Vacuum: from art to exact science

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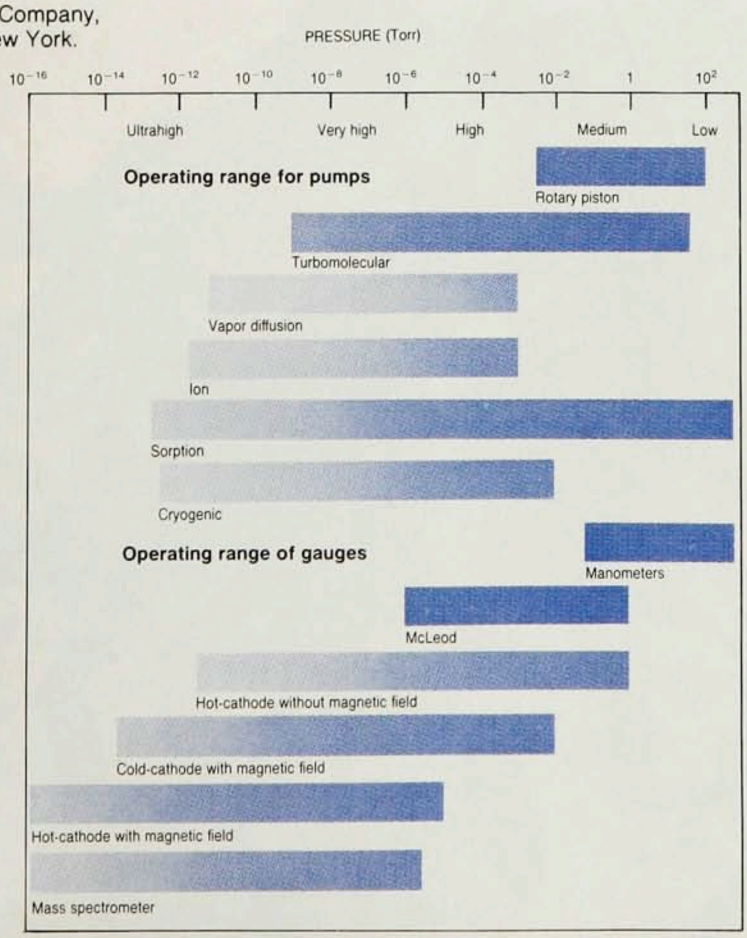
Vacuum is derived from the Latin word *vacuus* meaning empty. Absolute vacuum, a space entirely devoid of matter, is a theoretical concept only, never fully achieved by man or Nature. In modern usage, the word vacuum applies to any space at less than atmospheric pressure.

There are various degrees of vacuum: rough, low, medium, high, very-high, and ultrahigh (see table below). In vacuum technology, the common unit of pressure is the Torr (after Torricelli), $\frac{1}{760}$ of a standard atmosphere. For all practical purposes it equals the pressure exerted by a column of mercury one mm high.

The old adage that "Nature abhors a vacuum" has never been more fully appreciated than by vacuum technicians, plagued with leaks and outgassing problems, struggling to achieve even a modest vacuum in their equipment. Nature's closest approach to a perfect vacuum is found in free space. But even here one finds a few hydrogen atoms per cubic centimeter (10^{-16} Torr). Hydrogen would appear to be the universal contaminant, permeating all of space with no known natural barriers. In the most modern ultrahigh vacuum systems, hydrogen is the most prevalent residual gas. There appears to be no way to condense or trap it completely. The lowest pressures attainable are around 10^{-13} Torr. So even though Mother Nature abhors a vacuum, she still comes closer than man to the creation of a perfect vacuum.



***Gas parameters** and operating pressure ranges for vacuum pumps and gauges.*

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The Magdeburg hemispheres

Vacuum research appears to have had its beginning around the middle of the seventeenth century with the discovery of the air pump (vacuum pump) by the great German scientist and technologist, Otto von Guericke. Some time in the 1650's he succeeded in developing an air pump with an exhaust arrangement that separated a definite volume of air from the vessel to be exhausted and gave it up to the atmosphere—the principle used in most mechanical pumps today. With this pump, von Guericke was able to exhaust quite large vessels and study the properties of vacuums. He appears to have been much impressed with the magnitude of the force exerted by atmospheric pressure (14 lbs/in^2); many of his experiments were arranged to demonstrate this force. His most notable and highly publicized was the Madgeburg hemispheres experiment (figure 1), in which he put two small hemispheres together to form a sphere and evacuated it by means of his air pump. 16 strong horses were unable to overcome the immense force of the atmosphere and pull the hemispheres apart.

Von Guericke called his air pump a "syringe". The term suction pump was also frequently used in the early literature. This is misleading, because it is important to understand that a vacuum pump cannot reach into a vessel and pull out the gas molecules. At best, all that any pump can do is act as a sink or hole into which the molecules diffuse and never return. As long as the gas diffuses out of the vessel faster than it leaks in, the pressure will continue to decrease. The low-pressure limit is reached when these two flows become equal. Thus the permeation and outgassing (spontaneous evolution of gas) rates of the materials used in a vacuum system are as important as the tortuous path over which the gas must diffuse to reach the pumps.

From the beginning, vacuums have been produced for a purpose. Scientists needed a vacuum environment in which to do research—for example, to increase the mean free path of an electron, ion or neutral-particle beam in the residual gas of some devices, or to provide an environment free of chemically active gases for surface or deposition studies. Whatever the reason, in the early days, vacuum technology was generally practiced by scientists who lacked training in the field, and whose main scientific pursuits were research in other fields. Under such circumstances, it was not too surprising that vacuum technology became to be known as black magic with string, Glyptal, sealing wax and all the rest.

Early industrial applications for vacuum were for the production of light bulbs, x-ray and radio tubes. Chemically active "getters" played a more important role in producing

and maintaining the vacuum in these devices (by adsorbing residual gas) than did the original exhaust equipment. During World War II, heavy demands were placed on the vacuum equipment manufacturers to supply large quantities of high-speed vacuum systems for numerous applications, but there was precious little time for scientific research on vacuum techniques. At that time, pressures of 10^{-6} Torr were routinely produced and measured in industry. At these pressures, an atomically clean surface is contaminated by adsorbed gas in just a few seconds. In the laboratory, there were isolated cases indicating that lower pressures had been produced, but they could not be readily measured.

