Theory and circuitry of instruments for measuring extremely low pressures

ELECTRONIC VACUUM GAUGES

By A. A. SCHULKE*

JUST a few years ago, the production of low pressures was an art known to only a relatively few physicists and engineers. Today, vacuum has become one of industry's most important tools. Radio and television would be impossible without it, and its uses range from the production of jet engines and atomic bombs to the manufacture of phonograph records and thermos bottles. Fig. 1 illustrates a few of these processes. It may be seen that the range of pressure used in these applications is well over 100,000,000 to 1!

The use of such a wide range of pressures has made it necessary to develop a large variety of gauges for their measurement. The most popular of these instruments are essentially electronic and because of their increasingly widespread use it is inevitable that the electronic technician or plant electrician will be called upon to service them. This article will lay the foundation for this future service work by outlining the principles of some of the most popular of these gauges.

For many years, atmospheric pressure was used as the base for vacuum measurement. Since this pressure varies with geographical location, time of day and barometric changes, it proved a poor reference line. In recent years it has become customary to make vacuum measurements on an absolute scale. A theoretically perfect vacuum is taken as the reference level. With this as our zero, any vacuum less perfect than this exists at some definite pressure above this zero level.

If we should take a long glass tube, sealed at one end, completely fill it with mercury and then, by holding a finger over the open end so that no air is admitted, carefully place it in a small cup of mercury (Fig. 2), the mercury will settle down and stand at some definite height (H). A vacuum will be created in the space above the mercury column. The height of this column will be determined entirely by the pressure of the air on the open surface of the mercury in the cup. At sea level this will be about 760 mm. If the air pressure is reduced by taking this device to some great altitude, as for example, to the top of Mount Everest, the air pressure will be able to support the mercury column to a height of only about 235 mm. If we enclose this mercury tube inside a tight box (dotted lines in Fig. 2) and attach a vacuum pump to the box to reduce the pressure further, the mercury column would fall still lower.

The height of the column is therefore a function of the pressure which may be expressed in terms of the column height as so many millimeters of mercury. This is usually abbreviated to "mm Hg." The mercury manometer (Fig. 2) is not useful for measuring pressures below 1 mm or so, other gauges being used for this purpose. Yet the unit (mm Hg) is still used to indicate the degree of partial vacuum obtained.

By using a classification system somewhat similar to that adopted for radio and television channels, we can loosely classify vacuum systems capable of producing pressures as low as 10^{-3} to 10^{-4} as "high"; those operating

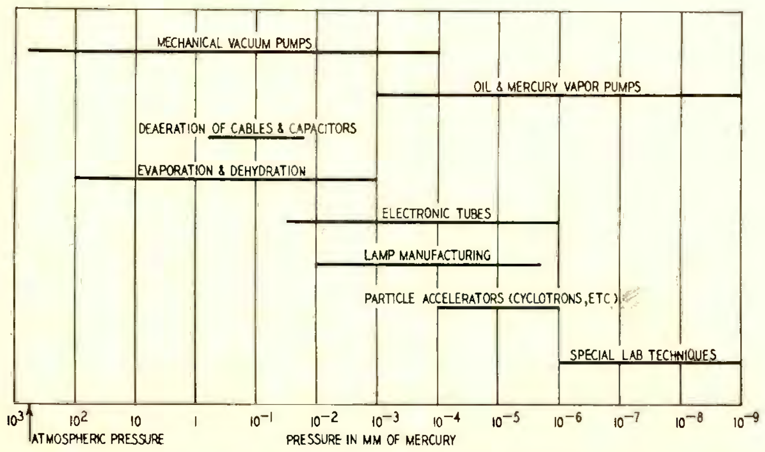

Fig. 1—Typical pressure ranges of some common pumps and processes.

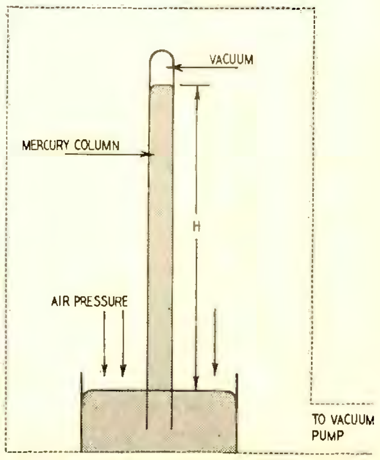

Fig. 2—Mercury-column pressure gauge.

