# Chapter 7

# Vacuum Gauges

# Contents

## 7.1 Introduction

Once we have reached low pressure we must have some method of measuring that pressure. No one gauge can handle the entire range of vacuum pressures that we can produce, so we use a combination of gauges. Regardless of the care with which a gauge is manufactured and calibrated, the pressure read by the gauge may differ from the actual system pressure due to several reasons.

The placement of the gauge in the system is important. The pressure in the gauge will not usually be the same as the pressure in the vacuum chamber because of the conductance of the connecting pipes. Some gauges act as sources of gas due to excessive outgassing while other gauges actually act as pumps. For UHV work "nude" gauges are used that sit in the chamber without any tubulation.

Most gauges react differently to different gases, so knowledge of the gas composition is needed if we want to know the pressure exactly. As gauges are exposed to a variety of atmospheres in a system, their characteristics may change.

Ideally we would recalibrate the gauges periodically, but this is seldom done due to the expense and difficulty of calibration. Keep in mind when you read about a vacuum pressure that it may well be different than the value quoted.

We can divide gauges into different categories. Some gauges measure the pressure directly (force per unit area) or based on the force it applies. These include the liquid and capacitance manometers. Other gauges operate by measuring a quantity that is pressure sensitive such as thermal conductivity or viscosity. These include the thermocouple gauge and the viscometer gauge. Other gauges ionize the gas and measure the amount of ionization which is proportional to the pressure. These include hot and cold cathode ionization gauges and the Residual Gas Analyzer.

The ranges of pressure in which the different gauges operate is shown in Figure 7.1.

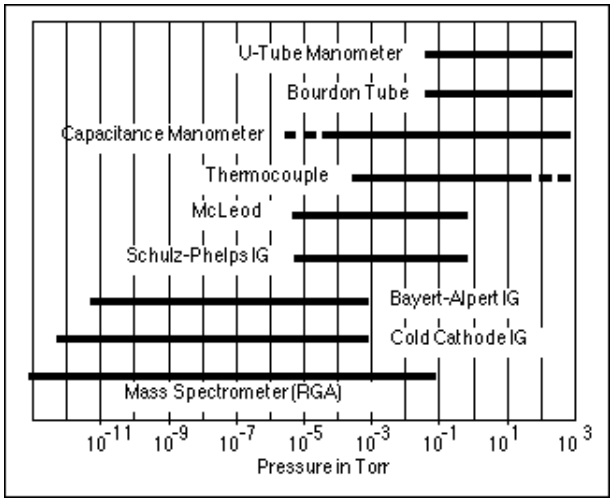


Figure 7.1: Ranges for Common Vacuum Gauges

## 7.2 Mechanical Gauges

**Range** From several atmospheres down to 0.1 Torr.

Mechanical gauges use a pressure difference to produce macroscopic movement of an in-

dicating needle. One of many variations, the Bourdon gauge, is shown in Figure 7.2. Evacuating a tube in the gauge shown allows the tube to coil up and this moves the needle on the dial. Such dials are rugged and read continuously. They can read from above atmospheric down to about 0.1 Torr. These are useful for measuring rough vacuums. The same types of gauges are used on tanks of pressurized gas.

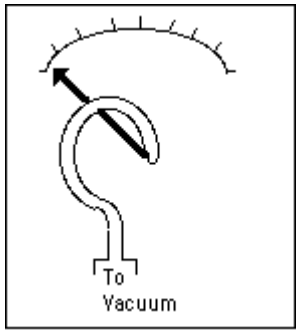


Figure 7.2: Bourdon Gauge

## 7.3 U-Tube Manometers

**Range** Atmospheric to 0.2 Torr

Recall that in Chapter 6 we used this type of gauge to define the unit of Torr. We fill a U-shaped tube with a liquid and connect one side to the vacuum. The second side can be open to air, as shown in Figure 7.3, or evacuated to high vacuum. A difference in the height of the liquid in the two legs of the manometer will arise when the pressures above the two surfaces are different. By measuring the height difference between the two columns of a fluid we can determine the pressure difference. We assume that forces due to surface tension and capillarity are negligible in comparison to forces arising from the pressure difference.