The Golden Years 1945–1965

Immediately after the war and for the next 20 years, a number of

In von Guerike's experiment *demonstrating the immense force of the atmosphere, 16 horses were unable to separate the evacuated Magdeburg hemispheres.* *Figure 1*

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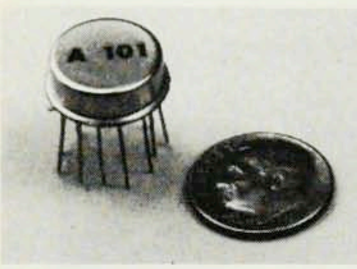

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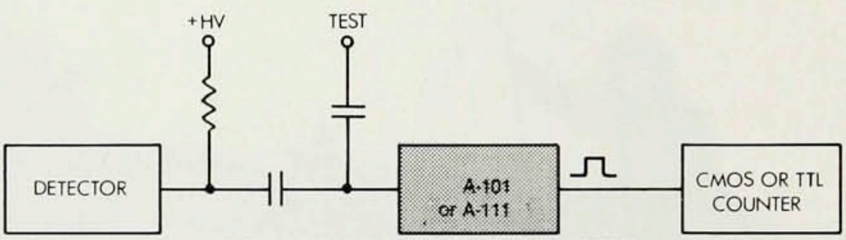

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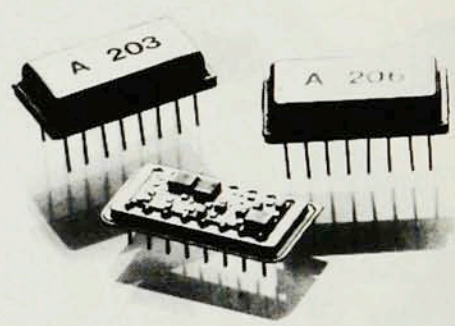

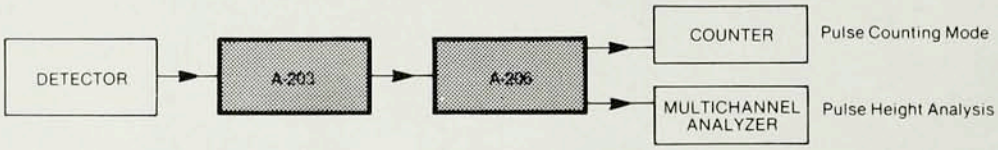

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laboratories, notably at MIT, Westinghouse, General Electric, Bell Telephone, and the National Research Council of Canada, began seriously to study the fundamental physics and chemistry of vacuum technique. The central sounding board and clearing house for much of this work was the annual conferences on physical electronics organized by Wayne Nottingham at MIT. The 1949 publication of Saul Dushman's new book, *Scientific Foundations of Vacuum Technique*, characterized the environment for a new era of vacuum technology.

Out of these two decades of research after the war came, first of all, a better understanding of the sorption and migration of gases and vapors on surfaces, and the permeation of gases through solids. This was made possible by the ability to produce and measure accurately gas pressures below 10^{-9} Torr. In 1949, only a few scientists throughout the world were able to obtain and measure pressures below 10^{-9} Torr, and this required tedious processing with laboratory-built equipment. By 1960, commercially available vacuum systems routinely attained pressures below 10^{-9} Torr in just a few hours, starting from atmospheric pressure. This was adequate for practically all industrial applications and most scientific requirements of that period.

By the early 1960's, laboratory vacuum gauges and partial-pressure analyzers had been demonstrated with the capability of measuring pressures as low as the 10^{-16} Torr characteristic of outer space. Pressures of 10^{-10} Torr gave the surface physicist many hours to perform experiments on atomically clean surfaces without contamination by residual gases.

Since 1965, fundamental measurements of sputtering phenomena, surface sorption and diffusion have continued to give a better understanding of the basic principles on which vacuum technology is founded, but they have not led to any basically new concepts for vacuum equipment. This information has been used to refine and optimize existing equipment. Most improvements in recent years have been directed to making the vacuum equipment more convenient and durable for specific applications, and to the incorporation of modern solid-state electronics and displays.

While this article must by necessity be brief, it seems worthwhile to look at some of the outstanding developments in vacuum pumps and gauges during the past 50 years.

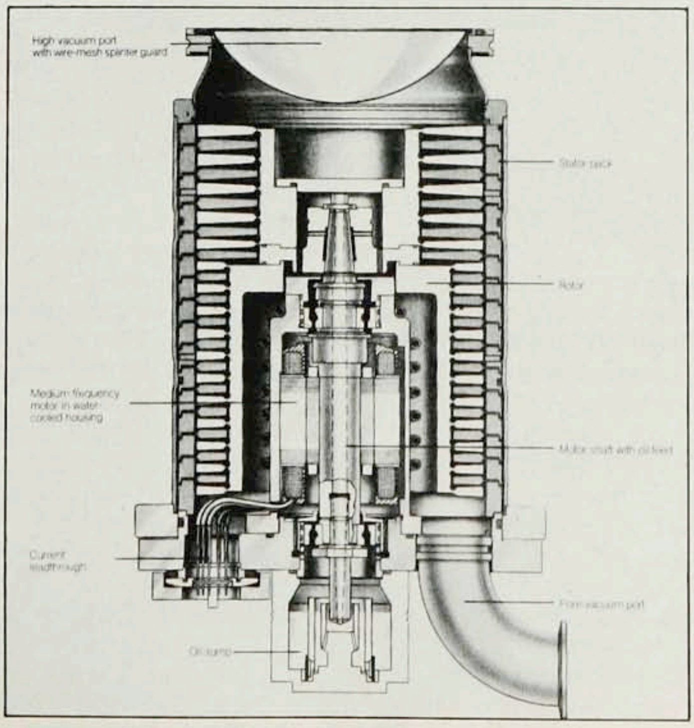
Vacuum pump developments

The speed of most pumps is nearly constant over a wide pressure range. It depends essentially on the diameter of the pump opening. There is however a lower limit to the pressure obtainable with a given pump, even with no outgassing in the vacuum system; and as this ultimate pressure is approached, the speed drops off. The small quantity of gas flowing back into the system from the pump determines this low-pressure limit.

The rate at which a gas flows in a vacuum system at a given temperature depends on the pressure of the gas and on the size and geometry of the system. It is convenient to characterize the type of flow by a dimensionless parameter K_n, called the Knudsen number. This number is defined as the ratio of the mean free path of the gas molecules (table 1) to a characteristic dimension of the constraint through which the gas is flowing—the diameter of an orifice or tube, for example.

During the early stages of pump-down in a vacuum system, the pressure may be high enough

Modern turbomolecular mechanical pump, *capable of producing pressures as low as 10^{-10} Torr without liquid nitrogen trap.* *Figure 2*



to keep the Knudsen number below 0.01. Under these conditions, collisions between molecules occur more frequently than collisions between molecules and the walls. Consequently, intermolecular collisions become important in determining the transfer of momentum through the gas, and the flow depends on the coefficient of viscosity. Such flow is called viscous flow or, if no turbulence is present, streamline flow.

In the later stages of pumpdown, when the Knudsen number becomes greater than one and molecular flow exists, the interaction of gas molecules with the walls is, in general, very complex. For an atomically smooth surface, gas molecules may be specularly reflected in a perfectly elastic manner, such that the tangential velocity component remains unchanged. For specular reflection, the walls exert no influence on the temperature or mass flow of the gas. In practice, however, only a small fraction of the gas molecules is specularly reflected from ordinary surfaces. The walls of a vacuum system are atomically rough, with irregular spaces that may trap molecules temporarily. Reflection from a such surface is diffuse, with motion equally probable in all directions, independent of the angle of incidence. Depending on the gas and wall material, the molecules may actually condense on the surface and then evaporate after attaining either partial or complete thermal equilibrium, because the temperature of a gas at equilibrium cannot be different from the temperature of its container. For large Knudsen numbers, almost all collisions by the molecules are with the walls, and the distance between collisions is the mean characteristic dimension of the container, rather than the mean free path characteristic of the pressure. Nevertheless, the molecules maintain a Maxwellian velocity distribution.