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still lower, say to 10^{-6} mm Hg, as "very high" and those few systems capable of going beyond this point, "ultra high."

To produce high vacua, it is necessary to work harder and harder to obtain less and less. The greatest effort must be applied to obtain practically nothing! Well, not quite nothing. Inside the average television tube, which is at a pressure of about 3×10^{-3} mm Hg, there are approximately 10^{14} (100 million million) air molecules per cubic centimeter. At the lowest pressure yet obtained in the laboratory, each cubic centimeter still contains more than 200 millions of these molecules.

Most vacuum gauges, certainly all those which may be classified as electronic, operate by ionizing these molecules in some way and then measuring the resultant current. Some of these gauges are listed in Fig. 3, together with the regions of pressure in which they usually operate.

McLeod and Knudsen gauges

Two nonelectronic gauges, the McLeod and Knudsen, which do not use this principle, are worth mentioning because they are the basic gauges used for calibrating all others.

The McLeod operates on the principle of taking a sample of gas of known volume V_1 from the vacuum system at a pressure P_1, which is too low to measure. This sample is then compressed into a smaller volume V_2 at a higher pressure P_2, which can be measured by a mercury column. The unknown pressure P_1 may then be easily calculated by Boyle's law, $P_1 V_1 = P_2 V_2$.

This gauge, though simple and easily calibrated, is not in general use as a vacuum gauge primarily because it is slow to read (it requires 10–15 minutes for one pressure measurement), is not continuously reading and cannot be read remotely. It is also very difficult to use at pressures below 10^{-4} mm Hg.

The Knudsen gauge consists of a thin sheet of metal suspended between two heated plates located on opposite sides and at each end of the sheet. Gas molecules entering the region between the sheet and the plates gain momentum from the heated plates and bombard the sheet with greater force than those molecules which happen to strike other areas of it. The sheet will therefore be deflected away from the heated plates and the amount of the deflection, proportional to the number of gas molecules present, will be a direct measure of the pressure in the system.

The Knudsen gauge is unique in that its action is independent of the kind of gas or vapor pressure of the gas in the vacuum system. No other gauge has this property and the Knudsen gauge is thus the only absolute gauge we have. It is also a continuous-reading device, although somewhat slow in responding to pressure changes in the vacuum system.

Unfortunately, it has several serious disadvantages which preclude its more general use. The principal ones are that it is delicate and must be rigidly mounted on a vibration-free support, it cannot be read remotely and the pressure range of any given gauge is relatively narrow. Although the Knudsen gauge principle can be used to measure pressure from about 10^{-2} to 10^{-8} mm Hg, this can be done only by using instruments with different suspensions and heater temperatures.

The Alphatron

This is the newest of the vacuum gauges and since it was placed on the market comparatively recently it is not in very general use.

The heart of the device is a sealed radium source of about 200 milligrams, placed inside an ion chamber. Alpha particles emitted from this source at a constant rate cause ionization of some of the gas molecules from the sample taken of the vacuum system. Since these ions are collected in the chamber at a rate proportional to the number of gas molecules present, the response of the gauge should be linear. This has been found to be so for a range of pressure extending from about 10 to 10^{-3} mm Hg.

The output current from is gauge is very low, about 2×10^{-7} microamperes at 10^{-3} mm Hg. A very-high-gain d.c. amplifier must be used to measure this minute current. The lower limit of pressure will measure about 10^{-4} mm Hg since, at this pressure, the ion current produced by the gauge has about the same magnitude as the grid current of the amplifier tube in the first stage. Input resistors for this amplifier range from 100 to 10,000 megohms—far beyond the range of most service shops to check.

The gauge appears to have few disadvantages and much to recommend it. The probe head containing the fairly husky radium source, although safe as constructed, should be taken apart only by someone trained in the handling of radioactive materials. Thus, it is likely that any field service done on this gauge will be limited to the d.c. amplifier. Other possible disadvantages are its comparatively high cost and the fact that it operates in a pressure region now occupied by well-established and substantially cheaper gauges.

Among its advantages are these: The source of ions requires no power supply and is self-regulating, it is very rugged and not easily broken, there is no filament to burn out and the gauge cannot be harmed by exposure to full atmospheric pressure.