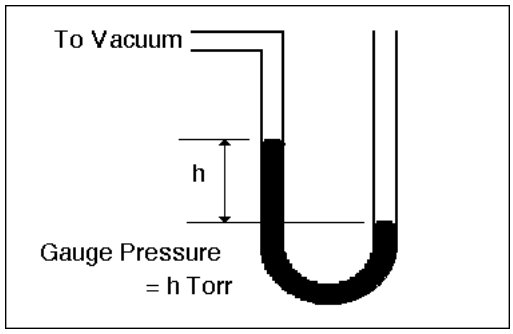


Figure 7.3: Open Tube Manometer

Then we can write the sum of forces on a portion of the fluid in the tube. Forces arise from the pressure on the top and the bottom of the fluid column, and from the weight of the fluid. Assuming that the tube has a constant cross section $A$, the weight of the fluid is $\rho\, g\, h\, A$, where $\rho$ is the density of the fluid, and $h$ is the height difference of the two columns.

$$P \cdot A - P_0 \cdot A = \rho\, g\, h\, A \quad \text{or}$$
$$P = P_0 + \rho\, g\, h \qquad (7.1)$$

The common fluid used is mercury, although other fluids are occasionally used. If we use mercury the height difference, in millimeters, is the pressure in Torr.

One end of the manometer is connected to the vacuum at pressure $P$. In an open tube manometer the second end is open to atmosphere and the height $h$ measures gauge pressure, $P - P_0$. To get absolute pressure we must add atmospheric pressure. In a

closed tube manometer the second end is at 0 Torr (ideally) and we measure absolute pressure.

The limitations of the manometer should be obvious from its operation. A closed tube manometer relies on the pressure above the closed tube being 0 Torr. Mercury has a sizable vapor pressure (1.2 mTorr at 20°C) and so this is a false assumption. We also must be concerned about capillarity, surface tension, and adhesion between the liquid and the tube. Once the mercury gets dirty it tends to stick erratically to the glass. These forces were neglected in computing the sum of forces above.

For a single manometer the lower limit on pressure is about 1 Torr, corresponding to 1 mm of height difference. Increased resolution can be obtained by putting two manometers in series, but the effort to do so exceeds the benefit of better resolution.

The readings are continuous and are insensitive to the composition of the gas. The pressure read is directly based on the definition of pressure.

Mercury or oil vapors can contaminate the system unless we use vapor traps. A manometer is bulky, heavy and breakable. Mercury and glass are fairly sticky, so inaccurate readings are quite possible, especially at low pressure.

## 7.4 McLeod Gauge

**Range** 10 Torr to $10^{-6}$ Torr.

This is a modification of a manometer that can measure absolute pressure of gases quite accurately, and is used to calibrate other gauges.

As shown in Figure 7.4, it traps a fixed volume of gas from the vacuum and then compresses its volume, raising the pressure to a point where it can be easily read. The McLeod gauge measures pressure intermittently rather than continuously.

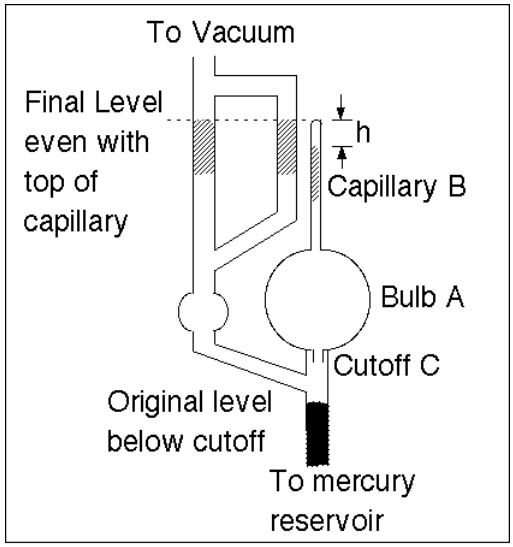


Figure 7.4: McLeod Gauge. The pressure is proportional to $h^2$

A vacuum is established with the mercury level at the original level shown in black. To measure the pressure, the mercury level is raised trapping a volume $V_0$ of gas at the vacuum pressure $P_v$. The volume $V_0$ is the combined volume of the bulb A and the capillary B.

