Chapter 5: Subatmospheric Total Pressure Gauges

The pressure gauges that will be described in this section are used to monitor the environment in a vacuum vessel so that processes conducted under subatmospheric conditions may be understood and made to repeat. As with other topics in vacuum technology, the subject of pressure gauges can be subdivided several ways. Gauges could be lumped together based upon the pressure range in which they operate, the physical principle behind their operation, or by size, cost or complexity. We have chosen to use the time honored method of grouping gauges to be discussed primarily by the physical basis of operation. In this scheme, gauges are grouped into the following four categories: gauges that measure the physical force exerted on a surface, gauges that measure momentum transfer by gas molecules, gauges that measure heat transfer, and gauges that measure gas density by ionization of gas molecules.

Examples of each of these four categories are:

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Experiments and processes are performed every day in vacuum vessels that have total pressures ranging from $10^{-13}$ Torr to almost atmospheric pressure (760 Torr). This pressure range extends almost 16 decades! No one pressure gauge available can accurately measure the pressure across this enormous range. The gauges that are sensitive enough to be accurate at extremely low gas densities would be swamped if not seriously damaged if operated at pressures above $10^{-3}$ Torr. For each of the vacuum gauges that will be covered, we will make every effort to describe the application that is appropriate for the gauge and also give useful notes on materials compatibility, mechanical durability, and susceptibility of gauges to outside influences.
Force Measurement Pressure Gauges:

**U-Tube Manometer:**

Historically, the liquid level gauge was the first to be used as a means of monitoring pressure changes. Water was the liquid used initially, but its low density required that a gauge capable of measuring atmospheric pressure would be over 30 feet tall. Mercury replaced water as the higher density of mercury (13.6 times more dense than water) allowed for much more compact gauges to be built. The basic principle of operation of simple liquid level gauges is as follows: a "U" shaped glass tube having a vertical section one meter tall is filled approximately half way with liquid mercury. A valve on the "reference" side of the tube is opened to an operating high vacuum pump, the air pressure above the mercury is reduced to $10^{-5}$ Torr or less, then the reference valve is closed. At this point the gauge inlet side of the U-tube may be connected to a vacuum system. If the system is initially at atmospheric pressure, the mercury column height difference, $H$, between the reference and gauge legs of the U-tube should be approximately 760 mm. If the vacuum system connected to the gauge inlet is evacuated, the difference in height between the two legs of the U-tube will reduce.

**Sample Problems:**

5.1 If the height difference between the reference and gauge legs of a mercury filled U-tube manometer connected to a vacuum vessel is 100 mm, what is the pressure measured in the vacuum vessel?
5.2 What are the disadvantages of a mercury filled U-tube manometer?

![U-tube manometer diagram]

Figure 5.2 U-tube manometer.

**McLeod Gauge:**
The pressure range over which liquid level gauges read can be extended if a sample of the gas to be measured is isolated from the vacuum vessel and compressed in a well controlled manner to amplify the force per unit area thus making the pressure easier to measure accurately. A McLeod gauge accomplishes this through the use of a movable mercury reservoir, a bulb of known volume, a set of capillary tubes and a tube allowing for connection to the vacuum vessel (see figure 5.3). Lowering the mercury reservoir will allow gas from the vacuum vessel to fill the bulb of known volume situated directly below the closed capillary. This sample of gas is then isolated from the vacuum vessel by the rising mercury reservoir at the cutoff level. At this same time, the captured gas is compressed into the sealed capillary tube. It can be shown for a calibration constant $k$,

$$P = kh^2$$

Hence the McLeod gauge was technical breakthrough when invented in that it covered 4 decades of pressure range with superior accuracy.
**Bourdon Tube Gauge**

![Diagram of Bourdon Tube Gauge]

