BASIC VACUUM PRINCIPLES AND MEASUREMENT

By Woodrow Farrow - Reprinted with permission from Specialty Gas Report

Vacuum: a space that is relatively empty of matter, especially when that void has been created through artificial means. The earth's atmosphere exerts a pressure upon us (known as the atmospheric pressure), which can be measured in a number of ways. At sea level, the standard pressure is described in different units as:

101,300 Pascals (Pa)
1,103 millibar
760 Torr
760 mm of Hg
29.92" of Hg
14.7 psia

The foregoing is the "dictionary definition" of vacuum. Not bad. It's simple, and to the point . . . and pretty appropriate even for high-tech applications. How to get there (achieve a space that is relatively empty of matter) is not so simple. As a matter of fact, getting there is one of the most critical operations in the production of specialty and medical gases. What kind of equipment is used and when? What is the best practice as far as technique and process are concerned?

Without knowing the answers to these questions, it is impossible to create pure or mixed gases with any guarantee that the gas purity of the gas you put into the cylinder will remain that way for any length of time. Without that guarantee, it's impossible to be in the specialty or medical gas business.

The term "vacuum" is used to describe the zone of pressure below atmospheric pressure.

This article revisits the basics of vacuum technology; i.e., what is a vacuum and how is it measured? Once the basics are understood, the more sophisticated aspects of the technology can be better understood.

How is a Vacuum Created?

The creation of a vacuum typically requires a chamber, piping and a pump (or pumps). The simplified sketches nearby can help you understand how the pump reduces the number of molecules inside a vacuum chamber.

As the number of molecules in the chamber (Figure 1) is decreased, it becomes more difficult for the molecules to reach the vacuum pump and therefore to be removed from the chamber.

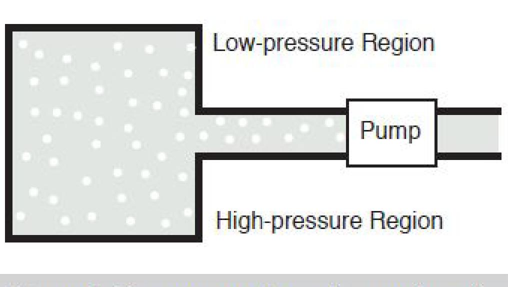

Figure 1. *The pump reduces the number of molecules inside the vacuum chamber.*

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Generally, four regions of vacuum are described: rough, medium, high and ultra¬high vacuum (Figure 2). The boundary of each region cannot be rigidly defined, but these terms are useful when discussing the actions of molecules inside the vacuum system.

Ultrahigh Vacuum: Below 1 x 106 millibar (1 x 109 millitorr)
High Vacuum: 1 x 105 millibar (1 x 106 Torr) to 1 x 10¬8 millibar (1 x 109 Torr)
Medium Vacuum: 0.1 millibar (75 millitorr) to 1 x 105 millibar (1 x 106 Torr)
Rough Vacuum: Atmospheric pressure to 0.1 millibar (75 millitorr)

Terms and Definitions (see also Table 1)

1.2 Volume: The most common units are liters and cubic feet; to convert from cubic feet to liters multiply by 28.3.

1.3 Temperature: I don't think I need to do much explanation, but it is important to remember that a rise in temperature in the chamber or piping can result in a pressure rise.

1.4 Outgassing: Is the gas load created by the evolution of gases from O-Rings, chamber surfaces or piping surfaces. The evolution of gases creates a gas load that must be removed by the pump from the vacuum systems, in order to reach the desired vacuum level.

1.5 Conductance: Is the amount of gas that can travel through a particular device per unit of time. The conductance through any device varies with pressure. I have always tried to explain conductance by using the analogy of water being conducted through a hose. Both water through a hose and gases through a vacuum piping system are fluids through restrictive devices.