In common with many other gauges, the response of the Alphatron varies with different gases. When measuring the pressure of a vessel containing helium, for example, the output current from the gauge will be only one-tenth as much as for air at the same pressure. Fortunately, however, the gauge response is almost the same for air as for water vapor. For this reason it should become a great favorite with the dehydration industry.

Thermocouple gauge

Of all the gauges available for the measurement of low pressure, the thermocouple type will probably be of greatest interest to the readers of RADIO-ELECTRONICS. Extremely rugged, simple and foolproof in operation, it cannot be damaged by operation at full atmospheric pressure. The control circuit requires only a few relatively inexpensive parts and the range of pressure measured is almost ideal for the vacuum systems used in the average shop or basement laboratory.

Its essential elements (Fig. 4) are a heated wire and a thermocouple. The operation of the gauge depends on the fact that over a certain range of pressure, the heat conductivity of a gas depends on the number of gas molecules (gas pressure) present. This means that with a constant current to the heated wire, the wire will be relatively cool when the pressure is high (poor vacuum and low output from the thermocouple) and will get progressively hotter as the pressure is reduced (better vacuum and higher output from the thermocouple).

The extreme simplicity of this gauge and of the electrical circuit used with it may be seen from Fig. 4. To operate the gauge it is only necessary to set

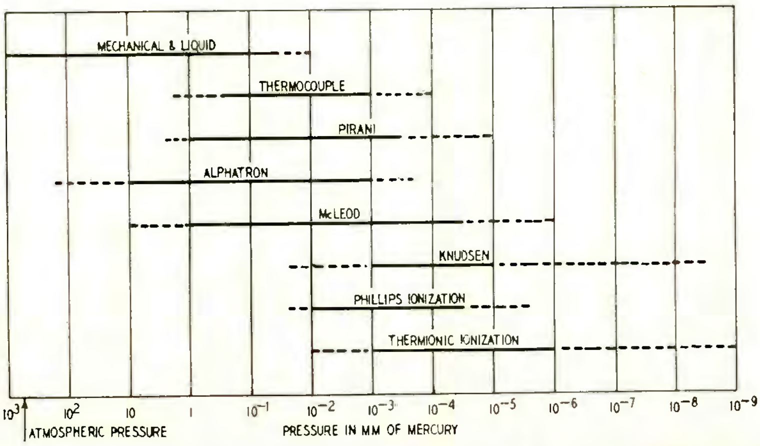

Fig. 3—Some of the various vacuum gauges and the ranges achieved by them.

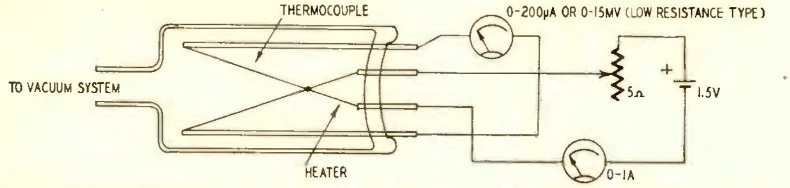

Fig. 4—The schematic and control circuit of a thermocouple vacuum gauge.

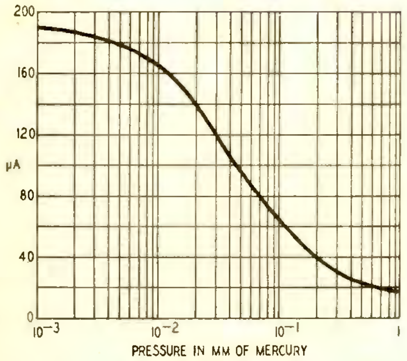

Fig. 5—The calibration curve for the model 501 thermocouple gauge.

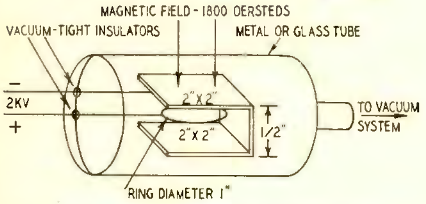

Fig. 6—Diagram of the Phillips gauge.

the heater current to the value marked on the tube (usually about 0.62 ampere) and read the output current on a microammeter or millivoltmeter.