**Figure 5.3** McCleod Gauge principle

**Figure 5.4** Bourdon tube pressure gauge.
The Bourdon Tube Pressure Gauge is comprised of a leak tight case with a glass plate in front to allow a view of the pressure indicator dial and pressure scale. The curved metal tube elastically deforms and the end deflection is proportional to the differential pressure across its wall (think of a garden hose trying to straighten out when the water is turned on). This deflection is mechanically transformed into a rotation of the indicator dial by a rack and pinion mechanism. There are several variations of the basic design, some having evacuated cases and reference tubes that protect the mechanism inside the case from the environment of the vacuum system. Small, inexpensive Bourdon tube gauges (2" diameter faces) may be accurately read from atmospheric pressure down to 100 Torr. Larger, more sensitive gauges (8-9" diameter faces) can read down to 10 Torr.

Bourdon tube gauges are simple, inexpensive and relatively rugged. As such, they are often found on high vacuum systems as a means of verifying the gross pressure conditions in a vacuum system.

Mechanical Diaphragm Gauge

![Diagram of Mechanical Diaphragm Gauge](image)

**Figure 5.5** Cross-section of a mechanical diaphragm gauge.

The mechanically actuated diaphragm gauge makes use of a thin flexible metal diaphragm that deflects in proportion to the pressure differential across it. By means of levers and pulleys this deflection is amplified and transformed into rotational motion of a pointer in front of a calibrated dial face. Since the gauge side of the diaphragm is exposed to the environment of the vacuum system, care must be taken to control exposure of the gauge to oils, water, or reactive gases.
Capacitance diaphragm gauges, or capacitance manometers, are another variety of pressure gauge that rely upon the pressure differential across a flexible diaphragm as a means of pressure measurement. In this gauge, the flexible diaphragm is made the variable element in a three-terminal capacitance potentiometer; for a given input voltage, the change in capacitance as a function of diaphragm deflection is measured, and translated into pressure units. The absence of mechanisms with backlash and counter forces means superior accuracy, repeatability over a mechanical diaphragm gauge. Capacitance manometer heads are available in a series of sensitivities; the less sensitive models being more rugged. Some of the most sensitive units can measure pressures as low as $10^{-5}$ Torr. These gauges measure pressure as an aggregate kinetic manifestation of the molecules and hence are not gas-species sensitive.

Sample Problem:
5.3 A capacitance manometer is used to measure the pressure in a vacuum vessel during a sputter deposition operation. If the process gas is changed from argon to xenon what will be the effect on the pressure reading made using the capacitance manometer?
Capacitance manometers can measure pressure very accurately in the pressure range for which the head was designed. Since the displacement of the diaphragm is very small in sensitive capacitance manometer heads, the pressure readings may be thrown off by temperature changes in the environment around the gauge head. Situations to avoid include placing the manometer head next to an operating hot cathode ion gauge or a liquid nitrogen cold trap. To decrease the effects of variable room temperature on the gauge readings, some manufacturers have included heating elements in the gauge that serve to maintain a constant operating temperature.

**Thermal Conductivity Gauges**

**Thermocouple Gauge:**
The most basic of the pressure gauges that measure the change in thermal conductivity of a gas to infer pressure is the thermocouple gauge. A constant electrical current is supplied to the filament inside the gauge to which a thermocouple is spot welded. As pressure is reduced during evacuation, fewer gas molecules impinge upon the heated filament per unit time, and the filament therefore operates at higher temperatures. Filament temperature is monitored using the thermocouple, and is transformed into pressure units at the gauge read-out dial. Since some molecules are better at acquiring thermal energy than others, these gauges are gas species sensitive.
Figure 5.8 Cutaway view of a thermocouple gauge and a schematic of the gauge and control circuitry.

The operating range of most thermocouple gauges is between atmospheric pressure and $10^{-3}$ Torr. Thermocouple gauges are very widely used in the vacuum industry due to their low cost, ease of installation, use, ruggedness, and small size. Common applications for this type of pressure gauge include measurement of the foreline pressure of a high vacuum pump. The major disadvantage of the gauge is its inherent slow response to pressure change. The pressure range of operation of simple TC gauges is from about 1 Torr to $10^{-3}$ Torr. As rugged and reliable as these gauges are, the quality of the pressure measurement will be seriously degraded if any foreign fluid, such as pump oil, is allowed into the gauge body where it may become pyrolyzed on the hot filament. Gauges are often mounted vertically with the gauge inlet pointing downwards for this reason.

