launch into space. Such a structure would have to be quite large—of the order of 46 square meters (500 ft^2) per kilowatt of electric power produced—but this problem appears simple relative to those presented by the nuclear turbo-electric system.

Although it seems probable that, with most of the systems described; specific weights as low as about 5 kilograms per kilowatt can be achieved, it does not seem likely that the value can be reduced below about 2.5 kilograms per kilowatt with any of them. Two systems have been suggested with which, at least conceptually, specific weights below 1 kilogram per kilowatt could be achieved. These are a radioisotope cell system (*3*) and a variable-temperature dielectric system (*4*). Both of these systems require thin-film techniques. Both methods appear worthy of further investigation. Possibly other methods based on new uses of thin films will be conceived in the future.

Conclusion

The development of electric-propulsion systems with sufficiently low specific weights and sufficiently long lifetimes for interplanetary missions is difficult, but with good engineering judgment and stubborn perseverance, success appears likely. The ultimate benefits, in terms of man's ability to travel greater distances through space in less time and with vehicles of less initial weight and size than those currently visualized, appear to warrant an effort at least as great as that now being made to develop such systems.

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Ultrahigh Vacuum Instrumentation

The general subject of the measurement techniques associated with ultrahigh vacuum are reviewed.

T. A. Vanderslice

In the past decade there has been an enormous increase in the use of ultrahigh vacuum equipment, at first in the laboratory and more recently in commercial production facilities (*1*). For many applications, pressures of the order of 10^{-9} atmosphere—that is, approximately 10^{-6} torr (1 torr=mm-Hg =1/760 atm)—are entirely adequate. Even at these pressures, surfaces that are originally free of absorbed gases become covered with absorbed gas in only a few seconds. With pressures of 10^{-9} torr and lower, significant recontamination of the surface does not occur for several hours. Pressures of 10^{-8} torr and below are generally called the ultrahigh vacuum range.

Ultrahigh vacuum is indispensable in many investigations of the reaction between a surface and a gas, or of the properties of the surface itself. The success of an experiment in the laboratory depends to a large extent on knowledge and control of the variables affecting the experiment. In investigations of properties of surfaces, for example, the surfaces are often contaminated by unknown amounts of unknown impurities. When two surfaces are rubbed together in air, one can ask to what extent the surfaces are in contact or to what extent the absorbed impurities are in contact. In many investigations of dry sliding, the surface films may act as lubricants, and it is clear that sliding in the absence of absorbed films would lead to entirely different results. Pressures in outer space are very low, and any clean surfaces formed by frictional movement remain free of absorbed layers.

Since clean surfaces tend to seize,

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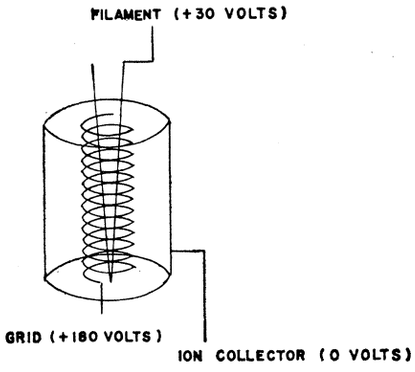

Fig. 1. Ionization gauge.

lubrication of space vehicles can create new problems. Ultrahigh vacuum techniques are also important where gas of high purity is necessary. For example, for studies of the interaction of electrons, ions, and atoms in a gas, gases of a very low impurity level are required, as the cross sections for collision are highly dependent on the types of gases present. Gases of high purity are also required in thermonuclear devices in which elements such as deuterium and tritium undergo thermonuclear fusion and produce energy.

Many of the techniques of modern ultrahigh vacuum technology were developed by early workers in the field, such as Langmuir and Dushman. These scientists developed the mercury-diffusion pump and used back-out techniques and cryogenic pumping. There is extensive indirect evidence that ultrahigh vacuums were produced in the 1930's, but no easy and reliable method of measuring pressure was then available. Even today, methods for measuring pressure still lags behind methods of producing low pressures. If a vessel is evacuated by some low pressure (say, 10^{-10} torr) and then sealed off from the pumps and immersed in liquid helium, the pressures attained in the system are calculated to be lower than 10^{-30} torr. (In some cases the reported pressure depends on the enthusiasm of the public relations department of the institution in question!) In this article I review the general subject of instrumentation for measuring vacuums, for readers in fields where ultrahigh vacuum techniques are of general interest. Vacuum measuring devices can be divided into two main categories: (i) instruments that measure the total pressure of all components present in the system, and (ii) devices that measure the individual components which contribute to the total pressure.

