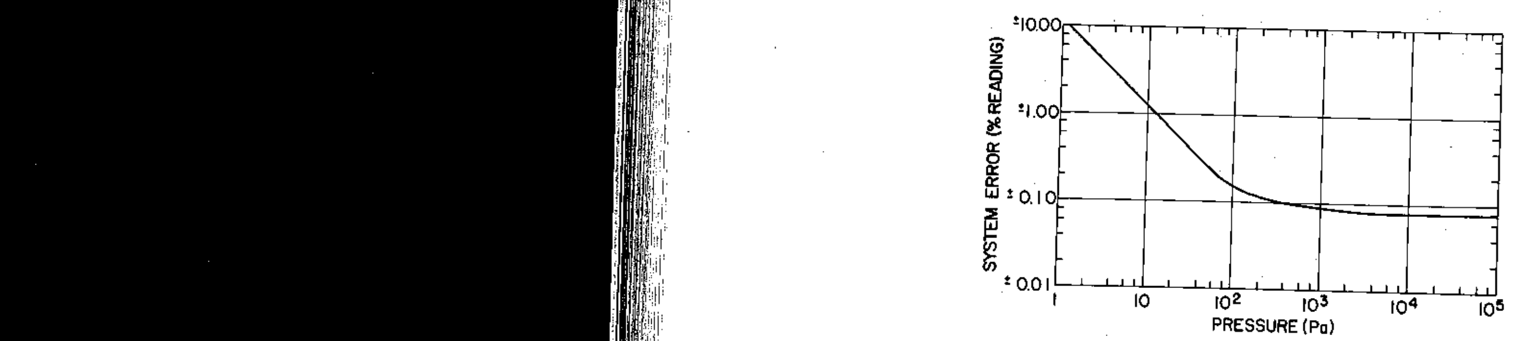

Fig. 5.7 Performance curve for a capacitance manometer with a 10^5-Pa full-scale transducer. Reprinted with permission from *Industrial Research/Development*, January 1976. Copyright 1976, Technical Publishing Co.

heaters that maintain the ambient temperature at about 50°C and avoid some of the problems of ambient temperature change. Many transducers can be operated at temperatures as high as 250°C. The readings, however, must be corrected for thermal transpiration (see Section 2.3.4). Stable operation of a transducer requires that the thermal expansion coefficients of the diaphragm and electrode assemblies be well matched, but in practice designs must make a trade-off between expansion coefficient and corrosion resistance. Without proper temperature regulation a transducer may have zero and span coefficients of 5 to 50 ppm full scale and 0.004 to 0.04% of reading per degree celsius, respectively, at ambient temperature [6]. Proper temperature regulation can result in an order of magnitude improvement in the zero and span coefficients.

Capacitance manometers can be operated over a large dynamic range, a factor of 10^4 to 10^5 for most instruments, but the overall system accuracy deteriorates at small fractions of full head range, as illustrated in Fig. 5.7 for the 1.3×10^5-Pa head. Transducers with a full-scale deflection of 130 Pa have been checked in the 2.5×10^{-2} to 6.5×10^{-4}-Pa pressure range by volumetric division and have been found to be linear to the lowest pressure and in agreement within 0.6% plus 5.3×10^{-5} Pa [7].

5.2 INDIRECT-READING GAUGES

In this section the most familiar indirect-reading gauges are discussed. Indirect gauges calculate pressure by measuring a pressure dependent property of the gas. In the pressure range above 0.1 Pa, energy and momentum transfer techniques can be used for pressure measurement. The spinning rotor gauge [8,9] operates on this principle. It is a research instrument suitable as a secondary standard [10,11]. Thermal conductivity gauges measure the heat transfer between two surfaces at different temperatures. A Pirani or a thermocouple gauge is found on every vacuum system for measuring pressure in the medium vacuum region. Ionization gauges, which measure gas density, have found wide acceptance. Hot cathode gauges are used in the Schulz-Phelps and the Bayard-Alpert geometries; together they span the pressure range 100 Pa to 10^{-9} Pa. Systems operating in the 10^{-3} to 1 Pa range often use the simpler Penning cold cathode gauge. Hot and cold cathode magnetron gauges which are capable of operation at pressures as low as 10^{-11} Pa are found on some ultrahigh vacuum systems but are not used on ordinary high vacuum systems.