Sample Problem:

5.5 A thermocouple gauge is used to measure the pressure in a vacuum vessel during a sputter deposition operation. If the process gas is changed from argon to xenon what will be the effect on the pressure reading made using the thermocouple gauge?

**Pirani Gauge:**

In the Pirani gauge, the reference filament (or compensator) is enclosed in a leak-tight glass envelope evacuated to a pressure of less than 1 Torr. In a similar glass envelope which is open at the gauge inlet end is housed the gauge filament. As gas density exposed to the gauge filament changes, the gauge filament, which is heated using a constant electrical current flow, experiences a change in electrical resistivity and this is measured in the Wheatstone bridge circuit and displayed in pressure units on the readout dial. As with other gauges that measure the thermal conductivity of gases, the Pirani
gauge does not read pressure changes instantaneously. Some time is required for the heated filament to respond to changes in its environment.

![Diagram of Pirani gauge and control circuit](image)

**Figure 5.9** Pirani gauge drawing (above) and control circuit (below).

**Convectron Gauge:**
A useful (and patented) modification of the thermal conductivity gauge allows for measurement of convection currents at higher pressures, increasing the range of this gauge to atmospheric pressure. Convectron gauges typically include a gold plated tungsten sensing wire surrounded by a cylinder wound with kovar wire. This cylindrical temperature compensator helps to reduce the effect changes in ambient temperature has on the gauge readings. The large volume inside the compensator provides space for convection currents to develop at higher gas densities (1 Torr to atmospheric pressure), improving the resolution of the gauge at the high pressure end of its range of operation. Because this gauge uses convection currents to infer gas pressure,
orientation of the gauge is critical. The body of a convectron gauge should always be oriented horizontally (as shown below, in figure 5.8).

**Figure 5.10** Cutaway view of a convectron gauge.

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**Gas Ionization Gauges**

Gas density (and pressure) may be deduced from the ability of the gas to undergo ionization caused by electron impact with the gas molecules. The ionization gauges that will be discussed here are both designed for use in the medium to ultra-high vacuum range ($10^{-3}$ Torr to $10^{-10}$ Torr).

**Hot Cathode Ionization gauge:**

Also called the Bayard-Alpert gauge, the hot cathode ion gauge is a simple and reliable gauge that is widely used in vacuum processing industries. The triode (three electrode) design is easily understood if we examine each component independently, become familiar with its function, then see how they work together. The filament is usually a thin ribbon of tungsten which is in the shape of a coil or inverted "vee". Low voltage electric current from the gauge power supply is passed through the filament which heats up much like the filament in an incandescent light bulb (operating temperature of a gauge filament is almost $1800^\circ$C). In addition to heat and light, the filament emits enormous quantities of electrons which can collide with gas atoms and in that collision, eject an electron from the gas atom making it an ion. Electrons from the filament are attracted to a helical "grid" or electron collector which is maintained at a positive voltage of approximately $150$V with respect to the filament. The additional energy input into the electrons by the electron collector bias is to insure efficient ionization of gases in the gauge. Finally, the gas ions created are collected on an ion collector operated at zero volts with respect to the electron collector.
The operating range of hot cathode ionization gauges is from $10^{-3}$ Torr to $10^{-9}$ Torr. These gauges are small in size, relatively easy to operate and accurate to +/- 10% of
the reading in the pressure range in which they are designed to operate. Volatile contaminants (hydrocarbon oil, process gases, etc.) may impair proper operation of the ion gauge. If this occurs, one may restore the gauge by performing a "degassing" operation in which current is supplied to the gauge electrodes to drive off the unwanted contamination. Most commercial ion gauge control units provide for "degassing" operation and also prevent operation of the gauge at a pressure at which the gauge would be damaged. Response time of ion gauges is quite fast, and this attribute is used for process control and vacuum system Two common configurations of hot cathode ionization gauge are shown in figure 5.10. The nude gauge is less frequently used, as it protrudes into the vacuum system and may interfere with the process being conducted.