Total-Pressure Measuring Devices

Hot-cathode devices. The devices commonly used to measure pressures below 10^{-4} torr are ionization gauges for total-pressure measurements and mass spectrometers for partial-pressure measurements. An ionization gauge is commonly a triode consisting of a hot filament as a source of electrons, a grid operated at positive potentials with respect to the filament, and an ion collector operated at a slight negative potential with respect to the filament (Fig. 1). The filament serves as an electron source, and the grid, as an electron collector. A fraction of the electrons traveling between the filament and the grid strike and ionize gas molecules, and a fraction of these ions are collected by the ion collector. In a gas at pressures below 10^{-4} torr, the number of ions produced by the passage of a stream of electrons through the gas is proportional to the density of the gas molecules. Therefore, a measure of the ions produced is a measure of the gas density, or, at a given temperature, a measure of the pressure.

The conventional ionization gauge (Fig. 1) typically has the grid at + 180 volts, the cathode at + 30 volts, and the collector at ground potential. In spite of the apparent simplicity of the ionization gauge, pressures below 10^{-8} torr had never been measured by an ionization gauge until about 1950. Indirect evidence, such as rate of surface contamination and rate of poisoning of cathode surfaces, indicated that pressures below 10^{-8} torr had been achieved. Wayne Nottingham, Massachusetts Institute of Technology, hypothesized (*2*) that the lower limit to measurement in a conventional ionization gauge was caused by an x-ray effect. He proposed that electrons emitted by the filament strike the grid, ejecting soft x-rays which in turn eject photoelectrons from the ion collector. On an external ammeter, a photoejected electron leaving the collector produces a deflection in the same direction as an ion arriving. Therefore, when the pressure is low enough so that the positive ion current and the photocurrent are of the same order, pressure measurements are no longer possible.

In 1950 (*3*) R. T. Bayard and D. Alpert verified Nottingham's hypothesis and described an ionization gauge with a low pressure limit of the order of 10^{-11} torr. Their solution to the problem caused by the x-ray generated current

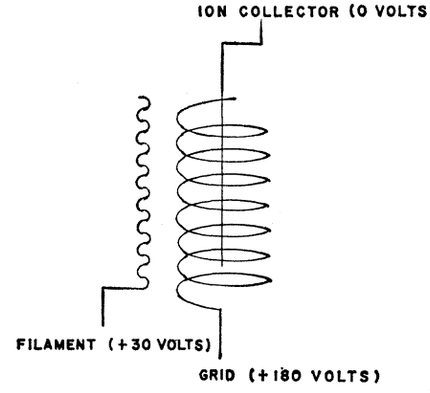

Fig. 2. Bayard-Alpert ionization gauge.

is elegant in its simplicity; they decreased the solid angle presented to x-rays at the grid by constructing the ion collector of a small wire (Fig. 2). The Bayard-Alpert ionization gauge has the filament outside the cylindrical grid and the fine-wire ion collector inside. Thus, because of its favorable location, the ion collector measures a large fraction of the ions formed inside the grid but intercepts only a small fraction of the x-rays produced at the grid. The gauge was calibrated by evacuating a system to less than 10^{-10} torr and allowing helium to leak into the system at a known rate until the pressure could be read on a standard McLeod gauge. The time dependence of the rise in pressure constitutes a check on the gauge's linearity. The Bayard-Alpert ionization gauge has three major advantages over a standard ionization gauge. (i) The small surface area of the ion collector decreases the x-ray effect; (ii) the ion-collection efficiency is increased, because of the axial location of the collector; and (iii) the potential distribution between the grid and the ion collector is such that almost all the volume within the grid is available for efficient ionization.

An instrument was now available that

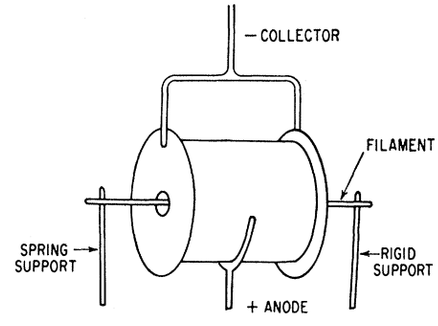

Fig. 3. Hot-cathode magnetron ionization gauge. [Conn and Daglish]

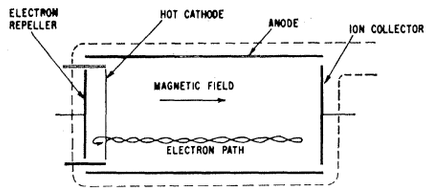

Fig. 4. Hot-cathode Penning gauge. [Houston]

was capable of measuring pressures below 10^{-8} torr, and an experiment could be performed with some assurance that the pressure due to impurity gases was low enough so that the surfaces would be kept relatively uncontaminated during an experiment.