The output current from the thermocouple is relatively high and may be read directly on a meter without intermediate amplication. The meter must be of the low resistance type, however.

One of the most popular thermocouple vacuum gauges is the model 501 all-metal tube manufactured by the National Research Corporation, Cambridge, Mass. It has a standard eight-prong octal base for the electrical connection, a threaded pipe for attaching the tube to the vacuum system and may be purchased for about $12.

The calibration curve for this gauge for dry air, and for 70-ohm impedance in the thermocouple output circuit, is in Fig. 5. This curve will not be valid for gases other than dry air, however, because the heat conductivities of these gases are not the same for the same pressure. Each gas will require its own calibration curve, but this is usually not a serious disadvantage.

The Pirani gauge, which will not be described here, is a variation of the thermal conductivity principle. In this gauge, the heated wire is part of a Wheatstone bridge circuit and the change of resistance, measured by the bridge, indicates the pressure.

Phillips ionization gauge

This extremely popular gauge overlaps the upper range of the thermocouple gauge and the lower range of the thermionic gauge, and frequently will take the place of both. It operates by maintaining a glow discharge between two electrodes in a magnetic field.

As pressures become lower and lower, the distance an electron must travel before it makes an ionizing collision with a gas molecule becomes greater and a glow discharge cannot be maintained for any reasonably low voltage between the electrodes. At a pressure of 10^{-3} mm Hg, for example, the average electron will travel about 2½ inches before making an ionizing collision. But at 10^{-4} mm Hg this distance increases to 25 inches—over 2 feet!

In the Phillips gauge the glow discharge is maintained between a circular anode and double cathode arranged in a magnetic field as shown in Fig. 6. Because of the potential difference between the ring and the cathode, an electron which finds itself near the lower plate will be accelerated upward. It misses the ring, however, and continues through the ring, traveling in a tight spiral about one of the magnetic lines. As it approaches the upper plate it is repelled and travels downward through the ring to repeat the process. This oscillation up and down may be repeated many times. This makes the path length of the electron much longer than it would normally be and the chance of an ionizing collision is greatly increased.

There is nothing particularly critical about the geometry of the electrodes, the magnetic field intensity or the voltage used with the gauge; but the calibration does depend on these factors. In general, large electrodes and high voltage seem better for low-pressure work. For pressures above 10^{-3}, lower voltage (1 kv) and smaller electrode spacing are necessary.

The purpose of the magnetic field is to cause the electrons to move in a tight spiral; the weaker the field the wider this spiral will be. As the electron spirals about one of the magnetic lines the path length is increased in the horizontal plane, just as it was increased in the vertical direction by oscillating up and down. Values of field intensity used have been reported as low as 300 oersteds and greater than 5,000. It is apparently not at all critical but it should not be so low that the diameter of the spiral path of the electron becomes large in comparison with the diameter of the ring anode. For any particular gauge there will probably be a particular field strength where the gauge reaches maximum sensitivity. But it may work well with a variation of 50 to 100% of this value.

Given a small lathe and a little shop experience, a Phillips gauge can be easily constructed. One such gauge was made of a 1½-inch diameter brass pipe. The magnet was housed inside the pipe with the ⅛ x ⅝-inch pole shoes, spaced 11/32 inch apart, also serving as cathodes. The 2-kv supply for the ⅞ x ⅝-inch anode was brought through the end of the pipe by a Kovar seal. This is a small glass-to-metal vacuum-tight insulator which can be obtained in a variety of sizes and styles from the Stupakoff Ceramic Co., Latrobe, Pa. With a field strength of 1,400 oersteds, the unit has been working very well for many months.

The electrical circuit for this gauge (Fig. 7) is also very simple. The 1-megohm resistor in series with the high voltage is a protective device used to limit the current in case of a short in the external circuit.

A typical dry-air calibration curve for a Phillips gauge is shown in Fig. 8. Since the response of the gauge will vary with different gases, the gauge must be calibrated for whatever gas is being used. The output of the gauge is high and—as for the thermocouple type—the output current may be metered directly.

This gauge is also very rugged and dependable and may be exposed to atmospheric pressure without harm. Because of its simplicity, the chances of trouble are greatly reduced and what difficulties do arise are usually due to the high voltage used.