5.2.1 Thermal Conductivity Gauges

Thermal conductivity gauges are a class of pressure measuring instruments that operate by measuring in some way the rate of heat transfer between a heated wire and its surroundings. The heat transfer between a heated wire and a nearby wall is pressure dependent in the $0.01 < Kn < 10$ range, where Kn is Knudsen's number. For $d = 10$ mm the pressure range is about 66 to 0.06 Pa, although the sensitivity of heat transfer with pressure is highly non-linear at each end of the scale. The heat transfer regimes in a thermal conductivity gauge are illustrated in Fig. 5.8. At high pressures where $Kn < 0.01$ the heat flow is given by (2.27) and is independent of pressure except for a small convection effect. In the $0.01 < Kn < 10$ region the *free molecular* heat flow is given by (2.28). In this region the heat flow is linearly proportional to the pressure, provided that the accommodation coefficient and the temperature difference between the heated wire and the case remain constant. In the lowest pressure region the heat flow is predominantly accounted for by radiation and conduction through the wire to the supports:

$$H = A\sigma\varepsilon_1(T_2^4 - T_1^4) + \text{end losses} \tag{5.1}$$

To extend the range of a gauge to its lowest possible pressure limit it is necessary to reduce the radiation and end conduction losses. The end losses are predominant only when the length of the wire is short. The radiant heat losses can be minimized by reducing the diameter and the emissivity of the hot wire. The emissivity of a clean tungsten wire is about 0.1, but in practice most are not clean. The upper pressure limit of a thermal conductivity gauge is determined by the saturation pressure of the thermal conductivity. This occurs at a Knudsen number of about 0.01. The two most commonly found gauges have upper pressure limits in the 15 to 150 Pa range, but tubes which read to 10^5 by taking advantage of pressure dependent convection losses [12] are available.

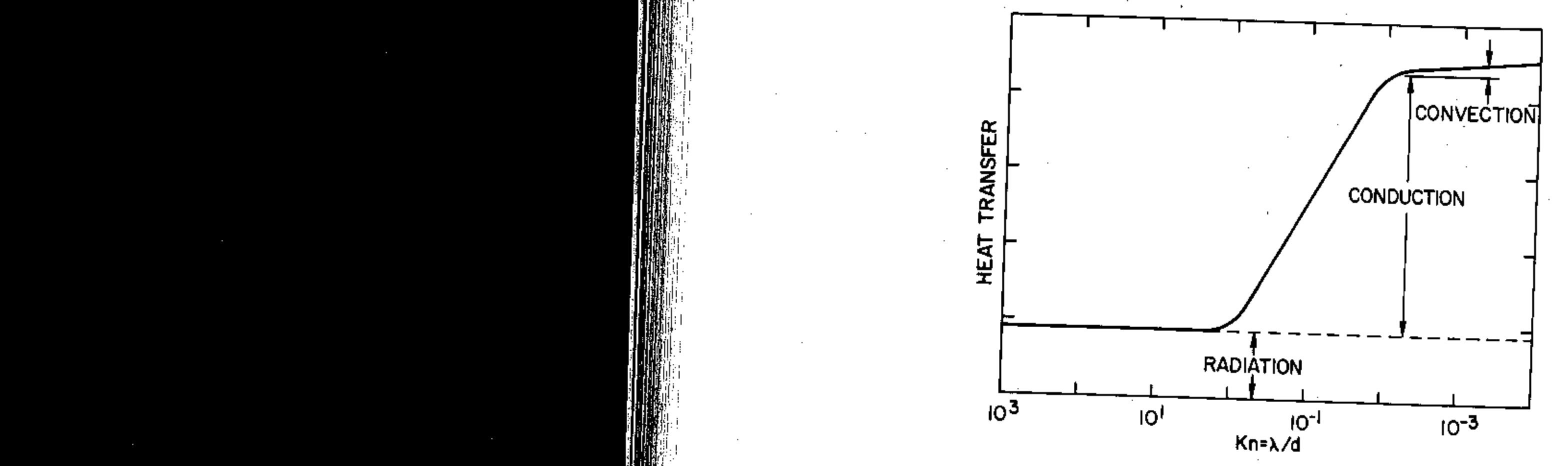

Fig. 5.8 Heat transfer regimes in a thermal conductivity gauge.

The sensitivity of the gauge is determined by tube construction and the gas as well as by the technique for sensing the change in heat flow with pressure. Tungsten is commonly used for the heater wire because it has a large thermal resistance coefficient. (When a semiconductor is the heat-sensitive element, the device is referred to as a thermistor gauge, even though it is strictly speaking a Pirani gauge.) Equation (2.28) describes the sensitivity of heat flow to a change in hot-wire temperature. The ratio of specific heats and thermal velocity in (2.23) depend on the gas species and in combination can produce as much as a fivefold difference in sensitivity between two gases. The accommodation coefficient α for clean materials can be of an order 0.1, but for contaminated surfaces it can be as high as unity. For most cases α is stable but not known. With all other factors well-controlled changes in emissivity and accommodation coefficient are large enough to allow thermal conductivity gauges to be used as only rough indicators of vacuum.

The change in temperature can be detected by monitoring the resistance of the heated wire. When a Wheatstone bridge circuit is used to measure the resistance change, the device is termed a Pirani gauge. Alternatively, the temperature change can be measured directly with a thermocouple, in which case it is called a thermocouple gauge.