It is clear that the x-ray effect in ionization gauges depends on the number of electrons striking the electron collector, whereas the ion current produced in an ionization gauge depends not only on the number of electrons but also on their path length. Therefore, the sensitivity of a hot-cathode ionization gauge can be greatly increased by applying a magnetic field to increase the path length of the electrons. Conn and Daglish used an arrangement consisting of a cylindrical anode, an axial thermionic filament, and an axial magnetic field (Fig. 3). The end plates, perpendicular to the axis and at a negative potential relative to the filament, were used as ion collectors. The increase in the path length of the electrons increased the sensitivity of the gauge by a factor of 100. Conn and Daglish pointed out the decrease in photoelectric effect, but the gauge was never used to measure ultrahigh vacuum.

Figure 4 shows a gauge developed by J. Houston (*4*) that is a variation of a Penning ionization gauge. Electrons from the hot filament are constrained by the axial magnetic field and have an average trajectory of 10^{8} centimeters. Houston measured total pressure of 10^{-12} torr and calculated that the gauge should be able to measure pressures of 10^{-15} torr.

Figure 5 is a gauge developed by Lafferty (*5*), which is a cylindrical magnetron operated at magnetic fields above cutoff. Very small electron-emission currents are used to prevent oscillations which would allow electrons to reach the ion collector, and the ion current is measured at one of the two negative end plates. Measurements of sensitivity and x-ray photocurrent at 10^{-11} torr indicate that the gauge is capable of measuring pressures as low as 10^{-14} torr. Ion emission from the hairpin filament did not appear to set a limit on the pressure measurement. The addition of an electron multiplier increases the ratio of ion current to photocurrent, and measurements at 10^{-11} torr indicate that pressures of 10^{-15} could, in principle, be measured.

Cold-cathode ionization gauges. Cold-cathode gauges have some obvious advantages over hot-cathode gauges. In most cases the power requirements are lower with cold-cathode gauges, and also there are no hot filaments to interact with the ambient gases. Cold-cathode gauges, however, tend to have higher pumping speeds than hot-cathode devices, and these higher pumping speeds result in lower pressure measurements in the gauge than in the system.

A common type of cold-cathode ionization gauge is the Penning gauge (Fig. 6). In this type of gauge the number of electrons striking the anode decreases with decreasing pressure, and consequently there is no lower limit to pressure measurements as a result of the x-ray effect. This type of cold-cathode gauge has high sensitivity, and its use eliminates the chemical reactions which may occur on a hot filament, but it has the disadvantages of high pumping speed, a tendency to oscillate at all pressures, and a long starting time at low pressures. A conventional multi-anode Penning ionization gauge appears to have linearity over a fairly wide pressure range.

Redhead (*6*) has described two types of gauges which are capable of measuring pressures of 10^{-12} torr and perhaps lower. The cold-cathode magnetron

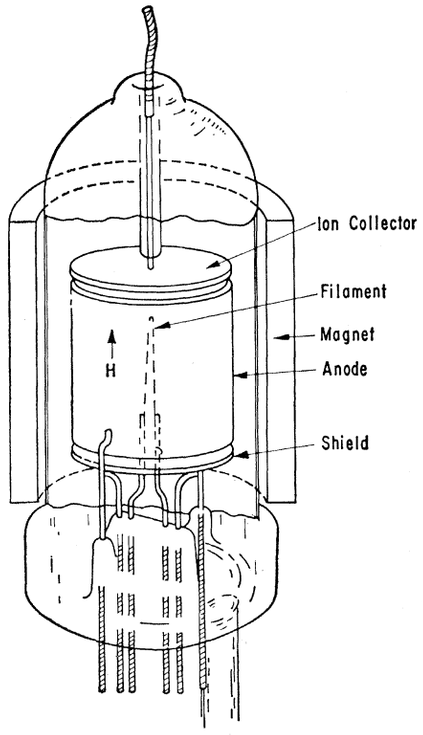

Fig. 5. Hot-cathode magnetron ionization gauge. [Lafferty]

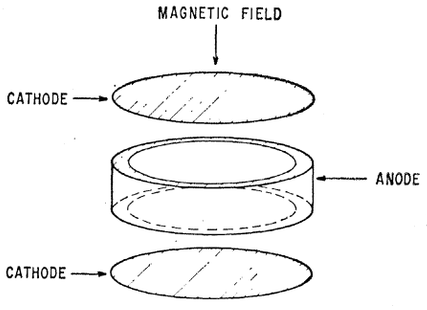

Fig. 6. Penning gauge.