The mercury is then raised until the level in the tube connected to vacuum is equal to the top of the sealed capillary, indicated by the dashed line. The compressed gas trapped

in the capillary is at a higher pressure, and keeps the mercury at a lower level, as shown in gray. The height difference between the two final mercury levels is $h$ and the capillary has a cross-sectional area $A$. Calling the final volume $V_f = hA$, by Boyle's Law the final pressure $P_f$ is

$$P_f = P_0 \left( \frac{V_0}{V_f} \right) \tag{7.2}$$

Assuming that the vacuum is at a low pressure,

$$P_f - P_v \approx P_f = h \text{ Torr} \tag{7.3}$$

and using $V_f = hA$ we can write

$$P_v = \left( \frac{A}{V_0} \right) h^2 \tag{7.4}$$

The gauges are calibrated by the manufacturer so that we can make a direct reading from 10 Torr down to $10^{-6}$ Torr. Gauges that measure to this level of precision are quite large. A smaller, easily portable McLeod gauge will measure down to $10^{-5}$ Torr.

This type of gauge makes a direct reading of pressure and is easily related to the basic definition of pressure. It is unaffected by the composition of the gas except for condensable vapors. If a condensable vapor such as water vapor is present it may condense upon compression and give a false reading of the pressure.

The gauge is not a continuous reading gauge, and it involves considerable operator intervention to make a reading. Vapors from the gauge can contaminate the system and thus the gauge must be carefully trapped. At the higher pressures in the capillary some vapors present in the system may be condensed leading to an incorrect reading. The gauge is bulky and breakable and contains mercury, a hazardous material. This gauge is primarily used for calibration of other gauges.

## 7.5 Capacitance Manometer

**Range** $10^{+4}$ Torr—$10^{-5}$ Torr, each gauge useful over 4 or 5 decades

This uses a metal diaphragm as one plate of a capacitor, as shown in Figure 7.5. If the pressure differs on the two sides of the diaphragm, the diaphragm will move and will change the capacitance. Typically the difference between two capacitors is used, with the diaphragm serving as a plate in both of the capacitors.

Absolute pressure units use a sealed chamber on one side that, through the use of getters, can be maintained at about $10^{-6}$ Torr. Differential manometers use chambers that are both open. A given sensor is only sensitive for a range of about 5 decades, although this may be chosen from the nine decades of operation, $10^{+4}$ Torr to below $10^{-5}$ Torr. At any given time two or three digits are displayed on the readout.

The gauge is easy to use and reads pressure directly. It is insensitive to the type of gas being used. The diaphragm is made of an inert metal and is not subject to rapid corrosion. It is a rugged gauge and can safely be exposed to atmospheric pressure while on. It covers a pressure range more nicely than most other competing gauges, and it can be

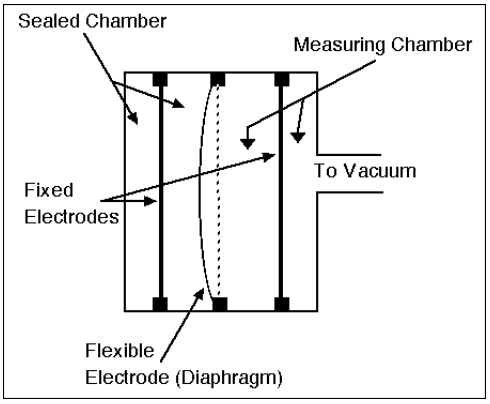


Figure 7.5: Capacitance Manometer or Diaphragm Gauge

made part of a control loop for process control. An example of what I mean by process control is "Maintain the pressure constant while changing the composition of a two gas mixture." This gauge is ideal for a sputtering system.

In an absolute unit the sealed chamber is prone to long-term changes in pressure which will change the calibration of the unit. The diaphragm is exposed to the gases in the system that may lead to long-term corrosion of the unit. The unit is quite temperature dependent, so the gauge head is temperature controlled. The zero of the unit tends to drift and must periodically be reset.