Table 1. Terms and Definitions

1.1 **Pressure** – the measurement of the number of molecules hitting a given surface
1.1.1 **Millibar** – the international standard (Pascals are also permitted)
1.1.2 **MilliTORR** – the more commonly used unit of measure in the USA
1.1.3 **Conversion Chart**

101,300 Pascals	= 1,103 millibar	= 760 TORR	= 760 mmHg
100,000 Pascals	= 1,100 millibar	= 750 TORR	= 750 mmHg
1,000 Pascals	= 10 millibar	= 7.5 TORR	
100 Pascals	= 1 millibar	= 750 milliTORR	
10 Pascals	= 0.1 millibar	= 75 milliTORR	
1 Pascals	= 1 x 10-2 millibar	= 7.5 milliTORR	
0.1 Pascals	= 1 x 10-3 millibar	= 0.75 milliTORR	

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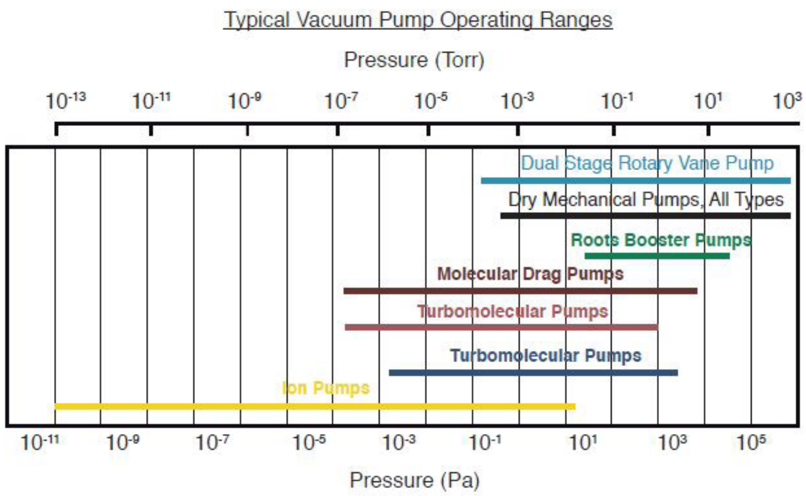

Figure 2. *Comparison Pump Range Chart*

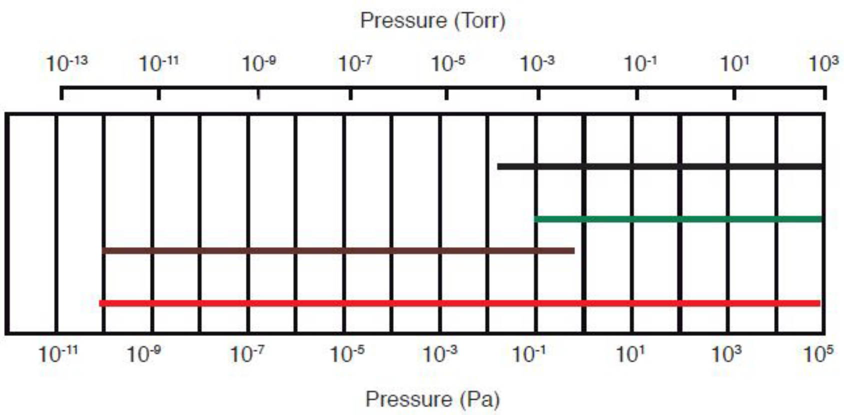

Figure 3. *Chart indicates the different types of gauges used to measure vacuum and the ranges in which they operate.*

In vacuum piping design, it's best to use the straightest, shortest and largest diameter possible piping, so gas molecules can easily move to the inlet of the vacuum pump and be removed from the system. As the pressure decreases in the vacuum chamber or piping, gas flow is restricted t a much larger degree (not quite exponentially) by small-diameter piping, bends, elbows and the length of the piping. Consider which will get you wetter.

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Measurement Gauge Considerations and Selection

When measuring a vacuum, you need to determine what type of gauge and in what range to use: Thermocouple-Pirani, Penning or Capacitance manometer — and their construction, operation and characteristics.

There is no universal vacuum gauge — one that will respond accurately throughout the range from atmospheric pressure to 1 x 1011 Pa (1 x 1013 Torr). Materials of construction, method of measurement (both direct and indirect), and electronics all contribute to the limitation of each type of gauge.