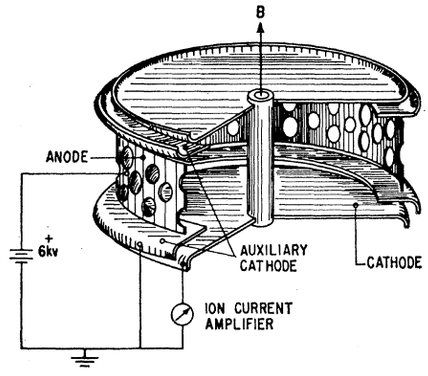

Fig. 7. Cold-cathode magnetron gauge. [Redhead]

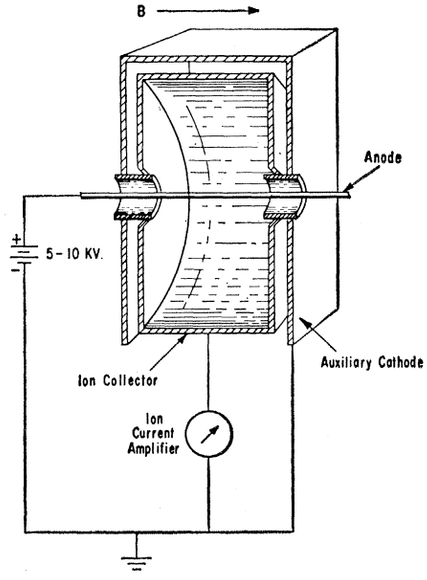

Fig. 8. Inverted cold-cathode magnetron gauge. [Redhead]

gauge (Fig. 7) has a perforated cylinder for an anode, and starting of the gauge is accomplished by having a potential difference of 6 kilovolts between the cathode and the anode. The ion collector is shaped like a spool and consists of an axial cylinder welded to two circular end disks. A second type of gauge described by Redhead is an inverted cold-cathode magnetron (Fig. 8). The anode is a tungsten rod, 1 millimeter in diameter, that passes along the axis through the holes in the end plates of the ion collector. The ion collector is a cylinder with its axis parallel to the axial magnetic field. Auxiliary cathodes are placed between the anode and the end plates to prevent field emission from the end plates. The gauge is normally operated with the auxiliary cathodes at ground potential, the anode at 6 kilovolts, and a magnetic field of 2000 gauss. Calibration of the inverted magnetron from 10^{-4} to 10^{-12} gives a relationship between the ion current (I) and the pressure (p) of $I = bp^n$, where b is a constant for the particular gauge being used and the exponent n is about 1.10. The inverted magnetron must be shielded from light at pressures below 10^{-10} torr.

Recently J. R. Young and F. P. Hession (*7*) have described a triggered cold-cathode ionization gauge that is capable of measuring pressures from 10^{-3} to 10^{-14} torr. Their gauge overcomes one of the chief difficulties encountered with a Penning gauge—the difficulty in starting the gauge at low pressures. They mounted a small filament opposite a small hole in one of the cathodes, as shown in Fig. 9. This filament is merely pulsed to low temperatures on starting the gauge, and the small burst of electrons that enter the discharge region initiates the discharge. In this manner the cathode-to-anode voltages may be kept low to minimize pumping. The gauge has the advantage that a hot filament is not present during operation and is used only when it is necessary to trigger the gauge.

Partial-Pressure Analyzers

In some cases there is a need to know not only the total pressure in a system but also the partial pressures of each of the individual gas constituents. The composition of gases in a system may vary markedly with various materials, with previous history, with temperatures, and so forth. It is particularly important in surface physics and surface chemistry to know the type of gases absorbed and desorbed from surfaces during the course of an experiment. Accurate ionization-gauge calibration also requires a knowledge of the gas composition. Measurement of partial pressures in ultrahigh vacuum systems requires small, bakeable, analytical spectrometers of very high sensitivity. Of these, many types of varying merit are available, and here I discuss several of the more important ultrahigh vacuum devices that have been described in the literature.

All mass spectrometers have certain features in common. These are (i) an ion source; (ii) a mechanism for sorting out ions according to their mass-charge ratio; and (iii) a method of detecting the ions. The principal difference between the various types of spectrometers lies in the means for separating the ions according to their charge-to-mass ratio. In the time-of-flight mass spectrometer, the ions are separated by their different rates of travel between fixed points. In the deflection-type mass spectrometer, the ions are accelerated and then passed through a magnetic or an electrostatic field, or both.