## 7.6 Pirani and Thermocouple Gauges

**Range** 100 Torr—0.1 mTorr.

Both Pirani and thermocouple gauges work on the same principle: a wire carrying an electric current will heat up until it reaches an equilibrium temperature. Joule heat in the amount $i^2R$ is produced by a current passing through a wire of resistance $R$. The wire will increase in temperature until an equal amount of heat is removed from the wire. The heat loss from the wire can occur via convection, conduction, or radiation. At high pressures convection dominates, and the wire stays cool; the convection is not very pressure sensitive. In the pressure range of about 200 Torr to 0.1 mTorr, conduction dominates and the heat transfer is very pressure sensitive. It is most common to use the gauge to measure pressure in this range. At low pressures the heat loss is due to radiation that is pressure insensitive.

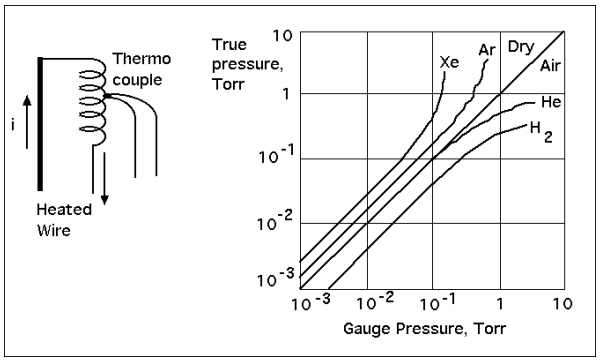


Figure 7.6: Thermocouple Gauge and Correction Factors

As the heat balance changes, the temperature of the wire changes, and hence the resistance of the wire also changes. By measuring either the temperature of the wire or the resistance of the wire we can determine the pressure.

The Pirani gauge measures the resistance (usually at constant current) while the thermocouple gauge, Figure 7.6, measures the

temperature of the wire. Both readings are quite non-linear with pressure, and the gauges are calibrated by the manufacturer. In the constant current mode of operation the useful range is 1 Torr to $10^{-4}$ Torr. By using a Pirani gauge and keeping the temperature(resistance) constant, the higher pressure limit can be raised to about 100 Torr. A few gauges use the convection cooling properties of gases and claim accurate readings at pressures up to atmospheric.

Continuous readings are possible, and vapors are measured as well as gases. No vapors are introduced by the gauge. The gauge can safely be exposed to atmospheric pressure.

The electronics must be calibrated. The gauge characteristics will change over time since the wire may become contaminated by gases in the system. The gauge is sensitive to the type of gas as is shown in the diagram above. This is due to the effect of convection especially at higher pressures.

## 7.7 Viscometer Gauge

**Range** $10^{-1}$ Torr to $10^{-4}$ Torr.

The viscosity of a gas varies with pressure in a well-defined way that can be derived from kinetic theory. Viscometer gauges use viscosity to measure pressure. One approach uses a wire in a tube with very little clearance between the wire and the tube. By using the wire as a torsion pendulum and observing damping of the oscillations, the viscous force can be measured and can be related to pressure. A variation uses a rotating ball in a spherical cavity.

The viscometer gauge is used to calibrate other gauges. It is quite accurate down to very low pressures, however it is quite delicate and cannot withstand bumps and excessive vibration. It is an expensive gauge.

## 7.8 Thermionic (Hot-Cathode) Ionization Gauge

**Range** 0.1 Torr to $10^{-11}$ Torr.

Pressure is proportional to the number of molecules in the system. If we can count the molecules we can compute the pressure. The thermionic ionization gauge uses a heated filament to produce electrons (thermionic emission) which are then accelerated by an electric field and cause ionization of the molecules in the system as seen in Figure 7.7. The positive ions are collected and their current is measured.

The ion current is proportional to the number of ions in the chamber which is proportional to the number of molecules and hence the pressure. Lower currents at lower pressures can be amplified for detection, and so we can change the sensitivity of the gauge.

Two basic types of ionization gauges are found. The Bayert-Alpert gauge is capable of measuring pressures from $10^{-3}$ to $10^{-11}$ Torr. The Schultz-Phelps gauge is designed to measure pressures as high as 1 Torr, but cannot measure below about $10^{-6}$ Torr.