Pirani Gauges

The term *Pirani gauge* is given to any type of thermal conductivity gauge in which the heated wire forms one arm of a Wheatstone bridge. A simple form of this circuit is shown in Fig. 5.9. The gauge tube is first activated to a suitably low pressure, say 10^{-4} Pa, and R_1 is adjusted for balance. A pressure increase in the gauge tube will unbalance the bridge because the increased heat loss lowers the resistance of the hot wire. By increasing the voltage, more power is dissipated in the hot wire, which causes it to heat, increase its resistance, and move the bridge toward balance. In this method of gauge operation, called the constant-temperature method and the most sensitive and accurate technique for operating the bridge, each pressure reading is taken at a constant wire temperature. To correct for changes that ambient temperature would have on the zero adjustment, an evacuated and sealed compensating gauge tube is used adjacent to the active gauge tube in another arm of the bridge. Bridges with a compensating tube can be used to 10^{-3} Pa.

122-126

The constant-voltage and constant-current techniques were devised to simplify the operation of the Pirani gauge. In each case the total bridge voltage or current is kept constant. The constant-voltage method is widely used in modern instruments because no additional adjustments need to be made after the bridge is nulled at lower pressures. The out-of-balance current meter is simply calibrated to read the pressure.

The constant-temperature method is the most sensitive and accurate because at constant temperature the radiation and end losses are constant. Because the wire temperature is constant, the sensitivity is not diminished in the high pressure region. This method does not lend itself to easy operation; balancing is required before each measurement. A sudden drop in pressure can also cause overheating of the wire if the bridge is not immediately rebalanced. Direct-reading, constant-temperature bridges that need only a zero adjustment are now commercially available, although at somewhat greater expense than a constant-

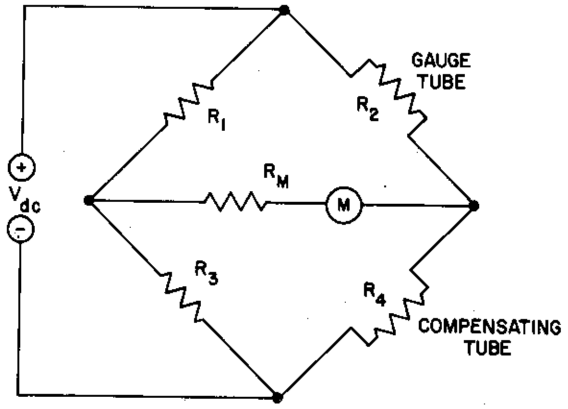

Fig. 5.9 Basic Pirani gauge circuit. Adapted with permission from *Vacuum Technology*, A. Guthrie, p. 163. Copyright 1963, John Wiley & Sons.

