

Sub Module 2.12

Measurement of vacuum

Pressure below the atmospheric pressure is referred to as **vacuum** pressure. The **gauge pressure** is **negative** when we specify vacuum pressure. Absolute pressure, however, is certainly positive! It is possible to use, U tube manometers, Bourdon gages for the measurement of vacuum as long as it is not high vacuum. In the case of the U tube with mercury as the manometer liquid we can practically go all the way down to -760 mm mercury but there is no way of using it to measure vacuum pressures involving less than a fraction of a mm of mercury (also referred to as Torr – short for Torricelli). A U tube manometer can thus be used for **rough** measurement of vacuum. Figure 91 (a) shows how it is done. A Bourdon gage capable of measuring vacuum pressure will have the zero (zero gage pressure) somewhere in the middle of the dial with the pointer going below zero while measuring vacuum and the pointer going above zero while measuring pressures above the atmosphere. A typical Bourdon gage capable of measuring vacuum is shown in Figure 91 (b). Again a bourdon gage can not be used for measurement of high vacuum.

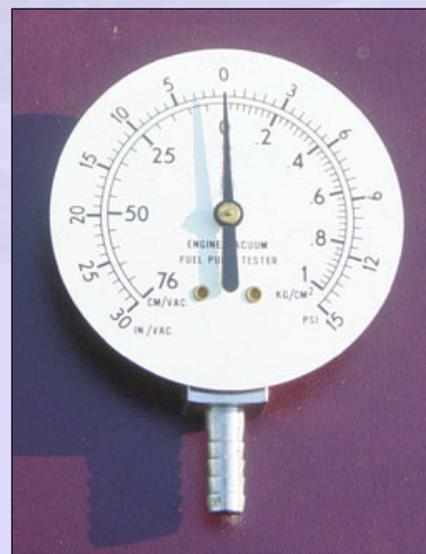
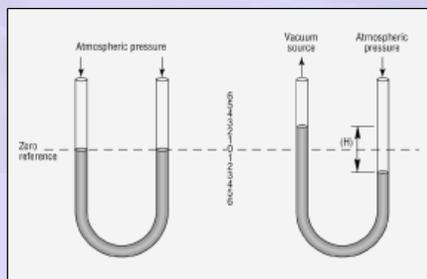


Figure 91 (a) Measurement of vacuum by a U tube manometer

(Visit <http://hydraulicspneumatics.com/200/FPE/Pneumatics/Article/True/6460/Pneumatics>)

(b) Bourdon gage to measure pressures above and below atmospheric pressure

(Visit <http://en.wikipedia.org/wiki/Image:WPGaugeFace.jpg>)

Now we discuss those instruments that are useful for measuring moderate and high vacuum ranging from, say 0.1 mm mercury to 10^{-6} mm mercury. Such low pressures (absolute pressures) are used in many applications and hence there is a need to measure such pressures.

McLeod gage:

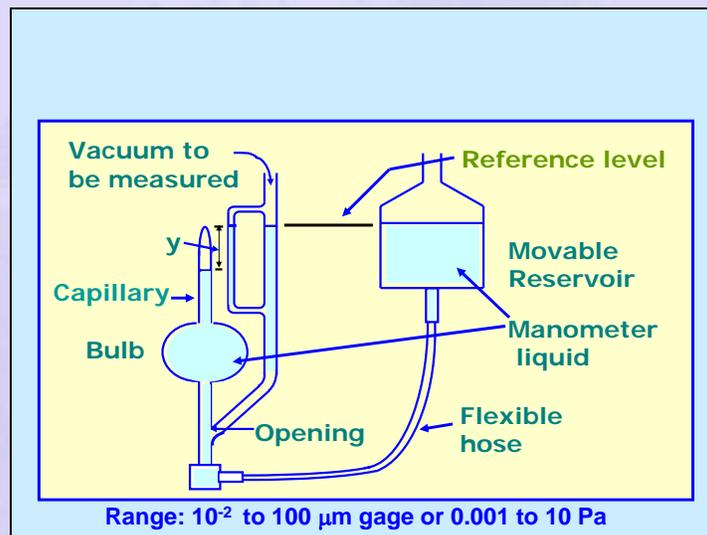


Figure 92 Schematic of a McLeod gage

McLeod gage is basically **manometric method** of measuring a vacuum pressure that is useful between 0.01 and 100 μm of mercury column. This range translates to absolute pressure in the range of 0.001 to 10 Pa. Note that this range will also translate to 10^{-8} to 10^{-4} bar. The principle of operation of the McLeod gage is as described below (refer Figure 92).

A known volume (V) of the gas at the vacuum pressure (p) given by the volume of the capillary, the bulb and the bottom tube up to the opening is trapped by lowering the movable reservoir down to the appropriate extent. It is then slowly raised till the level of the manometer liquid (usually mercury) in the movable reservoir is in line with the reference level marked on the stem of the forked tube. This operation compresses the trapped gas to a pressure

(p_c) equivalent to the head y indicated by the manometer as shown. The corresponding volume of the gas is given by the clear volume of the capillary $V_c = ay$ where a is the area of cross section of the capillary. The gage is exposed to the ambient and hence remains at the ambient temperature during this operation.