Although the output of this gauge

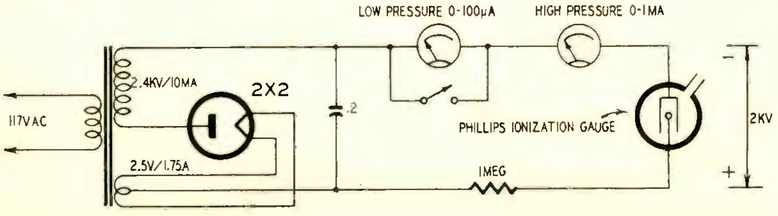

Fig. 7—Schematic shows the circuit for a Phillips ionization gauge.

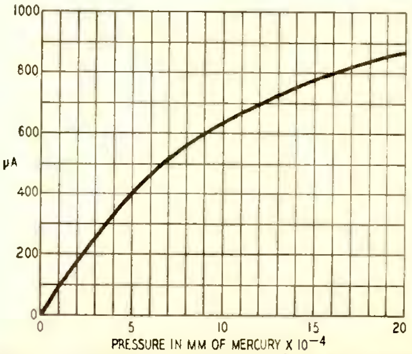

Fig. 8—Phillips ionization gauge curve.

is relatively high, in the higher pressure region of its range the output current will be reduced to only 10 μa or so when it is operating at pressures around 10^{-5} mm Hg. Because of the high voltage used, about 2,000, the insulation resistance must be greater than 1,000 megohms to avoid reading leakage currents comparable to the low output current. Another source of trouble is electrical breakdown of the insulators in the cable connectors at the gauge or power supply. Usually due to faulty design or damp locations, it can usually be corrected without difficulty.

Thermionic ionization gauge

The triode tube is the only device that can measure extremely low pressures, respond quickly to any change in pressure (useful for leak hunting) and still be read and operated at a considerable distance from the vacuum system.

The basic circuit for this gauge is shown in Fig. 9. Although it may seem simple, the actual device, as used industrially, may be somewhat bulky and complex. The reason for this is that the sources of voltage and current, shown on the diagrams as batteries, are replaced in the commercial form with voltage- and current-regulated power supplies. And a d.c. amplifier is almost always used to increase the output current to a more measurable value and to provide for a selection of scales so that a pressure range of more than 10,000:1 may be observed with the same gauge. Also included in the industrial version are a circuit for degassing the tube elements and a protective device for removing power from the filament in case the pressure should rise too high.

The gauge will work well with batteries, however, and a tube is frequently connected in this way to check the tube. It may also be used to calibrate other gauges.

In its original form, the thermionic ionization gauge was an ordinary triode tube, using a conventional positive plate and negative grid. When gas is collected in the tube, the positive ions, resulting from collisions between the gas molecules and the electron stream, are collected on the negative grid and the grid current used as a measure of the pressure.

It was discovered, however, that the gauge became much more sensitive when the grid was made positive and the plate negative. Under these conditions, electrons emitted by the filament are accelerated toward the positive grid. Some will be trapped there but many will pass through into the region between the grid and the plate. As they approach the plate, they are repelled back toward the grid and, when the pressure is low, this action may be repeated many times. The net result is an appreciable increase in the path length, a greater chance of collision with stray gas molecules and increased output current (greater sensitivity) from the tube.

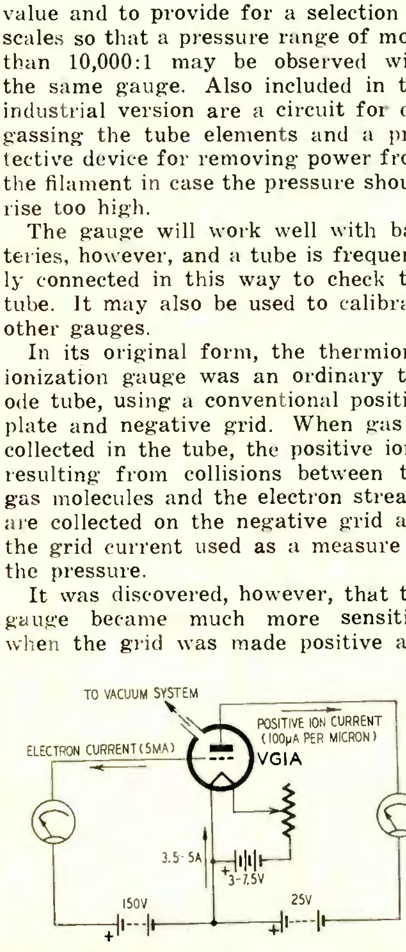

Fig. 9—The thermionic ionization gauge.

