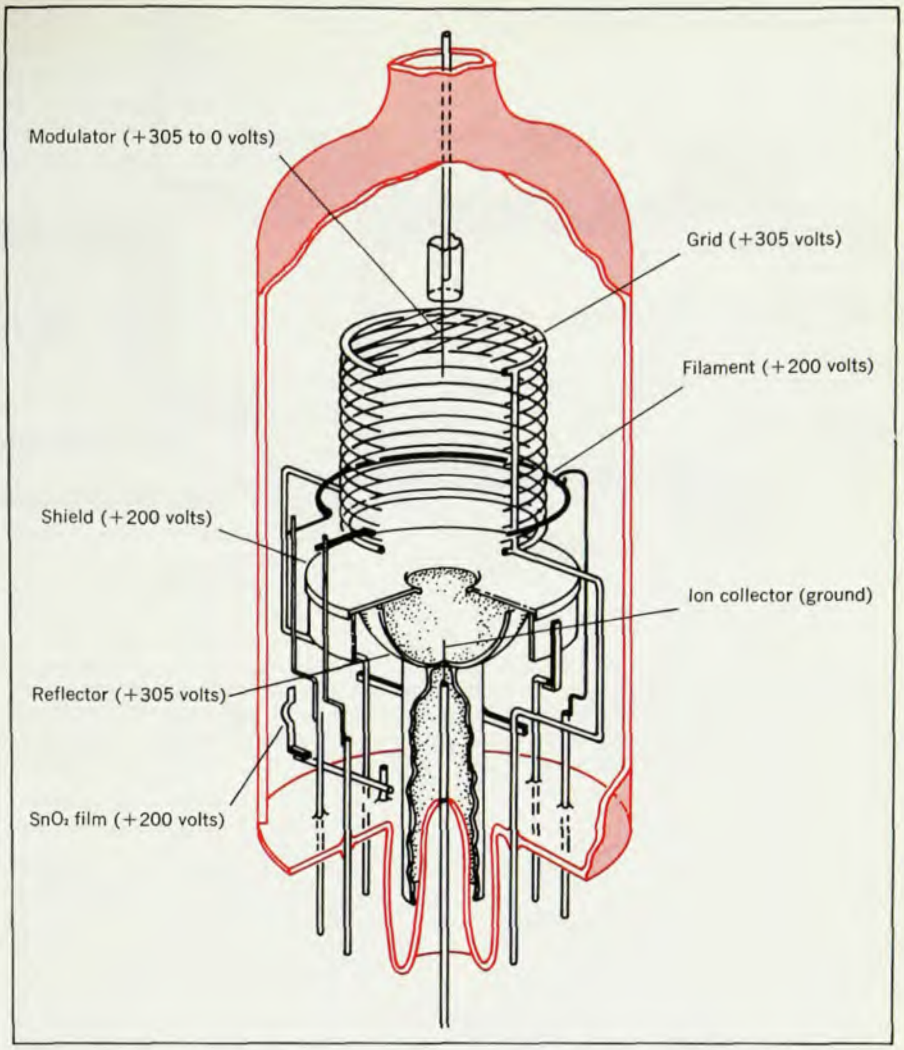
A closely related problem, the so called "Blears effect"[9] is associated with the use of tubulated, as compared with nude, gauges. The crux of this problem is the adsorption of gases on the tubulation between the gauge and the system proper. As a result the gauge may indicate a much lower pressure than exists in the system. The effect is most pronounced with oil vapors and water vapor, although normal ultrahigh-vacuum processing techniques eliminate these vapors. Carbon monoxide, however, can also present problems because of its relatively long sojourn time on surfaces such as glass, which frequently is used as the tubulation.[10] Thus a CO molecule from the system adsorbs and desorbs in its [illegible]rom the system to the gauge, [illegible] total [illegible] in the adsorbed [illegible]uc[illegible]han the time in [illegible]as[illegible]rmore, it [illegible] abil[illegible]ng remo[illegible] by [illegible]ng or ch[illegible] so [illegible]ssure [illegible] nat[illegible]der of [illegible] nil[illegible]urce of [illegible] i[illegible]ssure in [illegible]e" pre[illegible] in the remaining parts of the system.