Since the entire process is isothermal Boyle's law holds and hence we have

$$pV = p_c V_c = p_c ay \quad (97)$$

Manometer equation gives

$$p_c - p = y \quad (98)$$

Note that all pressures are in mm of mercury in the above and y is also in mm. The area of cross section a is in mm^2 and the volume V is in mm^3 . We eliminate p_c from Equations 97 and 98 to get

$$p = \frac{ay^2}{(V - ay)} \approx \frac{ay^2}{V} \quad (99)$$

The approximation is valid if the initial volume V is much greater than the final volume ay .



Example 33

⊙ A McLeod gage has a volume of 100 ml and a capillary of 0.5 mm diameter. Estimate the pressure indicated by a reading of 25 mm of mercury.

⊙ What will be the error if the approximate formula is made use of?

⊙ Volume of trapped gas $V = 100 \text{ ml} = 100 \times 10^3 = 10^5 \text{ mm}^3$

⊙ Capillary bore is $d = 0.5 \text{ mm}$ and hence the area of cross section of the capillary is

$$a = \frac{\pi d^2}{4} = \frac{\pi \times 0.5^2}{4} = 0.196 \text{ mm}^2$$

⊙ The gage reading is $y = 25 \text{ mm}$

⊙ Using accurate formula given by first part of Equation 99, we have

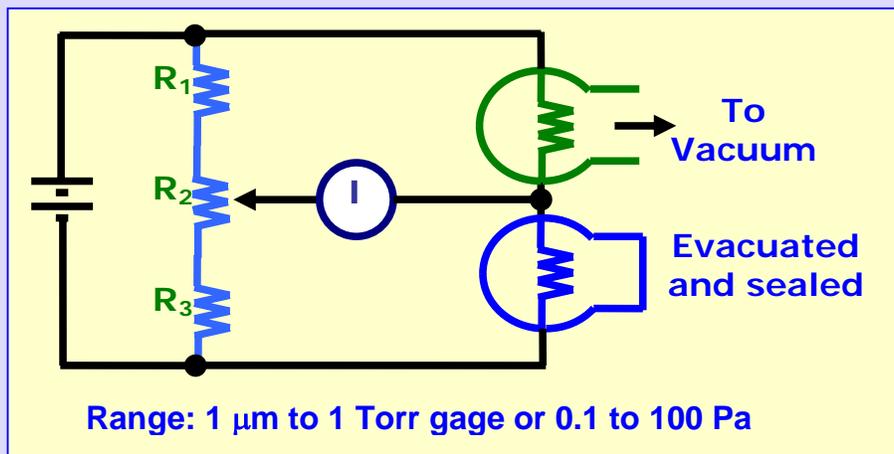
$$p = \frac{ay^2}{(V - ay)} = \frac{0.196 \times 25^2}{(10^5 - 0.196 \times 25)} = 0.00122724 \text{ Torr}$$

⊙ If we use the approximate formula (latter part of Equation 99), we get

$$p \approx \frac{ay^2}{V} = \frac{0.196 \times 25^2}{10^5} = 0.00122719 \text{ Torr}$$

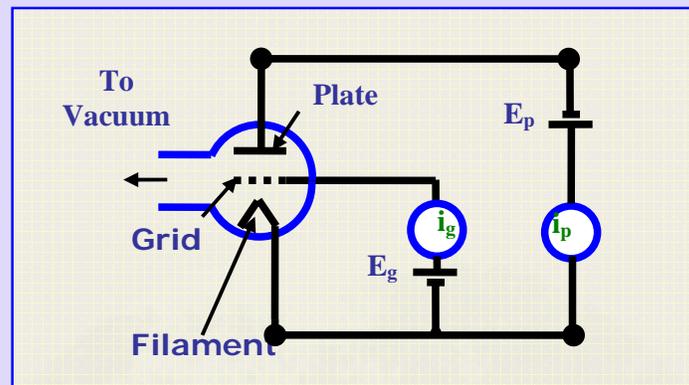
⊙ Thus there is negligible error in the use of the approximate formula.

⊙ The answer may be rounded to 1.227 milli-Torr.

Pirani gage:**Figure 93 Pirani gage with temperature compensation**

Another useful gage for measuring vacuum is the Pirani gage. The temperature of a heated resistance increases with a reduction of the background pressure. The rise in temperature changes its resistance just as we found in the case of RTD. As shown in Figure 93 the Pirani gage consists of two resistances connected in one arm of a bridge. One of the resistors is sealed in after evacuating its container while the other is exposed to the vacuum space whose pressure is to be measured. Ambient conditions will affect both the resistors alike and hence the gage will respond to only the changes in the vacuum pressure that is being measured. The Pirani gage is calibrated such that the imbalance current of the bridge is directly related to the vacuum pressure being measured. The range of this gage is from 1 μm mercury to 1 mm mercury that corresponds to 0.1 – 100 Pa absolute pressure range.