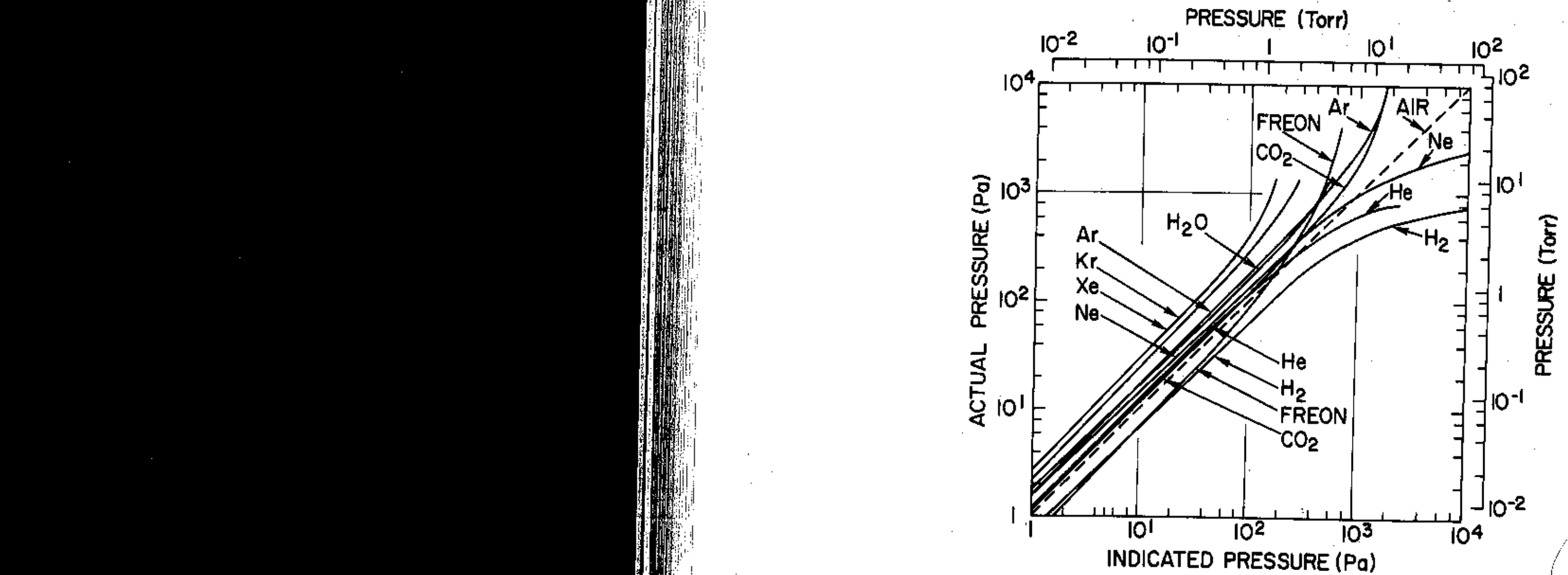

Fig. 5.10 Calibration curves for the Leybold TR201 Pirani gauge tube. Reprinted with permission from Leybold-Heraeus G.m.b.H., Postfach 51 07 60, 5000 Köln, West Germany.

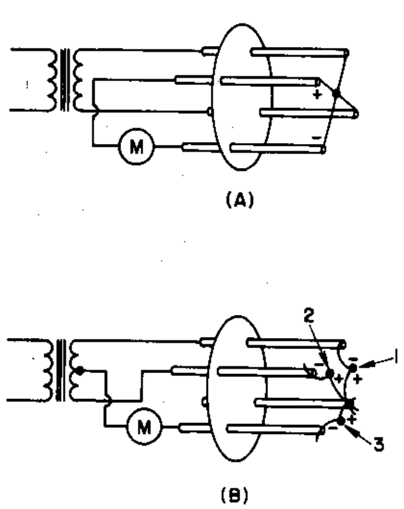

Fig. 5.11 Thermocouple gauge tubes for the 0-100 Pa range. (a) uncompensated gauge tube, (b) compensated gauge tube, (no. 3 is the compensating couple).

voltage or -current bridge. Modern circuitry has eliminated tedious bridge balancing. Because the heat conductivity varies considerably among gases and vapors, the calibration of the gauge is dependent on the nature of the gas. Most instruments are calibrated for air; therefore a chart like the one shown in Fig. 5.10 is needed when the pressure of other gases is measured.

Thermocouple Gauges

The thermocouple gauge measures pressure dependent heat flow. Constant current is delivered to the heated wire and a tiny thermocouple, perhaps iron- or copper-constantan, is carefully spot welded to its midpoint. As the pressure increases, heat flows to the walls and the temperature of the wire decreases. A low resistance dc microammeter is connected to the thermocouple and its scale is calibrated in pressure units.

Figure 5.11 shows the four-wire and three-wire versions of the gauge tubes. The four-wire gauge tube uses a dc meter to read the temperature of the thermocouple, while the power supply is regulated to deliver a

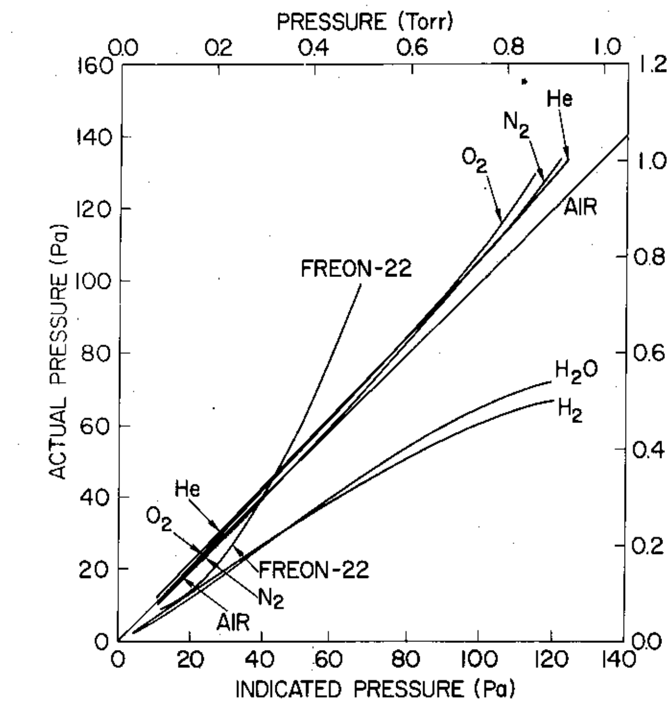

Fig. 5.12 Calibration curves for the Hastings DV-6M thermocouple gauge tube. Reprinted with permission from Hastings Instruments Co., Hampton, VA.