Most of the problems discussed so far in connection with the BAG also exist to varying degrees in other total-pressure gauges. Perhaps the outstanding advantage of the BAG is its simplicity of electrode structure. The total area and volume of metal electrodes is small, and the gauge can be easily degassed. The most satisfactory method of degassing is by electron bombardment; one to two tenths of a kilowatt at a kilovolt or less can be deposited in the structure without significant evaporation. Adequate degassing of the grid and ion collector requires temperatures of 1500 to 2000 K for at least a half hour. In gauges whose filaments are coated with ThO_2 or LaB_6 the high voltage for degassing must not be unrectified ac, or the cathode will be irreparably damaged by ion bombardment. Degassing by ohmic heating of the grid is inadequate for ultrahigh-vacuum work, because the necessarily high temperatures cause the grid to sag.

Improved hot-cathode gauges

The modulation technique is one way to extend the range of the BAG by one order of magnitude. Other gauges have been designed that have significantly lower pressure ranges but that lack the simplicity of the BAG. The first of these is the suppressor gauge, in which additional electrodes are introduced so that ions are accelerated from the grid volume and focussed onto the ion collector, whereas photoelectrons ejected from the collector by soft x rays are forced to return to the collector. The suppressor is located so that no line-of-sight path exists for soft x rays from the grid to reach it. Thus, no electron current should flow from the suppressor to the ion collector. However, the reflectivity for soft x rays is of the order of 25%, so that photoelectrons from reflected x rays still present difficulties. Redhead and J. Peter Hobson[14] have shown this gauge to be capable of measuring pressures in the range of 10^{-13} torr Adding a modulator electrode enabled them to extend the range by another order of magnitude. Yet the problem of photoelectrons together with the remaining problem of spurious ion current from electron-induced desorption of ions appear to be reasons for essential abandonment of this gauge.

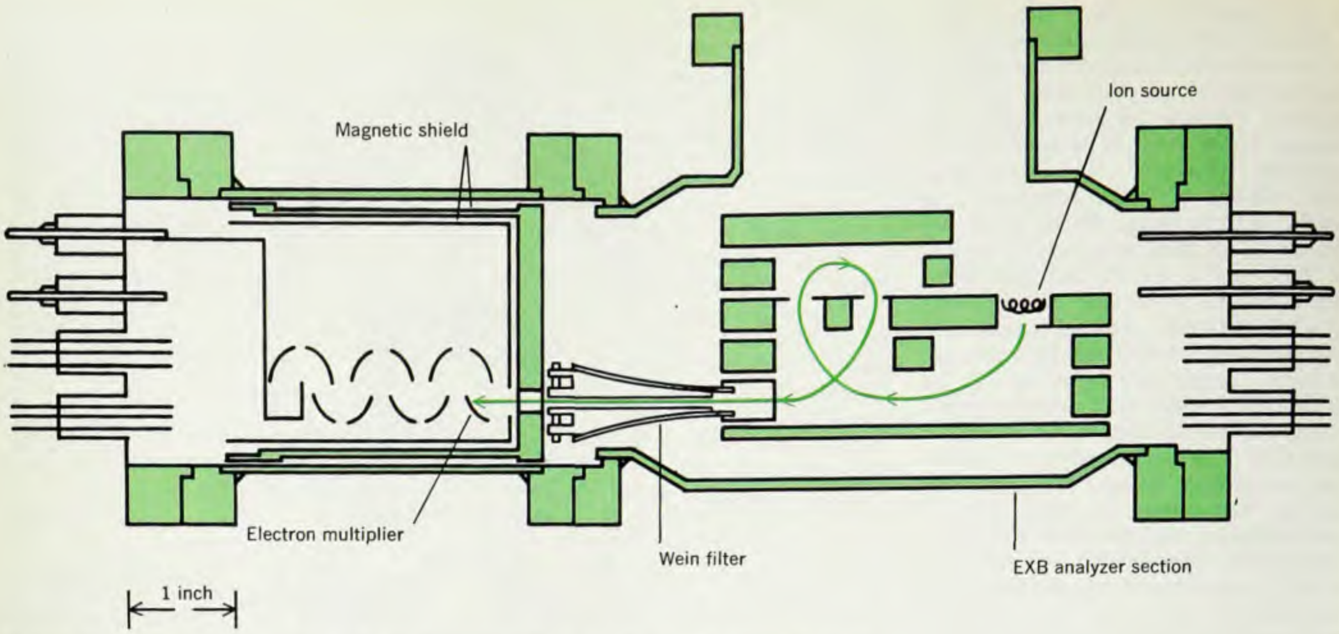
The buried-collector or extractor gauge[12] incorporates the best features of both the BAG and the suppressor gauge—a grid structure within which ion production is efficient, as well as ion-extraction and focussing electrodes to provide efficient ion collection. Somewhat lower electron emission currents must be used, on the order of 1 mA, because the space charge within the grid at higher currents destroys the ion optics. Redhead's version of this gauge is shown in figure 5. Its sensitivity is about equal to that of the BAG. The ion collector subtends such a small solid angle to the grid that soft x rays cause very little spurious current. Thus it can measure pressures 100 times lower than the BAG. The geometry also helps to limit the spurious current caused by surface-generated ions. Reduction of this current also results from the higher kinetic energy of the surface-generated ions that favors their being collected on the envelope, ion reflector and shield rather than on the small-area ion collector. The relative importance of surface-generated ions is some 500 times lower than it is for BAG. Even without the modulator electrode, the range of the extractor gauge extends well into the range of currently attainable ultrahigh vacuum, say 10^{-12} torr.