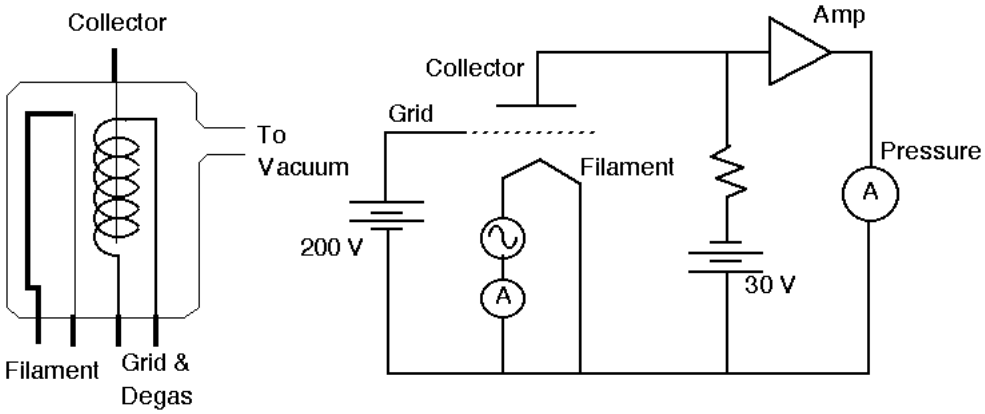


Figure 7.7: Thermionic Vacuum Gauge (Hot Cathode Gauge)

The ionization tube is calibrated against a primary pressure standard (such as a McCleod gauge or viscometer gauge) by the manufacturer and the proper emission current for the filament is given. This is typically 10 mA for most Bayert-Alpert tubes.

The grid in the tube serves a dual purpose. It serves as an accelerating electrode for the electrons and ions. It also can have a current passed through it in order to heat up the grid and the surrounding elements in the tube. This accelerates the outgassing of the tube elements and results in a truer reading of the pressure. However a well outgassed tube will start to pump on gases in the system by adsorbing them of the glass, and so may give a reading below the chamber pressure.

The collector current, $i_p$, is proportional to the ionizing current (filament current), $i_e$, and the pressure is proportional to the collector current. We can put these together to get

$$P = \frac{1}{S}\frac{i_c}{i_e} \tag{7.5}$$

where $S$ is the gauge sensitivity. For the Bayert-Alpert tube the sensitivity is about 9.3 $\text{Torr}^{-1}$. Thus if the filament current is 10 mA and the collector current is 0.03 mA, the pressure is $3.2 \times 10^{-4}$ Torr. Schultz-Phelps tubes operate at higher pressures and thus need less sensitivity. A typical value is 0.53 $\text{Torr}^{-1}$.

Very low pressures can be read. The scale is linear, and easy to read. Since the pressure signal is a current, it is easy to interface this into a control system.

The gauge must not be exposed to high pressures when it is on. If it is exposed to high pressure the filament may oxidize and break. Usually there are safety interlocks which turn off the gauge when the ionization current becomes too high, but even so the filament is stressed.

The gauge is very sensitive to the composition of the gas. Lighter gases (He, $H_2$, $H_2O$) will read low while heavier gases ($N_2$ $CO_2$, Ar) will read high. The determining factor is the ionization energy of the gas species.

Gauges are generally calibrated for air (78% $N_2$, 21% $O_2$, 1% Ar). Some typical sensitivities are given in Table 7.1. The true pressure is given by the gauge reading divided by the gauge sensitivity.

Table 7.1: Gauge Factors for Ionization Tube

| | | | | | |
|---|---|---|---|---|---|
| Air | 1.00 | $O_2$ | 0.85 | $N_2$ | 1.10 |
| He | 0.14 | $CO_2$ | 1.20 | | |

For example if the chamber contains Argon and shows a pressure of $6 \times 10^{-6}$ Torr, the true pressure is $(6/1.2) \times 10^{-6} = 5 \times 10^{-6}$ Torr.

The actual gauges can be purchased in glass tubes or "nude". Nude ionization tubes are mounted on a flange but stick directly into the chamber. This eliminates any factors relating to conductance of tubes, and is important at UHV pressures.

## 7.9 Penning (Cold Cathode) Ionization Gauge

**Range** $10^{-3}$ Torr—$10^{-13}$ Torr

Electrons are emitted from a cold cathode (room temperature) when we apply a large enough voltage. If we accelerate the electrons with the same field as was used to extract them, we can have energetic electrons capable of ionizing the gas in the system. We increase the mean free path of the electrons by applying a magnetic field. This increases the rate of ionization per electron, and we obtain an ion current that is large enough to measure even without amplification.