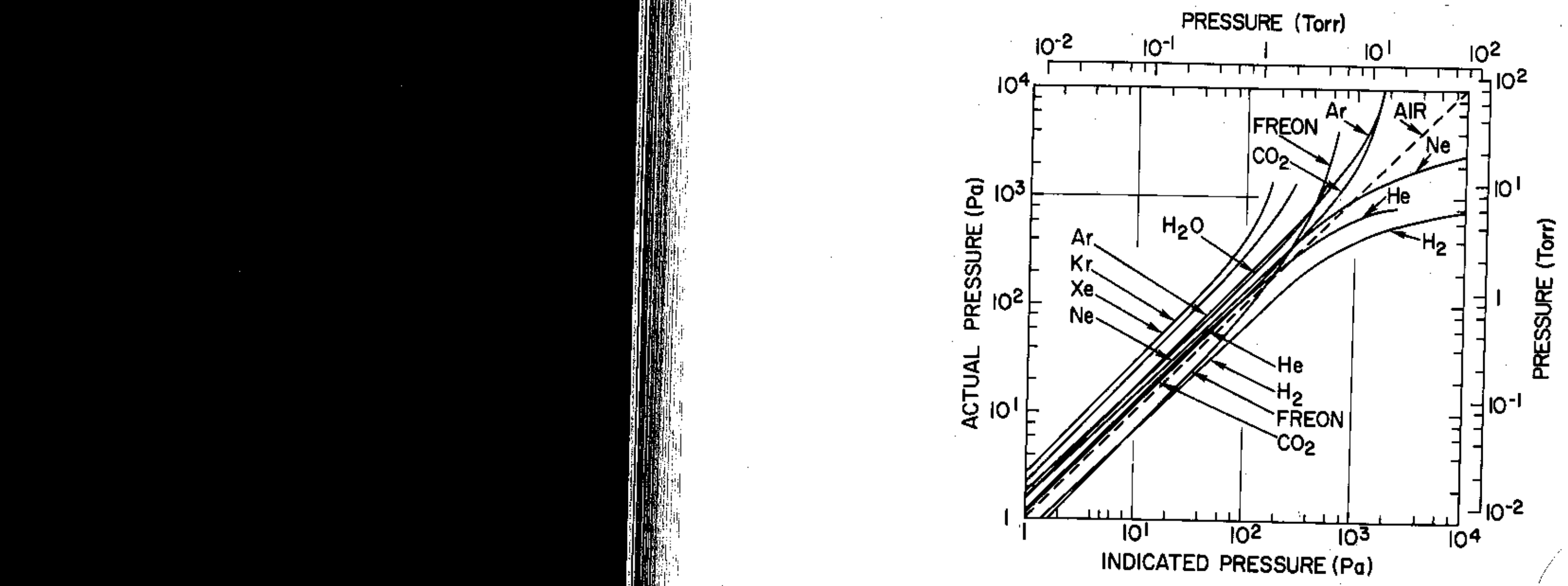

Fig. 5.10 Calibration curves for the Leybold TR201 Pirani gauge tube. Reprinted with permission from Leybold-Heraeus G.m.b.H., Postfach 51 07 60, 5000 Köln, West Germany.

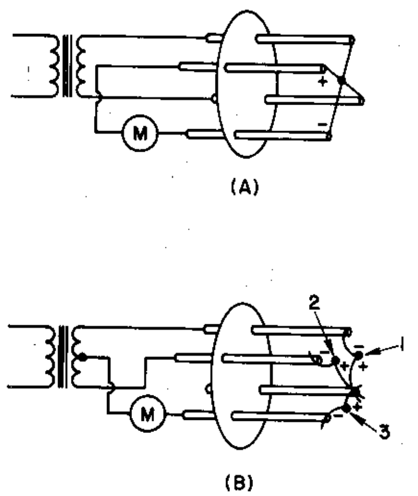

Fig. 5.11 Thermocouple gauge tubes for the 0-100 Pa range. (a) uncompensated gauge tube, (b) compensated gauge tube, (no. 3 is the compensating couple).

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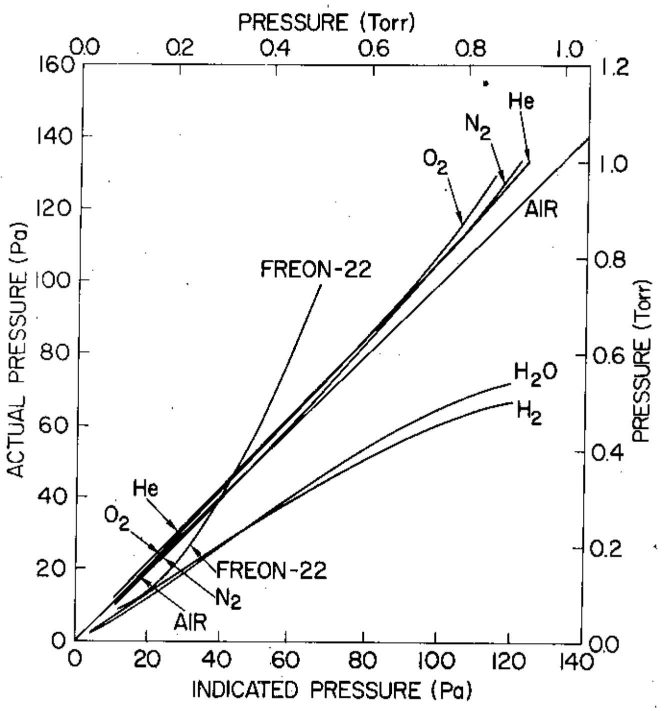