Extractor gauge, which is useful from 10^{-4} to 10^{-13} torr, has low spurious currents, because the ion collector has small solid angle to accept soft x rays as well as low efficiency for the collection of surface-generated ions. Figure 5

In the bent-beam gauge,[13] ions are extracted from the grid volume and electrostatically deflected through 90 deg to an ion collector. Thus the ion collector cannot directly "see" the soft x rays from the grid. The effect of electron-desorbed ions from the grid is reduced by a factor of 30 over that in the Bayard–Alpert gauge, compared to a factor of 500 for the extractor gauge.

An entirely different approach to gauge design is embodied in the "orbitron" gauge.[15] Because the spurious currents result from phenomena associated with collection of ionizing electrons on the surfaces, this gauge is designed to increase the number of ions per electron by increasing the electron path length. In the orbitron gauge the ionizing electrons orbit in the electrostatic field of a coaxial geometry. With careful design and construction an average electron path length of up to 1000 meters, some 10^5 times that in a BAG, is achieved. Consequently a small-area electron emitter can be operated at much lower temperature, reducing the chemical activity and change in gas species at the filament. The total power dissipated is lower, so the outgassing is greatly reduced. The x-ray effect remains and results in a spurious ion-collector current corre-



Cycloidal-type residual gas analyzer illustrates general features of a partial-pressure gauge. Ion source strips electrons from gas particles, and a magnetic field perpendicular to the plane of this schematic drawing analyzes the gas ions. The colored line indicates the path followed by the gas ions as they travel through the gauge. Figure 6

sponding to a pressure of approximately 10^{-11} torr.

Of all these hot-cathode gauges the choice for work at 10^{-10} torr or above should be the modulated BAG, whereas for work at lower pressures it should be the extractor gauge. These gauges are the most reliable and best understood; their operation is simple and involves minimum inconvenience.

Magnetic-field gauges

Like the orbitron gauge, magnetic-field gauges reduce spurious currents by increasing electron path length. One of the vacuum pioneers, Wolfgang Gaede,[16] appears to have used such a gauge well before interest in ultrahigh-vacuum measurements. The later work by F. M. Penning[17] has had a far reaching effect not only on gauging but also more specifically on pumping and crossed-field gas-discharge experimentation. (See Theodore Tom's article on vacuum pumps in this issue for a more complete description of the Penning discharge.)

The Penning gauge consists of a cylindrical anode with electrically isolated end caps that serve as cold cathodes. The gauge is immersed in an axial magnetic field of the order of or greater than 1000 gauss. A radial electric field results from the fact that a dense electronic space charge (between 10^9 and 10^{10} electrons per cm^3) is established within the anode volume, and the axial potential is suppressed to cathode potential. Electrons can drift perpendicular to the magnetic field and reach the anode only by undergoing a series of collisions with residual gas molecules. Current equilibrium exists such that the space charge is maintained. The cathode current is pressure dependent and spurious currents are insignificant. After careful calibration, gauges of this design can be used for total-pressure measurements in the ultrahigh-vacuum range. However, the dependence of ion current on pressure is not a simple, linear relation. On the average, the cathode current increases as pressure raised to a power of 1.1 to 1.4. Instability of the space charge with changes in pressure may lead to abrupt changes in the sensitivity, to regions of bistable operation, and to hysteresis.