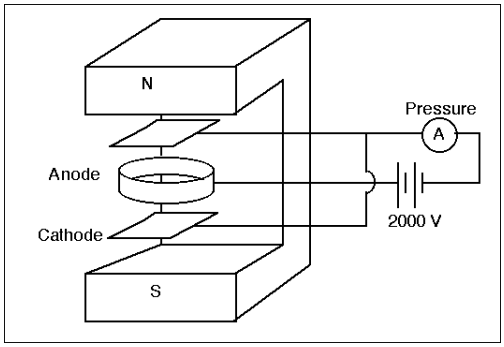


Figure 7.8: Penning Gauge or Cold Cathode Gauge. The current is proportional to the pressure.

Figure 7.8 shows the basics of the Penning gauge. A modification of the Penning gauge, the magnetron, can measure very low pressures down to $10^{-13}$ Torr.

You should have noticed the similarity between the Penning gauge and the ion-pump. A Penning gauge actually does act as a slight pump and indicats pressures that are slightly lower than chamber pressures. For this reason the conductance between the tube and the chamber must be relatively large.

The emission of electrons from the cathode can be hampered by the formation of an insulating layer such as a thick oxide. Periodically therefore the cathode should be cleaned. The gauges I have used can be cleaned simply with a fine emery paper followed by an acetone or alcohol rinse to remove grit.

The gauge is rugged, and can be exposed to atmosphere without harm. The electronics is easier to design than that for other gauges.

A high voltage source is needed. The gauge

is sensitive to the composition of the gas in the same fashion as the thermionic ionization gauge. You must not allow metal particles to fall into the gauge, especially magnetic materials!

## 7.10 Residual Gas Analyzer (RGA)

The RGA is a low-resolution mass spectrometer. It samples the gas in a system and typically produces a scan of relative amplitude of different ionized species versus mass of the species over a range of 1 to 200 amu. The RGA can be used to determine the absolute partial pressures of gases in the system, but is more commonly used to indicate what species are present in the system.

Complicating the analysis is the fact that in ionizing a molecule we may break it up into fragments. Thus water could be broken up into peaks at masses 18, 17, 16 and 1. The RGA manufacturer will provide data on common molecule "fingerprints"—what mass peaks will be seen and in what ratios. If the system contains many types of molecules, analysis becomes quite complicated and may require computer analysis.

An RGA is a powerful analytical tool serving to characterize the vacuum gases. It can be used quantitatively to determine absolute partial pressures of the various gases in the system, but this is a complicated task. Read O'Hanlon for further details.

The RGA is frequently used as a smart leak detector since it identifies the species of gas leaking. Thus a leak in a water line can be distinguished from an air leak, or a leak in a gas line. RGAs start at $10 000.

## 7.11 Other Gauges

**Alphatron:** A radioactive source is used to ionize gases. This is sensitive in the range of 1 Atmosphere to 0.1 mTorr, and the gauge is sensitive to the type of gas in the system.

**Convectron:** A variation of the Thermocouple/Pirani type gauge that uses the cooling properties of convection as well as conduction. This allows measurements of pressure from 760 Torr down to about 1 mTorr.

## 7.12 Costs

Two approaches to gauging are possible. Individual transducers may have individual controllers, or one multifunction controller may have cards inserted to run different transducers. For the second case, Table 7.2 are 1997 prices (Kurt J. Leskar Co. version).

Table 7.2: Costs for a Multifunction Controller

| Item | Pmax (Torr) | Pmin(Torr) | Cost |
|---|---|---|---|
| Multigauge controller to control 2 Ionization gauges, 2 capacitance manometers, and 4 thermocouple gauges: | | | \$3 500 |
| Bayert-Alpert Ionization Tube | $10^{-3}$ | $10^{-10}$ | \$300 |
| Capacitance manometer heads | 2 | $10^{-4}$ | \$800 |
| Thermocouple gauges | 2 | $10^{-3}$ | \$70 |
| Convection gauge | 1000 | $10^{-3}$ | \$120 |
| Cold Cathode Ionization Gauge | $10^{-2}$ | $10^{-3}$ | \$380 |