The positive ions produced as a result of these collision are collected at the negatively charged plate and the ion current measured with a sensitive microammeter or galvanometer.

If the emission current is kept constant and the electrode potentials remain fixed, the positive-ion current (Is this an *electronic* device?) will be directly proportional to the pressure and the gauge will be linear from 10^{-3} to beyond 10^{-7} mm Hg.

Although any triode will show this effect, special tubes have been developed for use as vacuum gauges. Two of the most popular are the D79510 made by Western Electric and the VG1A made by Distillation Products Inc.

To reduce leakage currents, these tubes are made with glass bulbs and do not have tube bases for the leads. Instead the leads are brought out through glass seals at the bottom of the bulb and, for the VG1A, the leakage current is reduced still further by bringing the plate lead out at the side. Other differences are that the grid wires are farther apart than in the conventional triode, the grid-to-plate spacing is greater and the bulbs have glass tubulations for convenience in attaching the tube to the vacuum system. The price of either of these tubes is about $25 and the control circuits for these will cost approximately between $250 and $425.

The output of a thermionic ionization gauge is relatively low. The VG1A, for example, when connected as shown in Fig. 9, will produce an ion current of about 100 μa for each micron (10^{-3} mm) of mercury, when used with dry air. Thus, for 10^{-4} mm the current would be only 10 μa, and this would be reduced to only 1 μa at 10^{-5}. A sensitive galvanometer is required to measure the ion current when operating in this region and a d.c. amplifier would be necessary to measure pressures below this.

Although the response of the gauge is linear, it is not the same for all gases and the data given are correct only for dry air. For other gases a correction must be made for the molecular weight of the gas or a calibration made against a McLeod or Knudsen gauge. When used with air, however, the operation of the triode ionization gauge has been found to be so predictable that it is being used more and more for the calibration of other gauges and it is a growing practice to measure a vacuum system in terms of the microampere output from the gauge. This is particularly true for the VG1A.

The life of a triode ionization gauge is difficult to predict but with the best of care and under conditions of constant low pressure it may last for 500 hours or more. As pressures increase to 10^{-3} the filament life will be somewhat shortened and the gauge should not be operated at all at higher pressures.

Oil or water vapor in the system will shorten its life to only a few hours and the admission of air to the tube at atmospheric pressure—or even at pressures very much lower than atmospheric—results in immediate destruction of the filament.

In conclusion, in addition to such considerations as pressure range, price and durability, the selection of a vacuum gauge will also depend on a variety of other factors. For example, the presence of oil vapor, which sometimes enters the vacuum system from the diffusion pumps, may cause hydrocarbon "poisoning" of the triode ionization gauge filament. The choice may, therefore, be made to use the VG1A tube in preference to the D79510, since the pure tungsten filament of the VG1A is more resistant to this effect than the thoriated tungsten filament of the Western Electric tube. However, the D79510 is more economical to operate because its thoriated tungsten filament requires less heating current.

The type and quantity of all contaminating vapors that may enter the vacuum system should also be carefully considered since these vapor will seriously affect the calibration of the gauge. This is a common difficulty in cyclotrons and other particle accelerators because gases such as hydrogen and helium are frequently admitted to the vacuum system for acceleration. When this occurs, it is necessary to choose between an absolute or relative measurement of the system pressure.

Other factors which may influence the selection of a vacuum gauge include the possibility of heated parts in the gauge causing decomposition of some of the gas in the system and (in the case of corrosive vapors), the likelihood of these gases attacking the gauge elements. The gauge itself may even influence the pressure in the system: the Phillips ionization gauge, for example, may act as a tiny vacuum pump and actually improve the vacuum because of the "getter" action of the glow discharge. This effect is very strikingly shown when the Phillips gauge is used on a small, closed, vacuum system at a pressure of about 10^{-4} mm Hg. As the gauge is operated, the pressures becomes lower and lower.

When all factors are considered, one "best" gauge will usually be found to satisfy specific requirements. With intelligent use and recognition of its limitations it can be relied upon to do a very dependable job. END