At the low pressures of concern here the establishment of the discharge is slow and unpredictable. Several solutions have evolved—incorporation of a trigger filament that can be flashed very briefly to supply the discharge-initiating electrons, incorporation of a β-emitting isotope such as nickel-63 into the cathode and utilization of an external source, either ultraviolet light or (if the envelope is metal) a γ-emitter such as cobalt-60. An additional disadvantage of the Penning gauge is its high pumping speed. I feel that the Penning-discharge gauge should only be relied upon for carrying out rough, order of magnitude, determinations of pressure.

Two similar crossed-field gauges have been presented by Redhead—namely the magnetron[18] and inverted magnetron[19] gauges. Both have coaxial, cylindrically symmetric geometries in externally applied, axial magnetic fields. As in the case of the Penning gauge, the principal deterrents to their broad acceptance, in addition to the magnetic field required, are the lack of linearity of current with pressure and the erratic behavior, which is presumably associated with changes in the electronic space charge.

Because of the nonlinear response of the crossed-field devices, extrapolation of behavior from calibration at pressures greater than 10^{-7} torr can be extremely misleading. In spite of these difficulties, the Penning, magnetron, and inverted magnetron gauges can, if properly constructed and interpreted, be useful to about 10^{-12} torr. They do avoid problems of ion desorption and the chemical effects of a hot filament. However, the selectively high pumping speeds for chemically active gases tend to negate these advantages of these gauges.

A "warm" magnetron gauge that has the desired linear response has been developed by James M. Lafferty.[20] The cathode operates at only about 1000 K, and the required magnetic field is lower, by a factor of five or so, than in the other crossed-field gauges. The soft x-ray effect is small, equivalent to a pressure of less than 2×10^{-14} torr, and spurious currents caused by electronic desorption of ions are expected and claimed to be very low. Operation of the gauge is not particularly straightforward because of electronic space-charge oscillations and energetic electrons reaching the ion collector. Consequently the electron current must be lower than 10^{-7} amps, and the stability is a function of magnet position. Although the gauge has reasonable sensitivity and has been shown to be linear down to the 10^{-13}-torr range, it requires too much sophistication on the part of the user, at least at the present time. Of all the total-pressure gauges, only the magnetron gauge and BAG have thus far been used in lunar and space probes.

Partial-pressure gauges

The total-pressure gauge progressively provides less useful information as pressures decrease. As one approaches the ultimate vacuum attainable, the influx of gases from the system and pumps becomes more and more important. One must obtain information that the total-pressure gauge cannot give. Moreover, as the complexity of the gauge operation and interpretation increases, one may as well accept further physical complexity and use a partial-pressure analyzer in order to gain infinitely more information. Several types of partial-pressure analyzers are commercially available; the choice of type is largely arbitrary. All suffer from difficulties in degassing that make it difficult to ascertain what percentage of each gas is representative of the system and what derives from the analyzer itself. Of course the instrument itself must withstand temperatures of about 400 deg C to enable the system as a whole to be processed. Figure 6 illustrates the general features of a partial-pressure gauge.

The analyzer used to separate gas components need not have the high resolving power of an analytical mass spectrometer; in general only simple gases with masses less than 50 atomic mass units are encountered. The analyzer must be equipped with an electron multiplier so that the ion currents can be amplified before they are fed into the electronic amplifier. The use of an electron multiplier imposes a further requirement that its gain be known and stable.

As with total-pressure gauges, spurious currents can occur. For example, when photons from the filament or soft x rays from the ion source arrive at the multiplier they increase the background signal. In addition spurious peaks in the spectrum may occur; they are caused most frequently by the electron-induced desorption of ions from surfaces in the ion source.

Ion-pumping speeds are usually less than those encountered with total-pressure gauges, although they cannot be ignored totally. The low pumping speeds result primarily because the ion source is constructed and operated to produce fewer ions at a given pressure. In the magnetic sector instruments, ions are given considerably higher energies than in other types of instruments; thus the ion-pumping speed can be expected to be somewhat higher. Just as with total-pressure gauges the conductance must be high between the partial-pressure analyzer and the remainder of the system. Furthermore the ion source must be "open" to minimize the effects of ion pumping and gas generation in the ion source.