Time-of-flight mass spectrometers. A time-of-flight mass spectrometer is an instrument in which ions of different charge-to-mass ratio are separated by the difference in the time they require to travel over a given path. Spectrometers of this type include the pulsed-beam analyzers, the omegatron, and the radio-frequency spectrometers. The pulsed-beam analyzer represents what is probably the most straightforward application of time of flight (*8*) to mass spectrometry; it consists of an ion source and an ion collector situated at opposite ends of an evacuated tube (Fig. 10). Ions are formed by electron bombardment between two electrodes of an ion source. The ion can be ejected through a grid in one of the electrodes by the application of a voltage pulse between these electrodes. The ions, as a result of the accelerating field, reach a velocity that is a function of their mass-to-charge ratio. The original bunch of ions from the ion source separate

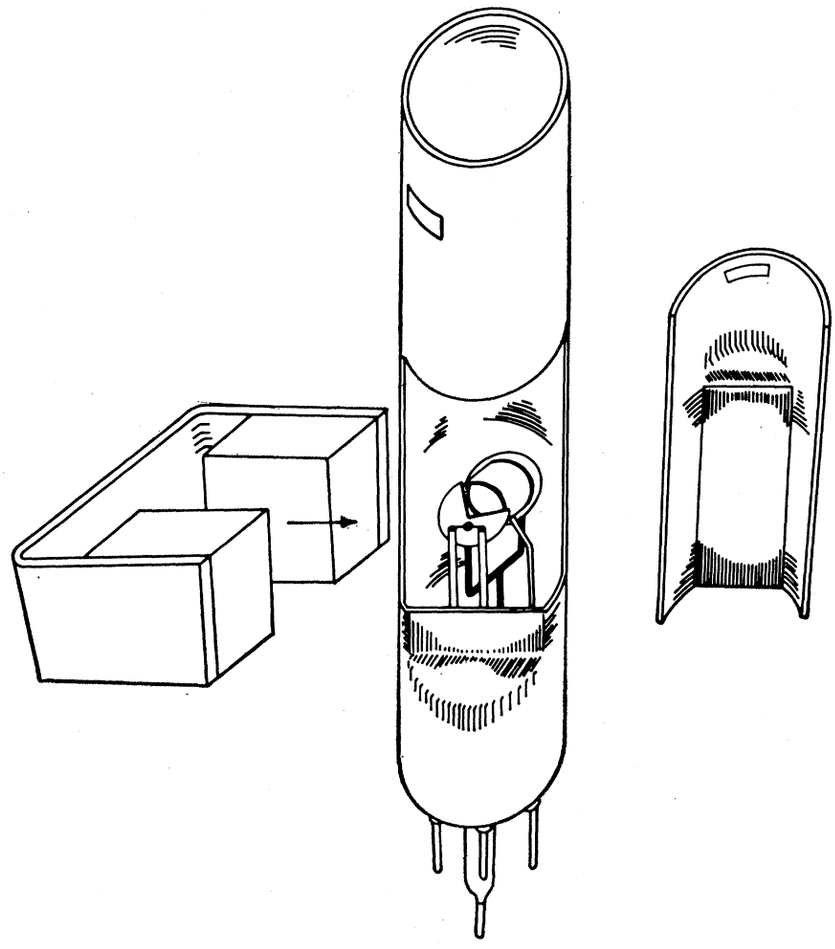

Fig. 9. Triggered cold-cathode gauge. [Young and Hession]

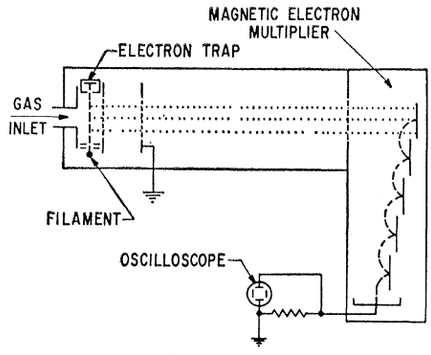

Fig. 10. Time-of-flight mass spectrometer.

into distinct groups as the ions pass through the field-free region between the source and the collector. Each group contains ions of a specific mass-to-charge ratio. The transit time, t, of ions of a particular mass-to-charge ratio (m/e), with velocity, v, through a distance, L, is described by the equation

$$t = \frac{L}{v}$$

If the potential difference through which the ions are accelerated is V, then

$$v = \left(\frac{2Ve}{m}\right)^{1/2}$$

and

$$t = L/\left(\frac{2Ve}{m}\right)^{1/2}$$

The ions will arrive at the ion collector at times determined by m/e, the heavier ions requiring the longer times.

An electron multiplier is generally used to detect and amplify the ion bunches or peaks. The output of the electron multiplier can be displayed on an oscilloscope synchronized with the ion-accelerating pulse. An important advantage of the pulse-beam, time-of-flight, mass spectrometer is its speed in analysis. A complete analysis can be obtained in a few microseconds by taking pictures of the output on an oscilloscope.