Fig. 5.12 Calibration curves for the Hastings DV-6M thermocouple gauge tube. Reprinted with permission from Hastings Instruments Co., Hampton, VA.

constant current to the wire. The current can be ac or dc. The three-wire gauge circuit reduces the number of leads between the gauge tube and controller and the number of vacuum feedthroughs by using ac to heat the wires and a dc microammeter to read the voltage between one thermocouple wire and the center tap of the transformer, which is a dc connection to the other junction. In both tubes the power delivered is not constant; instead the wire current is constant. Because the resistance of the wire is temperature dependent, the actual power delivered decreases slightly at high pressures. Both gauge forms are rugged and reliable but inaccurate. Calibration curves for one thermocouple gauge are given in Fig. 5.12.

5.2.2 Ionization Gauges

In the high and ultrahigh vacuum region where the particle density is extremely small, it is not possible, except in specialized laboratory situations, to detect the minute forces that result from the direct transfer of momentum or energy between the gas and a solid wall; for example, at a pressure of 10^{-8} Pa the particle density is only $2.4 \times 10^{12}/m^3$. This may be compared with a density of $3 \times 10^{22}/m^3$ at 300 K which is required to raise a column of mercury 1 mm. Even a capacitance manometer cannot detect pressures lower than 10^{-4} Pa. The basic principle used for the measurement of pressures lower than 10^{-3} Pa is the ionization of gas molecules and the collection of the ions and their subsequent amplification by sensitive and stable circuitry.

Each ionization gauge has its own lower pressure limit at which the ionized particle current is equal to a residual or background current. The best of these gauges have lower limits of an order of 10^{-11} to 10^{-12} Pa. In special research environments, where pressures far below 10^{-12} Pa may be encountered, the pressure is considerably below the limit of current ionization gauge technology. At a pressure of 5×10^{-15} Pa and a temperature of 4.2 K there are only 100 (nitrogen) molecules per cubic centimeter. Even with the most efficient ionization schemes available the ion current would be lost in the system noise. In those situations adsorbed gas can be collected on a particular surface for an extremely long time, after which the pressure pulse that results from flash desorption of the surface can be recorded [13].

In routine operation of high vacuum systems in the 10^{-1} to 10^{-7} Pa range the Bayard-Alpert and Schulz-Phelps hot cathode ionization gauges or the Penning cold cathode gauge are used. Each has its own pressure range, advantages, and disadvantages.

Hot Cathode Gauges

The operation of the ion gauge is based on ionization of gas molecules by electron impact and the subsequent collection of these ions by an ion collector. This positive ion current is proportional to pressure, provided that all other parameters, including temperature, are held constant. The number of positive ions formed is actually proportional to the number density, not the pressure; the ion gauge is not a true pressure measuring instrument but rather a particle density gauge. It is proportional to pressure only if the temperature is constant.

The earliest form of ion gauge, the triode gauge, consisted of a filament surrounded by a grid wire helix and a large diameter, solid cylindrical ion collector. This gauge, which is not illustrated here, looks a lot like a triode vacuum tube. Electrons emitted by the heated filament were accelerated toward the grid wire which was held at a positive potential of about 150 V. The external collector was biased about –30 V with respect to the filament and could collect the positive ions generated in the space between the filament and the ion collector. This gauge measured pressures as low as 10^{-6} Pa but would not give a lower reading even if indirect experimental evidence indicated the existence of lower pressures. Further progress was not made until after 1947, when Nottingham [14] suggested that the cause of this effect was an x-ray-generated photocurrent. Nottingham proposed that soft x-rays generated by the electrons striking the grid wire collided with the ion collector cylinder and caused photoelectrons to flow from the collector to the grid. Some photoemis-

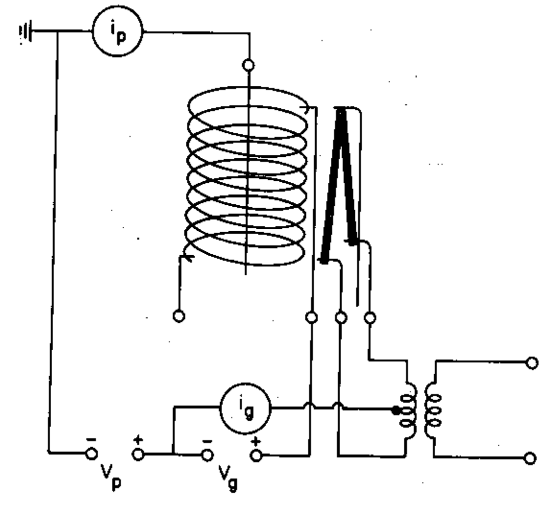

Fig. 5.13 Control circuit for a Bayard-Alpert ionization gauge tube.