The first analyzer to be extensively applied to ultrahigh-vacuum studies was the omegatron.[21] It is still widely used in work associated with the electronic-tube industry, particularly in Europe. In spite of its relative simplicity and compact size, it is not used in research studies, primarily because difficulties associated with the extremely small, positive-ion current output limit its extension to low pressures. The small output arises because the ionizing electron current must be low, of the order of 10 microamps or less, and because the gauge is not conveniently equipped with an electron multiplier

Another crossed-field device that is not in wide use is the cycloidal spectrometer (see figure 6). Here, the ions can be extracted to a shielded electron multiplier located outside the region of magnet poles if they are allowed to orbit $5\pi/2$ rather than the normal 2π radians. In this way a partial-pressure sensitivity of less than 10^{-14} torr can be obtained. I have used this type of analyzer extensively and have found it to have one distinct advantage over the magnetic sector types—the absence of ion peaks caused by ions generated at surfaces. Because the ion source is located in the magnetic field, the electron beam is well defined and only strikes surfaces that are located such that any ions released from them cannot enter the analyzer section.

The magnetic sector type spectrometer may be of the 60-, 90- or 180-deg variety, although the 180-degree-deflection type is difficult to equip with an electron multiplier. In the popular 60- and 90-deg instruments both the ion source and detector are located well outside the magnetic field in the analyzing section. As a result the ion source can be nude, that is, essentially totally open to the ambient to be sampled, and the multiplier does not have to be magnetically shielded. W. D. Davis has perfected and calibrated the 90-degree instrument; he has demonstrated that it is linear down to at least 10^{-14} torr.[22] With the conventional hot cathode, electron bombardment type of ion source, the spectrum can be easily misinterpreted. As Davis has shown, the major peaks in the spectrum obtained with the 90-degree instrument at pressures below 10^{-10} torr are caused by surface-generated ions. In typical order of decreasing importance these peaks occur at ratios of mass to charge equal to 19 (F^+), 16 (O^+), 35 and 37 (Cl^+), and 23 (Na^+). He eliminated this problem and concurrently reduced outgassing by using a warm-cathode magnetron source very similar to the Lafferty gauge described above.

Partial-pressure analyzers of the quadrupole type are widely used and have the decided advantage that they do not require a magnetic field. Since the introduction of this dynamic analyzer by W. Paul[23] and the subsequent development of the monopole,[24] both instruments have been refined for application to residual-gas analysis. Their advantages include compactness of size with relatively small surface area of electrodes, the ability to trade off resolving power for transmission or sensitivity by changing the applied fields, and ready adaptability to a nude ion source. The major disadvantages result from the arrangement of the ion source, analyzing section, and detector in line with one another. The detector must be shielded from photons from the ion source. In addition, the accuracy of positioning the field-forming electrodes must be carefully maintained through the thermal cycling of bakeout to 400 deg C.

The analyses at pressures of less than 10^{-10} torr indicate that the major residuals are H_2 and gases with mass 28 amu, which is largely CO. These gases appear to dominate irrespective of the type of pumping employed or the composition of the vacuum walls. (Helium is frequently a major gas constituent when glass is used, but its inactivity makes it tolerable). In many analyses obtained at the ultimate of the system, the major gases present have probably been generated in the ion source of the instrument itself. Hydrogen and carbon are impurities in all metals and diffuse out. Carbon monoxide covers the surfaces and slowly desorbs at room temperature and in the presence of light; it is a particularly difficult gas to eliminate. In some cases methane is present in significant amounts but often because it is not adsorbed with any efficiency on freshly evaporated metal surfaces and may be produced in sputter-ion pumps.

Under certain circumstances other methods of analysis may prove useful. For example, one can absorb gas on surfaces either by chemical or physical means and, after a predetermined accumulation time, desorb them by heating. One can identify the gases either by using mass spectrometry or by noting the temperature at which certain gases desorb. In the latter method, even after careful precalibration, the interpretation can be extremely difficult because the method does not have the high resolving capability that is the inherent property of the mass analyzers.

In this brief review we have necessarily neglected the onerous but mandatory task of calibrating both the total- and partial-pressure gauges. Mercury remains the only primary standard, and calibration against the mercury-filled McLeod gauge is limited to about 10^{-4} torr. Overlapping secondary standards must be used to extend the range by many orders of magnitude to the ultrahigh-vacuum range of current interest.

In summary I recommend that one adopt an extremely critical attitude not only toward the claims of others but to one's own measurements as well. And, especially in any experimental work below 10^{-8} torr, one should incorporate a combination of both total- and partial-pressure gauging.

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