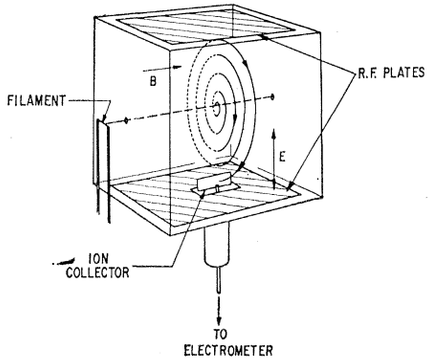

Fig. 11. Simplified omegatron. [Alpert and Buritz]

The omegatron is currently one of the most popular devices for analyzing residual gas composition in ultrahigh vacuum systems. Alpert and Buritz (*9*) described a simplified version of the original omegatron as reported by Sommer, Thomas, and Hipple (*10*). Their simplified version (Fig. 11) has the advantage of permitting convenient outgassing at high temperatures. A cylindrical beam of electrons is injected through a small opening parallel to a magnetic field and perpendicular to a radio-frequency electric field. A line source of ions is formed in the ionizing chamber. In a given magnetic field, H, ions with charge e and mass m have a unique cyclotron frequency, w_1, defined as

$$w_c = \frac{eH}{m}$$

When the frequency, w, of the applied electric field is equal to w_c for ions of a given e/m ratio, those ions gain energy and spiral outwards to a collector. H and w uniquely define one e/m ratio, since harmonic resonance effects possible in the cyclotron for e/m ratios of 1/3, 1/5, . . . , do not occur as a result of the continuous acceleration that ions receive in the omegatron. Ions with other e/m ratios are forced into smaller circular paths near the axis of the electron beam. The strength of the magnetic field, or of the electric field, or of both, may be varied for scanning the mass spectrum. The resolution of the omegatron varies linearly with the number of revolutions a resonant ion can make before being collected. The greater the number of revolutions, the better chance for the nonresonant ions to become out of phase with the impressed voltage. When the magnetic and the radio-frequency electric fields are uniform, the resolution may be increased by increasing the magnetic field, or by increasing the physical dimensions of the instrument. Efficient ion collection requires that the resonant ions remain in uniform fields until they are collected. Moreover, the long path of a resonant ion makes operation impossible at pressures where the mean free path of an ion become too short.

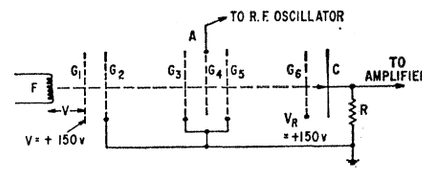

Fig. 12. Radio-frequency mass spectrometer. [Bennett]

Alpert and Buritz report effective resolution to mass 40 for an omegatron 2 centimeters on a side operating at 2100 gauss, with accelerating voltage of 90 volts and radio-frequency voltage of 2 volts. The radio-frequency oscillator was swept at frequencies ranging from 3 megacycles per second to 81 kilocycles per second to cover the mass range of mass 1 through 40. The simplified omegatron detects partial pressure to 10^{-9} torr and has a sensitivity comparable to that of a conventional ionization gauge. A. Klopfer reported the use of an omegatron structure to measure total pressures in the range below 10^{-10} torr. Oscillations in the omegatron were damped through the application of a high magnetic field. This approach appears to offer some promise as a means of making low total-pressure measurements.

Bennett and Redhead (*11*) have described a radio-frequency type of mass spectrometer. The general principle of operation is illustrated in Fig. 12. The description given here follows that given by Pirani and Yarwood (*12*). Electrons from the filament F are accelerated to the grid G_1, which has a potential of about 150 volts, positive with respect to the filament. The ions formed by electron impact, are then accelerated between the grids G_1 and G_2. These ions then enter the analyzer section A, which consists of three equally spaced grids—G_3, G_4, and G_5. The central grid, G_4, has a radio-frequency alternating potential applied with respect to G_3 and G_5, which are at ground potential. The ion-collector electrode C has a grid G_6 between it and the analyzer section, which is maintained at a positive potential with respect to ground. In order for the ions to reach C, they must surmount this retarding potential V_R. Whether the ions surmount this retarding potential depends on whether they gain or lose energy as they traverse the alternating field first between the analyzer grids G_3, G_4, and G_5. This is determined by the time of arrival of the ions at the grid G_3 in relation to the

instantaneous potential at that time at G_4. Those ions which gain energy do so to the maximum extent when

$$\left(\frac{2\pi}{v} + \Phi\right) = n\Phi$$

where v is the velocity of the ions, ϕ is the phase angle of the field when the ions pass G_3, and n is an integer. The mass-charge ratio m/e of the ions which acquire this maximum energy is given by

$$\frac{m}{e} = \frac{0.266v}{S^2 w^2}$$

where S is the separation between G_3 and G_4 and w is the frequency of the applied radio-frequency potential. A schematic drawing of a 20-gap linear radio-frequency spectrometer is shown in Fig. 13.