Mechanical Pumps. The first vacuums were produced by mechanical pumps that separated a definite volume of the gas from the vessel to be exhausted and gave it up to the atmosphere. Among such devices were piston pumps and the hand-operated Töpler pump. In 1905, the German vacuum scientist and engineer, Walter Gaede introduced his rotary mercury pump, and later his mechanical forepump. The forepump used a rotary piston with sliding vanes or valves. Oil served as a sealant and lubricant between closely fitted parts.

Mechanical pumps have changed very little over the years. The only significant changes in modern practice are the use of rotary eccentric pistons in place of vanes, multistage pumps for higher pumping speeds, and the introduction of gas ballasting for pumps handling condensable or soluble vapors. These pumps are usually used at pressures above 10^{-3} Torr. They frequently serve as back-up pumps for vapor diffusion pumps.

In 1913 Gaede made a significant advance in the design of mechanical pumps for the producton of high vacuum: a molecular pump that could attain much lower pressures with greatly increased pumping speeds. The molecular pump represented a radical departure in the design of vacuum pumps, in that there was no mechanical separation between the high vacuum and the fore vacuum. The gas is drawn from the vessel to be exhausted into the fore vacuum by a cylinder rotating with very high velocity inside a hermetically sealed casing. At low pressures under molecular-flow conditions, the gas molecules collide mostly with the walls of their container and tend to take up the direction of any wall motion. With such a pump, Gaede achieved up to 1.4 liters/sec—ten times faster than his rotary mercury pump.

By 1943, Manne Siegbahn at Uppsala had developed modified single-disk molecular pumps with multiple spiral grooves, capable of pumping 73 liters/sec at 10^{-3} Torr. Modern turbomolecular pumps (figure 2) have speeds as high as 3600 liters/sec, and they produce pressures as low as 10^{-10} Torr. In addition to achieving high instantaneous pumping speeds for gases and vapors, especially for heavier species, turbomolecular pumps require no refrigerant or drying traps.

Diffusion Pumps. In 1915 Gaede took the art of vacuum pumping yet another important step forward; he invented the vapor diffusion pump. Instead of using rotating metal parts to transfer momentum to the pumped gas, Gaede employed a high-velocity jet of mercury vapor. This was quickly followed by Langmuir's condensation pump in 1916. By combining Gaede's mercury-vapor pumps with Langmuir's liquid-air traps to condense the mercury vapor, it was possible to obtain pressures as low as 10^{-7} Torr, which, starting about 1920, met the demands of the rapidly expanding electronic tube industry.

In 1928, Cecil Burch in England found that certain high-boiling-point petroleum distillates could replace the mercury in diffusion pumps, thus eliminating the need for liquid-air traps. However, unlike mercury, organic pump oils have the disadvantage that they dissolve all kinds of gases and vapors that may form metastable compounds as well as true solutions. Furthermore, thermal decomposition of the oil may results in the formation of additional volatile products. Release of these gases and vapors into the high-speed jet causes backstreaming into the vacuum system, thus limiting the pressure utimately attainable with these pumps.

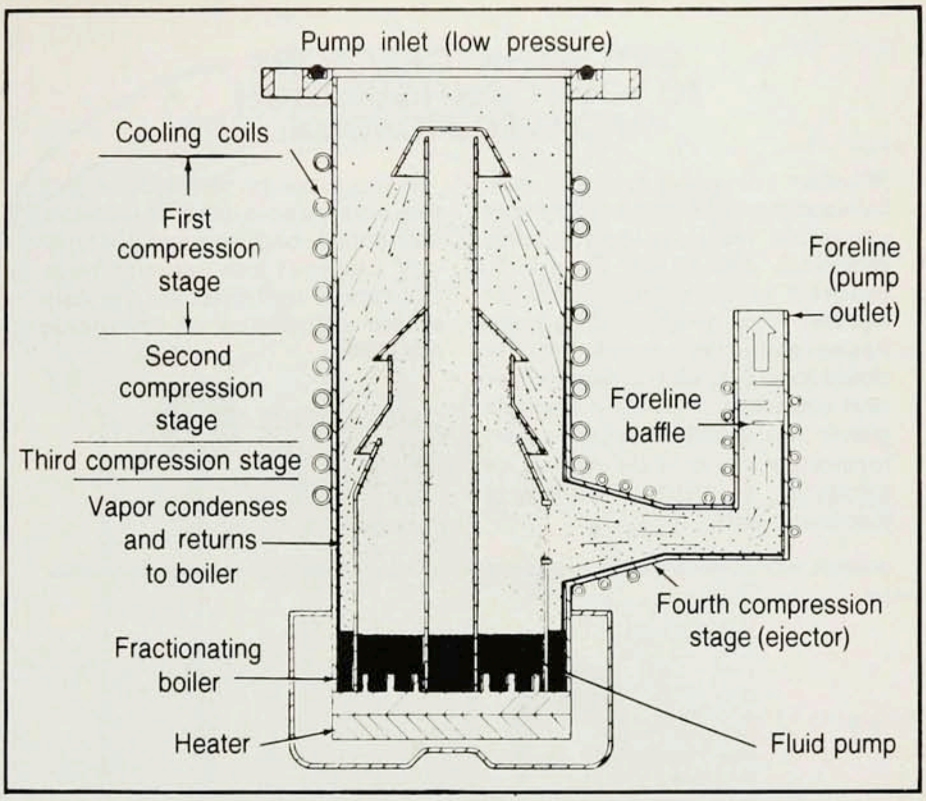
To minimize these detrimental effects, Kenneth Hickman and his colleagues in Rochester (N.Y.) developed the self-fractionating diffusion pump in 1936. In one form of this self-purifying pump (figure 3), condensed vapor flowing down the sides of the pump wall is first heated in the outer part of the boiler, where dissolved gases and vapors and light fractions of the pump fluid are vaporized and fed into the jets nearest the pump outlet. By the time the returning pump fluid reaches the center of the boiler, the volatile vapors and gases will have been driven off. Thus only the less volatile pump-fluid vapor that reaches the high-speed jet will contribute to the ultimate pressure by backstreaming.

Oil diffusion pumps have now largely replaced the early mercury diffusion pump because of their high speed, moderate forepump requirements, and low ultimate pressures without the use of refrigerated vapor traps. This was made possible not only by advances in pump design but also by the development of many excellent pump oils that have good thermal stability, high molecular weights, and low vapor pressures. the polyphenyl esters and silicones, for example, have vapor pressures as low as 10^{-10} Torr.