Figure 5.12 Hot cathode ionization gauges: glass envelope (left) and nude (right)

**Cold Cathode Ionization Gauge**

Operating in the medium to high vacuum range \((10^{-3} \text{ Torr to } 10^{-8} \text{ Torr})\), the cold cathode ionization gauge uses electrons emitted from electrodes maintained at electrical potentials of 10,000 volts to ionize gas in the gauge body. Ejected electrons are forced to orbit in a helical path by a strong magnetic field provided by the external permanent magnet. This increases the probability that gas molecules will be struck by orbiting electrons and become ionized and subsequently "counted".

Figure 5.13 Cold cathode ionization gauge.
The accuracy of cold cathode gauges is severely impaired by a dirty environment, as the number of electrons emitted from the cathodes is strongly dependent upon the cathode surface condition. Some models of cold cathode gauge may be disassembled for cleaning, but great care must be used during reassembly, as misalignment of the electrodes or magnet can cause the gauge to give inaccurate pressure readings.

**Momentum Transfer Pressure Gauges**

**Spinning Rotor Gauge (SRG):**
In the spinning rotor gauge, the drag caused by gas molecules hitting the surface of a magnetically levitated spinning steel sphere is used to infer gas pressure. The control unit for the SRG brings the levitated ball to a rotational velocity of approximately 400 RPM using a set of electromagnetic coils. Once the rotational speed is constant (as measured by a set of detector coils), the accelerating coils are turned off, and the steel sphere is allowed to "coast". The rate at which the rotation of the ball decreases is a function of the gas density and composition.

![Cutaway view of a spinning rotor gauge](image)

The pressure range of the SRG is from $10^{-2}$ Torr to $10^{-7}$ Torr. As the gauge is delicate, expensive, and requires several minutes for each pressure reading, its primary use is found in calibration of other gauges, and in precise vacuum measurements.

**For Further Reading:**


Answers to Chapter 5 Sample Problems

5.1  100 Torr.

5.2  There are some distinct disadvantages to the U-tube manometer that explains why they are not widely used. The pressure range of U-tubes is limited; carefully constructed models can only read pressure from atmospheric down to about 1 Torr. Mercury has the obvious health and safety concerns, but also may cause problems if the process being measured reacts chemically with mercury vapor. Other concerns include the substantial equilibrium vapor pressure of mercury at room temperature and the fragile nature of the glass tubulation.

Laboratory Exercise 5.1:

Pressure Gauge Identification and Inspection

Identify the vacuum gauge you have selected for this exercise:

A. Gauge Identification: What is the principle of operation? Who is the manufacturer? What is the gauge model number? Locate the manufacturer's literature from the bookcase and find the appropriate reference information. What is the advertised pressure range? Is the gauge gas specific? Are there any calibration curves available to aid in understanding the performance of the gauge as a function of pressure or gas specie?

B. Physical Inspection of Pressure Gauge: Inspect the gauge for signs of wear or misuse. What type of vacuum connection is provided? Is this connection appropriate for the application the gauge was designed for? Locate the gauge control unit and/or power supply (if applicable). Check electrical cables of the power supply for cracks in insulation.

Laboratory Exercise 5.2:

Operation of Spinning Rotor Gauge
Before beginning this procedure, read the operating manual carefully.

Procedure:
Assemble an operating vacuum system capable of attaining a pressure of $10^{-5}$ Torr or lower using an ion pump as the high vacuum pump. Operate the SRG following the instructions in the manual.

Discussion:
- What assumptions did you make in the gauge calibration?
- How did the gauge perform compared to the hot cathode ion gauge?
- Can you explain any inconsistencies you observed?