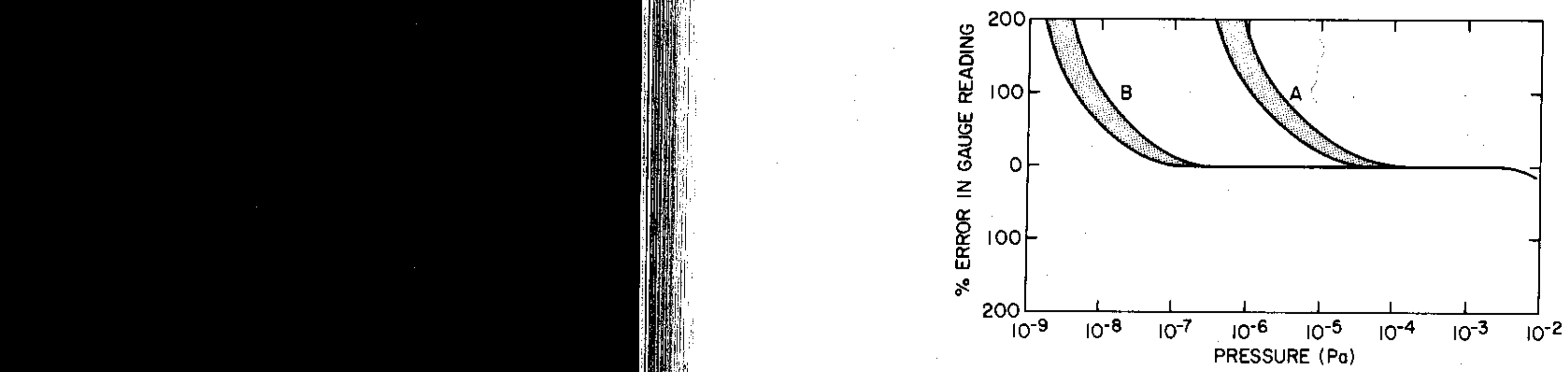

Fig. 5.14 Qualitative x-ray-generated error in ion gauge tube readings: (a) triode gauge tube, (b) efficient Bayard-Alpert tube.

sion is also caused by ultraviolet radiation from the heated filament. As they leave the collector these photo-electrons produce a current in the external circuit which is not distinguishable from the positive ion flow toward the ion collector and mask the measurement of reduced pressures.

In 1950 Bayard and Alpert [15] designed a gauge in which the large area collector was replaced with a fine wire located in the center of the grid (Fig. 5.13). Because of its smaller area of interception of x-rays, this gauge could measure pressures as low as 10^{-8} Pa. Today this gauge is the most popular design for the measurement of high vacuum pressures. It is available in a tubulated glass envelope (tubulated gauge) or mounted on a metal base (nude gauge). A more efficient design increased the sensitivity of the gauge tube by capping the end of the grid to prevent electron escape (Nottingham [16]) and reduced the x-ray limit even more by use of a fine collector wire. This efficient design can measure pressures as low as 2×10^{-9} Pa. Figure 5.14 qualitatively illustrates the x-ray limits of the triode gauge and the efficient Bayard-Alpert gauge.

The proportionality between the plate current and pressure is given by

$$i_p = S' i_e P$$

or

$$P = \frac{1}{S'} \frac{i_p}{i_e} \qquad \blacktriangleright (5.2)$$

where i_p and i_e are the plate and emission currents, respectively, and S' is the sensitivity of the gauge tube. This sensitivity has dimensions of reciprocal pressure, which in SI is Pa^{-1}, and is dependent on the tube geometry, grid and plate voltages, type of control circuitry, and nature of

the gas being measured. For the standard-design Bayard-Alpert tube with external control circuitry, a plate voltage of +150 V, and a grid voltage of 30 V the sensitivity for nitrogen is typically 0.07/Pa. Variations in tube design, voltage, and control circuitry can cause it to range from 0.05 to 0.15/Pa. The tube's sensitivity for other gases varies with the ionization probability. Alpert [17] has suggested that the relative sensitivity (e.g., the ratio of the absolute sensitivity of a gas to that of nitrogen) should be independent of structural and electronic variations and thus be more meaningful to tabulate.

The relationship between the gauge pressure and the unknown pressure is

$$P(x) = \frac{S(N_2)}{S(x)} P(N_2) \qquad (5.3)$$

or because the sensitivity has been normalized to nitrogen, $S(\mathrm{N}_2) = 1$,

$$P(x) = \frac{P(\text{meter reading})}{\text{Relative sensitivity of gas}(x)} \qquad \blacktriangleright (5.4)$$

With the help of (5.3) and Table 5.1 [18] the pressure of gases other than nitrogen can be measured with an ion gauge, even though all ion gauges are calibrated for nitrogen. This is done by dividing the gauge reading by the relative sensitivity of the gas of interest.