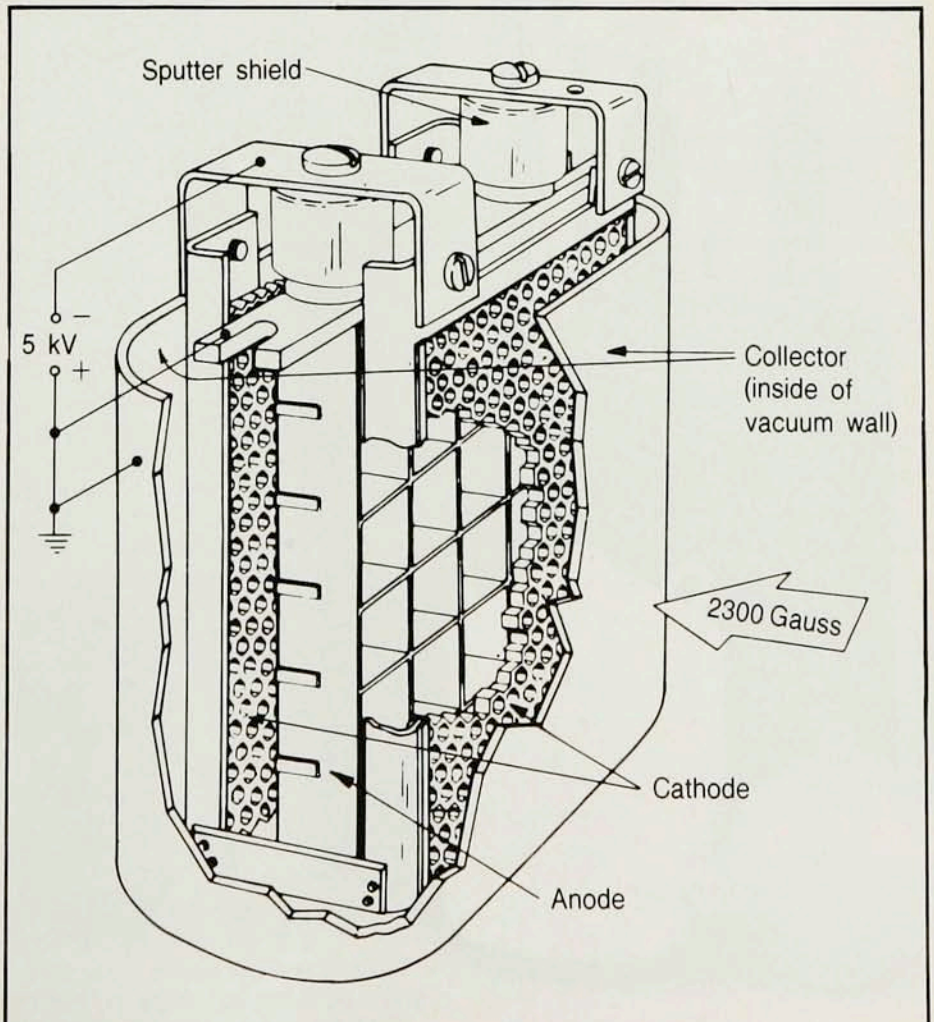
Ion Pumps. The cleanup of gas by an electrical discharge has been observed for over a century, but not until 1958 was this phenomenon deliberately used by Louis Hall on a large scale to remove gas in a vacuum system. We speak of gas "removal" in its broadest sense, because in most ion pumps the gas is not transported from the vacuum system; it is transformed into a condensed phase in the system. Thus the ion pump acts as a gas trap rather than as a pump.

Ion pumping is an extremely complicated process, which we will not describe here, involving sputtering, ion burial, chemical gettering, and other sorption processes occurring simultaneously in a Penning-type discharge (figure 4). In 1953, Raymond Herb at the University of Wisconsin developed a getter–ion pump, which uses an electrical discharge with no magnetic field and simultaneous evaporation of a chemically active getter material.

Ion pumps are used most efficiently at pressures below 10^{-5} Torr. They provide unusually clean pumping, free of the vapors associated with diffusion pumps, and requiring no refrigerated traps or baffles. They also need no forepump, once the pressure in



A multi-jet metal-diffusion pump *with ejector stage. A self-fractionating type boiler is used, with oil as the working fluid.* *Figure 3*