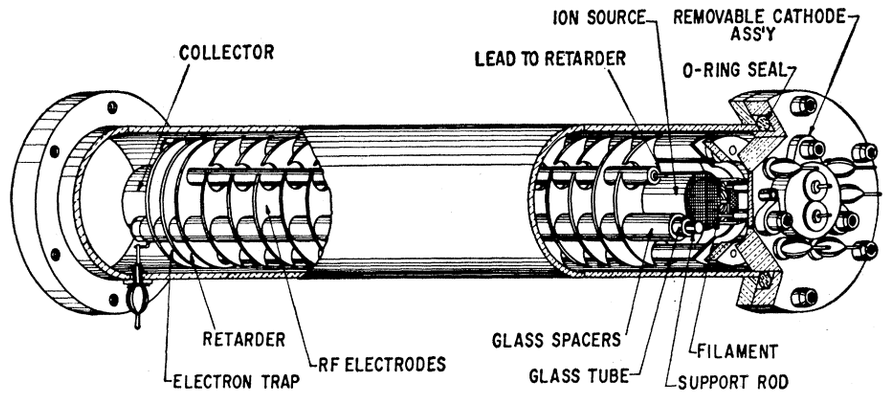

Fig. 13. Twenty-gap linear radio-frequency spectrometer.

Magnetic-deflection mass spectrometers. Magnetic deflection mass spectrometers have been widely used to measure the residual gases in ultrahigh vacuum systems. In the magnetic-deflection mass spectrometer the ions are accelerated by application of an electrostatic field and then are deflected, by application of a magnetic field, through an angle of 60, 90, or 120 degrees. The Dempster mass spectrometer is one in which the angle of deflection is 180 degrees. Reynolds (*13*) described a high-sensitivity mass spectrometer in which a nine-stage silver-magnesium electron multiplier was used to obtain output gains in the range of 10^6 electrons per ion. He was able to measure partial pressures of the order of 10^{-12} torr at a total pressure of 5×10^{-10} torr.

If a beam of positive ions accelerated by a potential V from an ion source is injected into a magnetic field of strength H, ions having different values of e/m will assume different radii of curvature. When the mass is expressed in atomic units (m), the magnetic field (H), in gauss, the radius of curvature (r_m), in centimeters, and the ion accelerating potential (V), in volts, the relationship can be expressed by the following equation:

$$r_m = \frac{144\,(mV)^{\frac{1}{2}}}{He}$$

For a given value of the radius of curvature, the ions may be distinguished by varying the magnetic field or the accelerating voltage. Therefore, the ion current reaching the detector at a given ion-accelerating voltage and magnetic field will depend on the ratio e/m for the ion. In this fashion, the presence of a small partial pressure of one gas component can be detected in the presence of a large pressure of other gases.

Davis and Vanderslice (*14*) have described a small, portable mass spectrometer of the magnetic-deflection type for studying residual gases under conditions of ultrahigh vacuum and for measuring transient pressures (Fig. 14). This spectrometer can withstand temperatures of 450°C, and operates in the ultrahigh vacuum range. It has a magnetic analyzer with 90-degree sector and radius of curvature of 5 centimeters, and it will resolve adjacent mass peaks up to approximately mass 140. A Nier-type ion source (that is, a hot-cathode source) is used. The ion detector is a ten-stage electrostatically focused electron multiplier with a gain of 10^7. Without the multiplier, pressures of 10^{-11} torr gave an output current of 10^{-15} ampere. The use of the multiplier increased the output current by a factor of 10^6 to 10^7, but because of the dark current of the multiplier, the net gain in sensitivity was only about 10^4. This is equal to the signal that would be produced by a pressure of 10^{-14} torr. Cooling the multiplier in liquid nitrogen decreased the dark current by a factor of 100, so that pressures of 10^{-15} torr could be measured. Counting individual ion pulses avoids the problem of leakage of direct current at low pressures, and partial pressures of 10^{-16} torr have been measured. By means of the multiplier, the signal level is raised to a point at which a low-output load resistance may be used to