Ionization gage:



Range: 1 to 10^{-5} μm gage or 0.01 to 10^{-6} Pa

Figure 94 Ionization gage circuitry

Very high vacuum pressures (higher the vacuum, lower the absolute pressure) are measured using an ionization gage. Schematic of such a gage is shown in Figure 94. Physical construction of the ion gage is as shown in Figure 95.

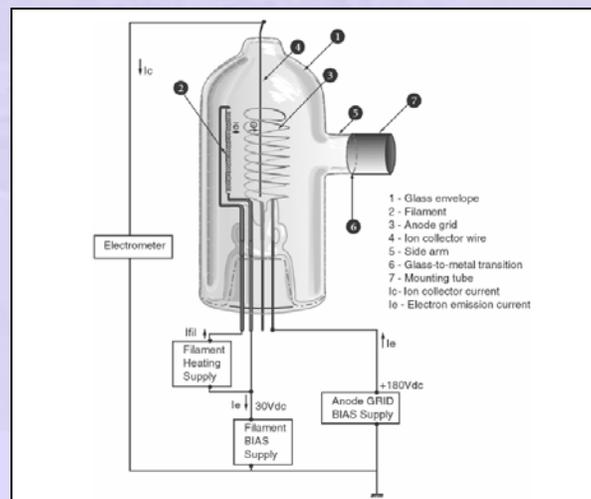


Figure 95 Ion gage construction

(Visit: thinksrs.com/downloads/PDFs/ApplicationNotes/IG1BAGapp.pdf)

The ion gage is similar to a triode valve which was used in radio receivers built with vacuum tubes, before the advent of transistors. The gage consists of a heated cathode that emits electrons. These electrons are accelerated

towards the grid, basically wire mesh, which is maintained at a potential positive with respect to the cathode. The high speed electrons suffer collisions with the molecules of the residual gas in the bulb (that is exposed to the vacuum space) and ionizes these gas molecules. The electrons move towards the grid and manifest in the form of grid current i_g . The positive ions move towards the plate that is maintained at a potential negative with respect to the grid. These ions are neutralized at the plate and consequently we have the plate current i_p . The pressure in the bulb is then given by

$$p = \frac{1}{S} \frac{i_p}{i_g} \quad (100)$$

Here S is a proportionality called the ionization gage sensitivity. S has a typical value of 200 Torr^{-1} or 2.67 kPa^{-1} . The gage cannot be used when the pressure is greater than about 10^{-3} Torr since the filament is likely to burn off. In practice the following is what is done:

The vacuum space is provided with different pressure measuring devices such as:

- a) U tube mercury manometer for indicating that the initial evacuation is complete, usually achieved by a rotary pump or a reciprocating pump.
- b) A Pirani gage to measure the reduced pressure as the higher vacuum is achieved by a diffusion pump or a turbo-molecular pump coupled with a cold trap.
- c) After the pressure has reduced to below 10^{-6} Torr the ion gage is turned on measure the pressure in the high vacuum range.

For more details the reader should look at books dealing with high vacuum engineering.

Alphatron gage:

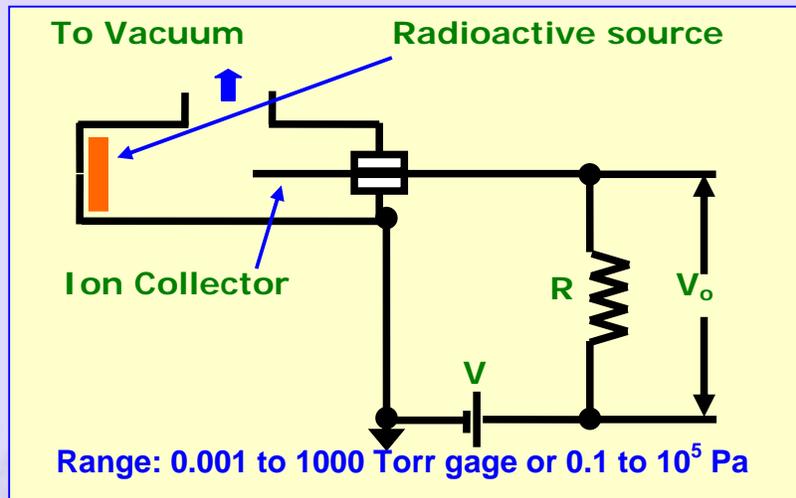


Figure 96 Schematic of an Alphatron gage

In the Alphatron gage ionization of the residual gas is brought about by alpha particles that are emitted by a radioactive material. The gage is similar to a common smoke detector in its operation. Since there is no hot cathode as in the case of ion gage considered earlier, the gage may be exposed to the atmospheric pressure without any fear of losing a filament! The rate of ion production is dependent on the residual pressure in the gage, and this pressure is the same of the vacuum pressure that is being measured. A collector electrode is maintained at a positive potential as shown in Figure 96. The ion current produces a potential drop V_o across the load resistor and this is indicative of the pressure. The output is fairly linear over the entire range from 1 milli Torr to the atmospheric pressure or 0.1 to 10^5 Pa.