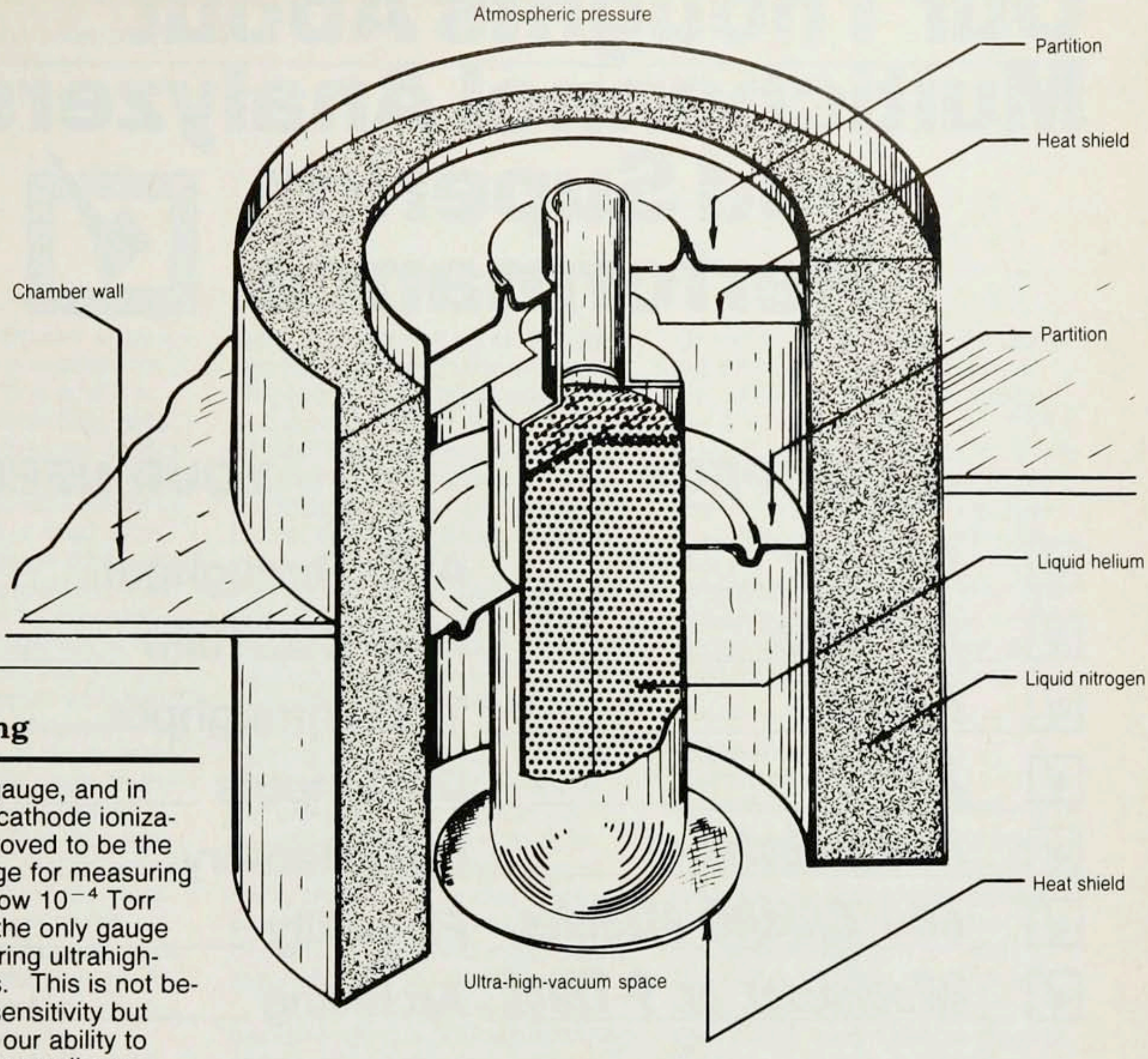


A sputter-ion pump *in which gas is trapped by ion burial and sputtered metal deposits.* *Figure 4* the system has been reduced to 10^{-3} Torr, where pumping action starts. Ion pumps have produced presures of less than 10^{-10} Torr in ultrahigh vacuum systems.

Cryogenic pumps, the final catagory of pumps in this survey, have become popular in the last quarter century (figure 5). There is not always a clear distinction between sorption pumping at low temperatures and cryopumping. Cryogenic pumping, usually refers to the removal of gas or vapor from the gas phase by condensation or absorption on a surface at ultralow temperatures, near the boiling point of liquid H_2 or He. This surface is frequently called a cryopanel.

At the boiling point of helium (4.2 K), the vapor pressure of hydrogen is about 10^{-7} Torr, and all other gases are at less than 10^{-10} Torr. Pumping speds of about 4 liters/cm^2 sec have been observed at boiling hydrogen temperatures.

The fast pumping speeds of cryopumps made them particularly suitable for use in large space simulators in the early 1960s. The gas molecules that leave a vehicle in space suffer practically no collisions and thus do not return to the vehicle surface. This condition can be simulated by a cryopump with panels that completely surround the test vehicle, because almost all the desorbed molecules from the vehicle condense on the panels. One also uses these low-temperature panels to simulate the black-void radiation sink of outer space.



__Cryogenic pump.__ The lower partition serves to keep the liquid helium level from the ultrahigh vacuum region. The gases in the vacuum-tight space condense, and the resulting vacuum serves as a heat barrier. *Figure 5*

Measuring almost nothing

The ionization gauge, and in particular the hot-cathode ionization gauge, has proved to be the most popular gauge for measuring gas pressures below 10^{-4} Torr since 1916. It is the only gauge capable of measuring ultrahigh-vacuum pressures. This is not because of its high sensitivity but rather because of our ability to measure extremely small currents. Collision with electrons is by far the simplest and most effective method of ionizing the residual gas, because of the relatively large cross sections involved.

Nothwithstanding its great popularity, the ionization gauge suffers from just about every conceivable fault one could imagine in a device for measuring pressure. In the first place, it doesn't measure pressure—it measures gas density. It does not provide an absolute method of measurement, and calibration is dependent on the nature of the gas. The ionization gauge may give inaccurate readings unless precautions are taken, because it may pump, dissociate, and react with the gas it is supposed to be measuring; it may generate gas of its own; it may produce other spurious currents that are mistaken for ion current; and it may have inherent electronic instabilities. In spite of all these difficulties, one can rely on a properly designed and operated ionization gauge to give pressure readings that are accurate to better than an order of magnitude—perhaps even a few percent under ideal conditions, when it is carefully calibrated for a known gas composition.

Before 1948, no one had measured pressures below 10^{-8} Torr with the triode ionization gauge (figure 6), even though there was evidence from surface absorption experiments that lower pressures were being attained. In 1947, Wayne Nottingham presented evidence of a residual current to the ion collector independent of gas pressure. This current was shown to be caused by photoelectrons ejected from the ion collector by soft x rays produced by 150-volt electrons striking the grid.

The solid angle subtended by the ion collector, as seen by the x rays, may be reduced by making

the collector area smaller or by removing it from the immediate vicinity of the grid. The goal is to do this without substantially reducing the fraction of the ions collected. Robert Bayard and Daniel Alpert were eminently successful in accomplishing this in 1950 with their well-known gauge (figure 7), in which the positions of the filament and ion collector are interchanged. A large fraction of the ions produced inside the grid are collected by the center wire, which is only 0.175 mm in diameter. The small surface area of the collector wire presents a solid angle to the x rays that is several hundred times smaller than that of a conventional collector. This arrangement has extended the low pressure limit of the gauge to the 10^{-11} Torr range. Because of its elegant simplicity, the Bayard–Alpert device is the most popular gauge in use today.

Another approach to the problem of extending the low-pressure limit of ionization gauges is that of increasing the sensitivity of the gauge. If the gauge is modified so that the electrons travel in longer paths before they are collected, the probability of their colliding with an ionizing gas molecule can be greatly enhanced, thus increasing the sensitivity of the gauge without increasing x-ray photoemission.

One way of increasing the gauge sensitivity is to use an electric or magnetic field to force the electrons into long spiral trajectories. In 1960, I developed a hot-cathode magnetron ionization gauge (figure 8) with a sensitivity of more than 10^8 Torr—10^7 times more sensitive than the conventional triode gauges. This device consists of a cylindrical-anode magnetron operated in a magnetic field with an intensity of about 2.5 times the cutoff value. Negative end plates prevent the escape of electrons. One of the end plates is carefully insulated and used as an ion collector. Electrons emitted by the filament spiral around it, and few ever reach the anode. The gauge has a linear characteristic down to 10^{-13} Torr. I avoided right emission, outgassing and evaporation of alkali metals from the cathode by using a lanthanum boride filament in place of tungsten.

In 1958, Paul Redhead in Canada also used a magnetic field to increase gauge sensitivity. He developed a cold-cathode inverted-magnetron gauge that uses crossed electric and magnetic fields to obtain efficient electron trapping in the discharge space to get maximum ionization at low pressures. Cold-cathode field emission starts the discharge at low pressures. The discharge current is quite high—on the order of 5 amp/Torr at 600 volts, with a magnetic field of 1000 oersteds.

The lowest pressure one can measure using a hot-cathode magnetron ionization guage with a conventional electrometer is about 10^{-14} Torr. One can get down to 10^{-16} Torr with this gauge by replacing the ion collector with a suitably shielded electron multiplier. This addition hardly seems justified, however, because with only slightly more complication one may use a quadrupole or magnetic partial-pressure analyzer, which will also identify the residual gases. In any event, gauges and partial-pressure analyzers are available or can be constructed to measure the lowest pressures that exist today. This represents a complete reversal of the situation 35 years ago.