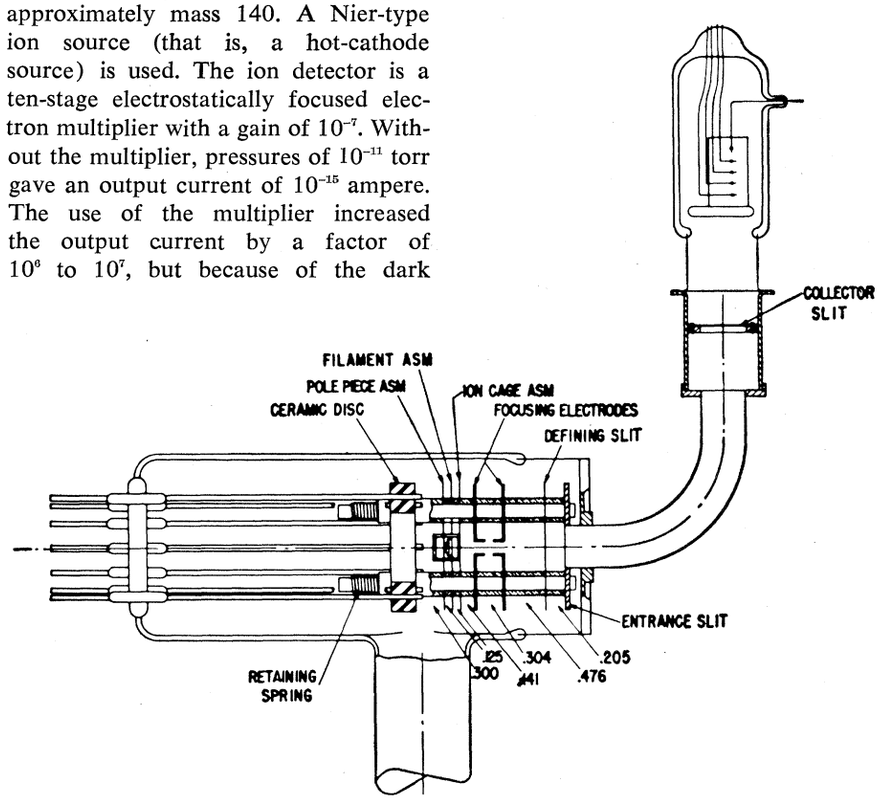

Fig. 14. Magnetic-deflection mass spectrometer. [Vanderslice and Davis]

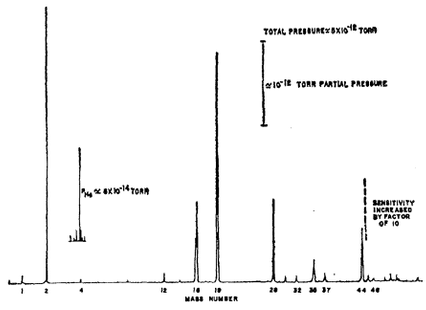

Fig. 15. Mass spectrum of residual gases in a vacuum system. [Hession]

get a short response time. This makes it possible to scan a large mass range and to display the spectrum on an oscilloscope. Different ion species may be observed almost simultaneously during the course of transient phenomena. Sweep rates as high as 1.5 miscoseconds per atomic mass unit have been used successfully. The surprising thing is the relatively high stability of the multiplier itself over long periods, and its long life.

The maximum possible sweep rate is governed by several factors. Probably the least important limitation is the rise time of the multiplier itself, which is of the order of 0.01 microsecond. A more important limitation is the overall bandwidth associated with the amplifier and oscilloscope. To faithfully follow the peak, the output circuit of the multiplier must be terminated in a resistance sufficiently small to give a decay time less than that of the signal itself. For normal sweep rates of 1 millisecond per atomic mass unit at mass 28, a value of 1 megohm is sufficient, but for sweep rates of 1 microsecond per atomic mass unit, this value must be decreased to about 10,000 ohms. The corresponding loss of signal voltage may be compensated by increased amplification, but the number of ions collected per sweep eventually decreases to the point where only individual pulses are produced. The familiar well-defined mass peaks then degenerate into a grouping of pulses, and the sensitivity for small signals decreases. The C^{13} O^{18} isotope has an abundance of 0.002 percent that of the C^{12} O^{16} isotope and provides a convenient method of calibration at partial pressures as low as 10^{-16} torr.

Figure 15 shows a spectrum recorded by Hession (*15*) with the commercial version of the instrument shown in Fig. 14. This is a typical spectrum observed in a well-baked system operated at pressures near 5×10^{-12} torr. The major peaks are H_2^2, O^{16}, F^{19}, and CO^{28}, plus N_2^{28} and CO_2^{44}. The O^{16} originates from ions evolved from the grid by electron bombardment, as demonstrated by G. Moore of the Bell Telephone Laboratories. The origin of F^{19} is not at all clear, but its presence demonstrates that the experimenter may derive a distorted picture of the species present in a vacuum system from total-pressure measurements.

Summary

A wide variety of instruments are available for measuring both the total pressure and the partial pressures of gases present in vacuum systems. The degree of sophistication and the accuracy of such instruments have been increased drastically in the last decade, and as the need arises, we may expect to see further improvement.

The area of gauge calibration which I have touched upon is a subject requiring much more extensive treatment than is possible in a brief article. Vacuum gauges serve many purposes; some of them merely measure the range of the gas density. If it is desired to know the gas density within 5 percent or better, many details concerning ion gauge calibration must be given careful consideration (*16*).

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