Gauge sensitivity is often given in units of microamperes of plate current per unit of pressure per manufacturer's specified emission current; for example, a typical nitrogen sensitivity is (100 μA/mTorr)/10 mA. This is a confusing way of saying the sensitivity is 10/Torr, but it does illustrate an important point; not all gauge controllers have the same calibration value of emission current, and not all gauge tubes have the same sensitivity. Checking the instruction manual can avoid potential embarrassment.

The classical control circuit is designed to stabilize the potentials and emission current while measuring the plate current. The plate current meter is then calibrated in appropriate ranges and units of pressure. The accuracy of the gauge is dependent in part on moderately costly, high quality emission current regulation. One gauge controller [19] avoids the problem of close regulation of the emission current by use of an integrated circuit to take the ratio of plate to emission current. Examination of (5.2) shows that except for a constant scale factor this current ratio is indeed proportional to pressure.

Tungsten and thoriated iridium ($\mathrm{ThO_2}$ on iridium) are two commonly used filament materials. Thoriated iridium filaments are not destroyed when accidentally subjected to high pressures—an impossible feat with fine tungsten wires—but they do poison in the presence of some hydrocarbon vapors. The remarks in Section 8.2 about filament reactivity with

Table 5.1 Approximate Relative Sensitivity of Bayard-Alpert Gauge Tubes to Different Gases[a]

Gas	Relative Sensitivity
H_2	0.42 - 0.53
He	0.18
H_2O	0.9
Ne	0.25
N_2	1.00
CO	1.05 - 1.1
O_2	0.8 - 0.9
Ar	1.2
Hg	3.5
Acetone	5

Source: Adapted with permission from *J. Vac. Sci. Technol.*, **8**, p 661. T. A. Flaim and P. D. Owenby. Copyright 1971, The American Vacuum Society.

[a] The pressure of any gas is found by dividing the gauge reading by the relative sensitivity.

gases in the ionizer of a residual gas analyzer also pertain to the ion gauge.

Ion gauge outgassing is accomplished by direct or electron bombardment heating. Either the grid wire is heated directly by connecting it to a low voltage high current transformer or the grid and plate wire are connected to a high voltage transformer and heated by electron bombardment. It is best to wait until the pressure is on a suitably low scale ($<10^{-4}$ Pa) before outgassing. An unbaked tubulated gauge should be outgassed until the walls have desorbed. (The pressure may be monitored during outgassing on gauges that use resistance-heated grids.) The time for this initial outgassing is variable but 15 to 20 min is typical. After the initial outgassing the tube should be left on. Subsequently only short outgassing times, say 15 s, are periodically needed to clean the electrodes. It is useful to operate the gauge at reduced emission (0.1 mA) because it will pump the least when the emission current is the lowest.

At pressures greater than 10^{-2} Pa space charge reduces the number of electrons capable of producing ionizing collisions and the apparent sensitivity is reduced. In addition, the mean free path becomes small and ions are scattered before reaching the collector. A high pressure gauge has been designed by Schulz and Phelps [20], versions of which are marketed by several manufacturers (Fig. 5.15). The close spacing of the electrodes allows this tube to be used at high pressures. Ion generation however, is reduced because the chance for an ionizing collision is proportional to the path length. A typical sensitivity for a Schulz-Phelps tube is 4×10^{-3} /Pa and a typical pressure range is 10^{-4} to 100 Pa. The ability to read lower pressures is again limited by x-ray-generated electrons. These tubes are excellent for monitoring chamber pressure during sputtering, reactive-ion etching, and other plasma processes. It is necessary to mount the Schulz-Phelps tube in a way that will prevent it from being affected by optical or other electromagnetic energy radiating from the plasma. This is accomplished by mounting it on an elbow and placing a piece of stainless screen over the end of the elbow at its entrance to the process chamber.

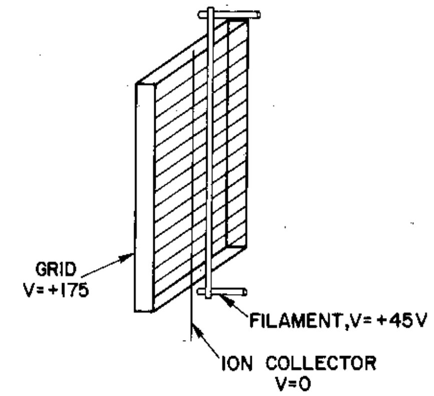

Fig. 5.15 Schulz-Phelps type ion gauge tube for operation at high pressures. Reprinted with permission from Varian Associates, 611 Hansen Way, Palo Alto, CA.

Cold Cathode Gauge

The cold cathode gauge developed by Penning [21] about 50 years ago provides an alternative to the hot cathode gauge which in some respects is superior but in other respects more limited. The gauge tube illustrated in Fig. 5.16 uses a wire anode loop maintained at a potential of 2 to 10 kV and grounded cathode electrodes. Surrounding the tube is a permanent magnet of about 0.1 to 0.2 T.

The arrangement of the electric and magnetic fields causes electrons to travel long distances in spiral paths before finally colliding with the anode. These long trajectories considerably enhance the ionization