It is interesting to note that pressure ranks among those physical quantities that man has measured over a range of more than 20 orders of magnitude. In the diamond presses at the General Electric Research and Development Laboratory, the largest static pressures reliably determined by the x-ray diffraction patterns of nickel are about half a million atmospheres, while the smallest total pressures measured in a vacuum system (by William Davis, in the same building!) are on the order of 10^{-16} atmospheres. The pressure at the center of the earth is estimated to be about 3.5 million atmospheres; in free space it is of the order of 10^{-19} atmospheres. Thus man still has four orders of magnitude to go before attaining and measuring in the laboratory the pressure extremes that exist, quite nearby, in Nature.

A professional vacuum society

The need for a technical society devoted exclusively to vacuum science and its application appears to have been recognized first by Frederick A. McNally in 1952. Through his efforts, an organizational meeting was held in New York on 18 June 1953, to discuss the formation of a permanent organization that would bring together both the theoretical and practical knowledge of the many different fields using vacuum as a production or research tool. This meeting resulted in the formal organization of the "Committee on Vacuum Techniques" less than a week later, and its formal incorporation in Massachusetts on 19 October 1953. Since its first symposium the following June in Asbury Park (New Jersey), with 35 papers and 295 registrants, the group has convened an annual symposium in every succeeding year. In 1957, the CVT changed its name to the American Vacuum Society, Inc. The first biennial equipment exhibit was held in conjunction with the 1961 symposium. Since 1965, an equipment exhibit has been a part of every symposium. These exhibits have proved to be of great interest to the registrants, and of considerable financial help to the AVS. More than 1300 attended its 27th National Symposium in Detroit last year, and over 350 papers were presented there.

Over the years, the AVS has developed a close association with the American Institute of Physics. In April 1963, it became an affiliate of AIP, and a full member society in 1976. The AIP has been publishing the *Journal of Vacuum Science and Technology* for the AVS since its inception in 1965. The Institute also manages the equipment exhibits at the national symposia. In 1967, AVS moved its offices from Boston to the AIP building in New York CIty, and in May 1968, a full-time Executive Secretary, Nancy Hammond, was engaged by AIP for the Society.

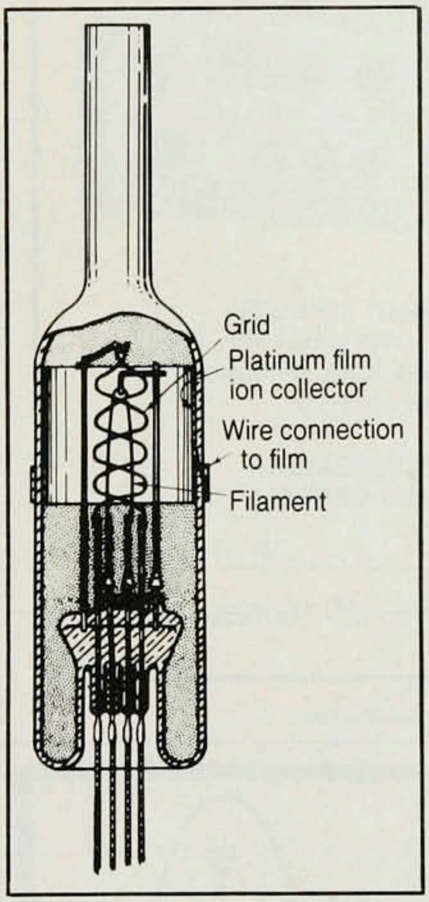
The AVS had continued to grow and prosper, reaching a peak of about 3100 members in 1968. Its membership declined to about 2200 by 1972 following government cutbacks in the space and other R&D programs. During the past five years, however, the AVS has started to grow again at an ever accelerating rate. Its current membership exceeds 4000.

If, in the 1960's, the AVS board of directors had insisted on limiting their interests to the production and measurement of vacuum, it is doubtful whether the Society would be in existence today. At best, I suspect, it would have a greatly diminished level of activity. Instead, the board formed new divisions to provide a home and give support to those new disciplines that had benefited most from improved vacuum technology. These included a vacuum metallurgy division in 1961, a thin film division in 1964, a surface science division in 1968, an electronic materials and processes division in 1979 and a fusion technology Division in 1980.

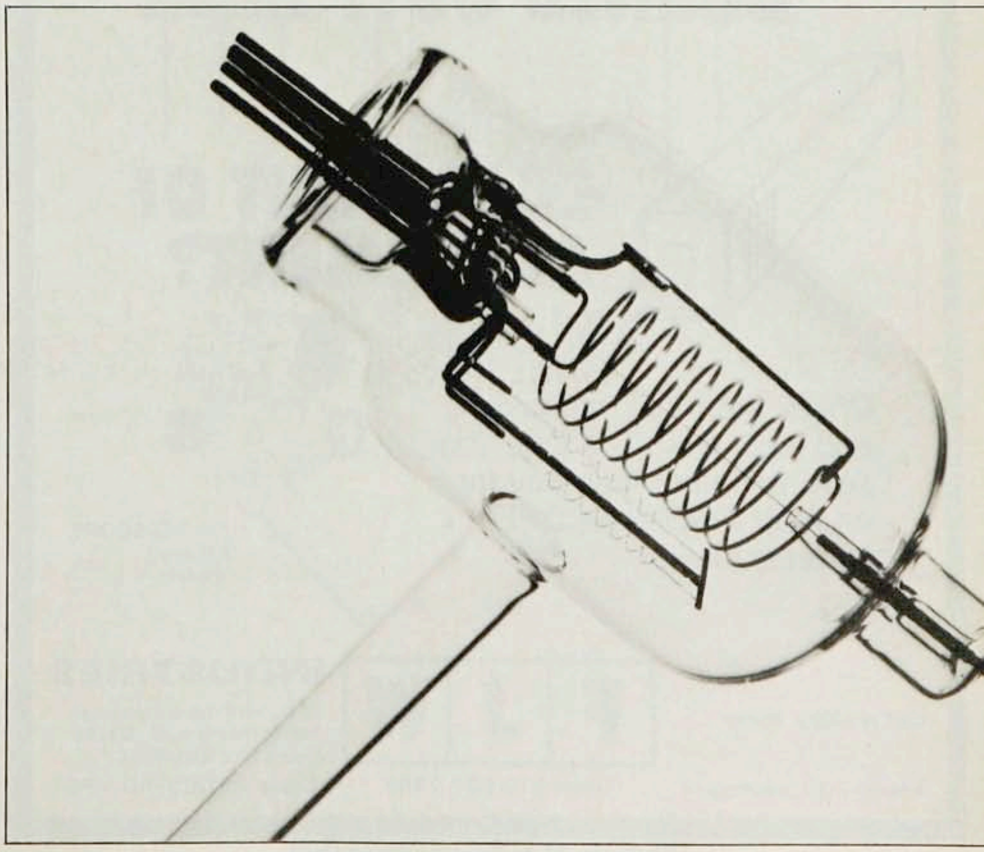
To keep the tail from wagging the dog that started all of this, the vacuum technologists in self-defense formed a home for themselves by setting up their own vacuum technology division in 1970. It will be noted that even though the AVS has now become a multidisciplinary society, there is a synergistic interaction between the divisions that extends beyond the fact that they all use vacuum as an important tool in practicing their trade. This has given the Society strength and tenacity.

The AVS has been very active in promoting vacuum education by publishing monographs and teaching courses at both the apprentice and advanced theory levels. It publishes a bimonthly newsletter. It has established grants, graduate scholarships and major awards in vacuum science and the related fields covered by its divisions. The Society also has an active standards committee, which has published many of its own standards and helped in developing national and international vacuum standards.

Other countries have also organized their own vacuum societies. Many of these, some 22 in number (including the AVS), are members of the International Union for Vacuum Science, Technique and Applications. The Union had its origin in 1958 in Namur, Belgium under the leadership of Emil Thomas. In its present form, it is an international confederation of national vacuum organizat;ions and excludes private membership. The interests of the IUVSTA encompass not only vacuum *per se*, but those disciplines that use vacuum as an important tool. Like the AVS, the Union is in the process of establishing divisions in surface science, thin films, vacuum science, electronic materials and fusion technology. It organizes an International Vacuum Congress every three years. Recently this Congress has been held in conjunction with the International Conference on Solid Surfaces. The last Congress was held at Cannes, France, in 1980, with more than 1000 in attendance. Two earlier Congresses were held jointly with National Symposia of the AVS in 1961 and 1971.



Early form *of triode ionization gauge. This gauge is degassed by passing current through the grid and filament, and by torching the glass envelope. Figure 6*



A modern version *of the Bayard-Alpert inverted-ionization gauge for the measurement of ultrahigh vacuum. Figure 7*

Electronics and vacuum technology

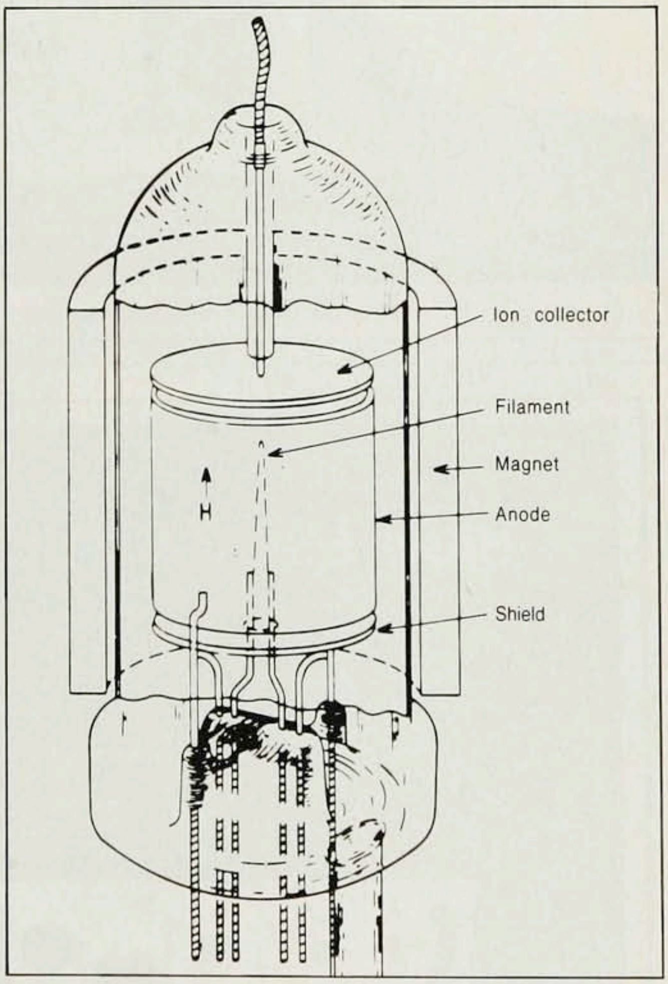
Historically, vacuum technology has played an important role in the development and production of many commercial and industrial products. These include x-ray tubes, lamp bulbs, many types of electron tubes, high-power vacuum circuit interrupters, and triggered vacuum gaps. Many modern electronic components no longer operate in a vacuum, but their fabrication depends on vacuum technology. Among these are solid-state power devices, integrated circuits, photoconductors, electroluminescent devices and ferromagnetic memory systems.

The quality and lifetime of electron tubes depend on the ability to produce and maintain a high vacuum in them. In early tubes, the vacuum was very poor. In many cases the inventor of the tube actually turned the poor vacuum to advantage. In some cases the presence of gas was essential for the tube's successful operation. In the early Roentgen "gas" x-ray tube, for example, the electron stream was produced by a cold-cathode low-pressure gas discharge. The current, applied voltage, and gas pressure were all interdependent. It was not uncommon in those days for a radiologist to use a series of tubes at different gas pressures to produce x rays of various energies. It was not until 1913, when vacuum technology had been sufficiently improved, that William D. Coolidge was able to develop a highly evacuated x-ray tube with a hot ductile tungsten filament to supply the electrons, so that the current could be adjusted independently of the applied voltage that determines the x-ray energy.

The quality of the vacuum has also played an important role in the performance of cathode-ray tubes and television picture tubes. In the early Braun cathode-ray tube, electrons were liberated from a cold cathode and concentrated by means of a gas discharge. The positive ion core in the electron beam produced a converging electric field, which focused the electron beam. Gas focusing cathode-ray tubes were necessarily slow because of the long ion transit times.

Improved vacuum technology made possible the development of the modern oxide-coated cathode electron gun by Manfred von Ardenne in Berlin and Valdimir Zworykin at RCA in the late 1920s. But 30 years later the vacuum technology practiced in cathode-ray television picture-tube processing had still not progressed to the point where gas-ionization effects were completely absent. Ion-trap electron guns were developed to avoid destructive sputtering of the oxide-coated cathode by positive ions generated in the electron beam. Before the aluminized backing was added to the television picture tube screen, ion-spot burns in the center of the phosphor screen were common. This was caused by bombardment of the phosphor by high-velocity negative ions formed by electron

Hot-cathode magnetron *ionization gauge for the measurement of extreme ultrahigh vacuum.* *Figure 8*



attachment. Finally, with the advent of the color TV tube, vacuum processing had advanced to the point where ion traps were no longer needed.

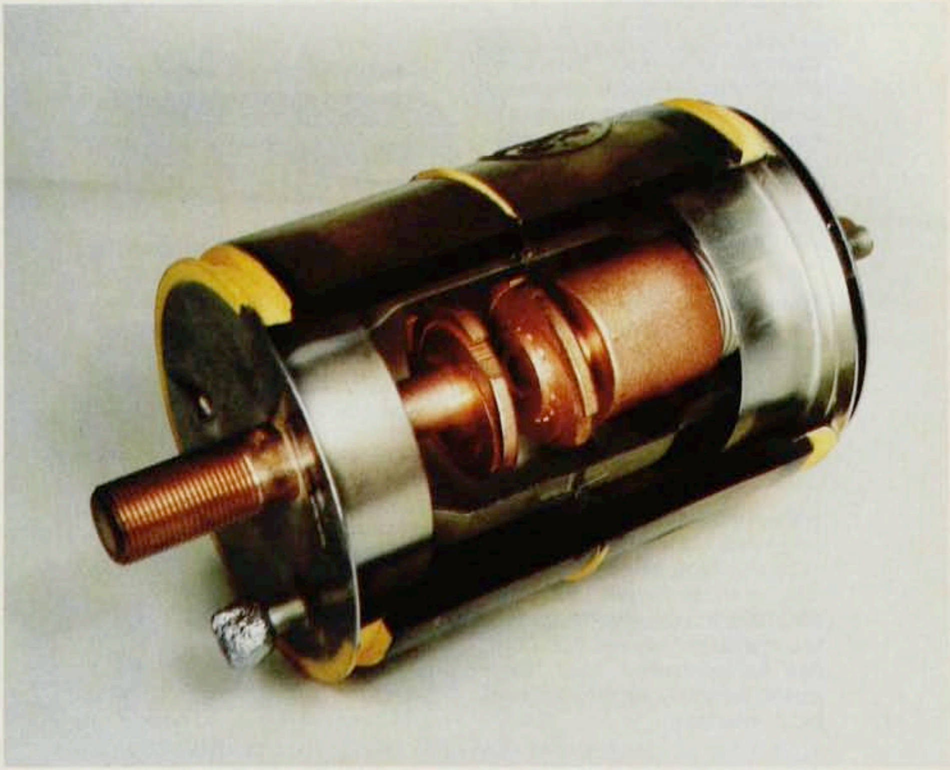
More recent examples of the influence of vacuum technology are the high-power vacuum circuit breaker and the sealed, triggered vacuum gap. The simplicity and elegance of reliably interrupting large currents in high-voltage circuits by separating two metal contacts enclosed in a vacuum has fascinated scientists and engineers for a long time, but early attempts were doomed to failure because of the lack of supporting vacuum and metallurgical techniques. In the early 1920's at Caltech, Robert Millikan, in his research on the field emission of electrons from metals, observed that vacuum gaps had a very high dielectric strength; many tens of kilovolts would not break down across a vacuum gap of only a few millimeters. Royal Sorensen (Caltech) applied this phenomenon in his invention of the vacuum switch. Some of the early work by Sorensen and General Electric showed great promise, but it soon became evident that the sealed vacuum switch of the early 1930s could not offer the high reliability demanded by the electrical utilities.

In these experiments of the early 1930s, a startling number of weaknesses were revealed. Vacuum technology at that time was still in a very rudimentary state. Large glass-to-metal seals were fragile and unreliable. Pressures lower than 10^{-6} Torr could not be produced and measured routinely in production vacuum systems. Vacuum techniques for producing the high degree of outgassing for long, trouble-free life in a sealed switch had not yet been developed.

Copper electrodes were used to make the arc stable at low currents and keep the contact resistance low, but this choice introduced several serious problems. One problem was the large amount of gas released in arcing. At high arcing currents, gas would accumulate in the vacuum switch on successive operations, thus destroying the vacuum and causing the switch to break down at low voltages. Several unsuccessful attempts were made at that time to obtain gas-free copper by vacuum melting.

Twenty years later at the suggestion of James Cobine, a former student of Sorensen's, my associates and I took a fresh look at this old problem. Rapid advances had been made in vacuum and metallurgical processing. New electronic instrumentation made it possible to study hitherto inaccessible vacuum arc phenomena. Basic scientific knowledge acquired from research on metal-vapor arcs could reasonably be expected to benefit vacuum-switch technology.

Among the various unsolved problems, the production and maintenance of a high vacuum in the interrupter, regardless of the severity of switching service, was of prime importance. Fortunately, large glass-to-metal seals, ceramic-to-metal seals and flexible metal bellows had been developed that



A modern 500 MVA vacuum interrupter. *Figure 9* were capable of withstanding the mechanical and thermal stresses expected in high-power vacuum interrupters. Furthermore, vacuum technology had advanced to the point where vacuums of the order of 10^{-9} Torr could be produced and measured routinely.

This progress over the years had solved two of the basic problems. However, the release of gas during arcing from the electrode materials, such as copper, had not been solved. Calculations showed that keeping the pressure below 10^{-5} Torr in a typical 10 000-amp switch requires the electrodes to have less than one part in ten million of gaseous impurities (or compounds that could be dissociated into noncondensable gases by arcing).

It was known that impurities tend to segregate in crystal grain boundaries. This prompted Malcolm Hebb to suggest experiments using electrodes made from single crystals of copper drawn from the melt. These electrodes proved to be remarkably free of gas, and they gave the first indications of a major technical breakthrough; but they were too expensive for large-scale manufacture. Zone-refined copper was then tried, making use of the techniques developed by the semiconductor industry for purifying silicon. This process was relatively inexpensive, and measurements made on zone-refined copper showed a total ungettered gas content of one part per billion. The residual gas was found to consist of 60% methane and 40% carbon monoxide, with traces of hydrogen. Zone refining had solved the gas-free electrode problem.

The ideal vacuum-switch electrode or contact must not only be gas-free; it must also satisfy several other requirements simultaneously. The contacts must not weld while carrying high momentary currents or when closing in on a short circuit. To minimize heating during the flow of normal continuous current, the electrical resistance must be low. The electrodes must be hard, so that they maintain their shape under the high mechanical stresses of rapid opening and reclosing normally encountered in a high-current interrupter. Finally, the vapor pressure of the electrode material must be high enough to maintain a stable arc at low currents, to prevent the generation of high overvoltages by an abrupt cessation of the arc current (current chopping). These problems were solved by the use of a gas-free two-phase alloy of copper and bismuth.

Notwithstanding its complexity, the vacuum arc has now been harnessed to serve as a useful high-power circuit interrupter (figure 9). Thanks to modern vacuum technology.

There are many other examples of the major impact of vacuum technology on modern industrial and commercial products. These include lamps which derive their light directly from metal-vapor plasma radiation, and, of course, all the solid-state power devices and integrated circuits that involve thin films, plasma, evaporation, sputtering, ion implantation, vacuum baking, and low-pressure chemical decomposition by pyrolysis. Vacuums may also be used to increase the evaporation rate of various substances without destructive heating, as in the case of dehydration of frozen fruit juices, penicillin or blood plasma.

Vacuum technology has been harnessed to become the workhorse for many modern industries. Shakespeare's title, "Much ado about nothing", is most appropriate for our field. In less than a half a century vacuum technique has changed from an art to a science. Companies have been founded solely for the purpose of manufacturing equipment to produce and measure vacuums. Professional societies have been organized and careers devoted exclusively to the science, technique and application of vacuum. □