All electronic gauges are subject to shifts in reading due to the "drift" inherent in electronic controllers. Both electronic gain (span) and the zero setpoint are adjustable, so care must be taken whenever gauge "heads" or electronic controllers are replaced, to verify both the span and zero of the new combination.

Direct gauges measure the pressure independently of the composition of the gas being measured. Indirect gauges are dependent on the composition of the gas being measured, such as the thermal conductivity electrical conductivity, or ionization capability.

Manufacturers offer combination gauges to mask the limitations of some of the technologies. For instance, a combination Pirani-Penning gauge can operate from atmosphere to 1 x 1011 Pa (1 x 1013 Torr). (Figure 3)

Pirani and Thermocouple Gauges

Thermocouple and Pirani gauges are classified as indirect gauges that typically operate from atmosphere to 1 x 102 Pa (1 x 103 Torr). Thermocouple and Pirani gauges differ a small amount depending on the manufacturer, but fundamentally they function in the same manner.

Pirani gauges have a slightly wider range and provide better resolution than thermocouple gauges. The basic theory of operation is the measurement of heat lost from a wire, at pressure below 1 x 102 Pa (1 x 104 Torr) there is so little gas present that the gauge cannot provide an accurate reading.

One of the thin wire filaments of a standard Wheatstone bridge circuit is placed inside the vacuum system and the other side in a reference gas. The gauge electronics measure the temperature loss of the wire inside the vacuum system and compares it to that of the reference wire, and then it displays the vacuum reading.

When large amounts of gas are present near the wire, a large amount of heat is removed from the wire, and a large amount of current is consequently required to maintain the temperature of the wire. The current required to maintain the temperature is directly proportional to the heat being conducted away by the gas present near the wire inside the vacuum system. As the amount of gas near the wire decreases, less heat is removed from the wire, and the electronics measure and report the lower amount of current required to maintain the temperature of the wire.

The composition of the gas significantly affects the reading (accuracy) of these gauges. Typically, the gauges are calibrated for air (78% nitrogen), and a factor must be applied to the gauge's reading for argon, helium or hydrogen. Argon absorbs heat much faster than nitrogen, while nitrogen is much faster than helium or hydrogen. As the pressure decreases, the offset due to the gas composition decreases as well.

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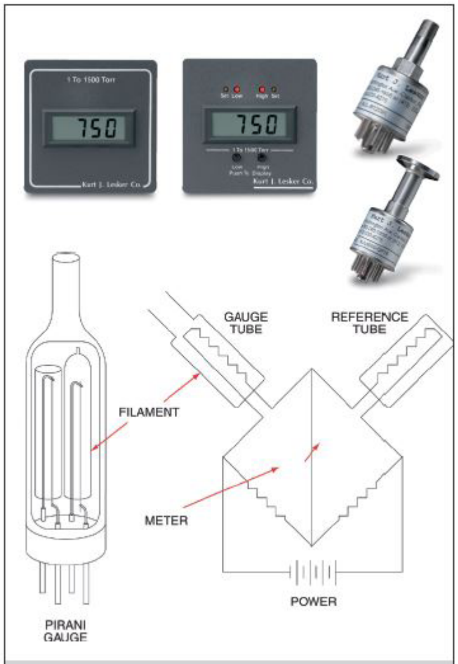

Figure 4. *Wheatstone Bridge and Pirani gauges*

Application of Pirani and Thermocouples

Thermocouple and Pirani gauges are inexpensive and are used primarily for measuring the vacuum in non¬corrosive and nonreactive chambers. Their use in semiconductor systems is limited because hot wires and reactive gases are generally not compatible.

Penning and Ion Gauges Operation

Penning (cold cathode) and ion (hot cathode) gauges are classified as indirect gauges that typically operate from one Pa (1 x 102 Torr) to 1 x 1010 Pa (1 x 1012 Torr). Penning and Ion gauges differ only a small amount, depending on the manufacturer, but fundamentally they function in the same manner.

Penning and ion gauges operate by ionizing gas within a magnetically confined cathode discharge. The combination of a strong magnetic field and the high voltage applied to the electrodes creates a directed plasma discharge of electrons. Ions are formed by the electron bombardment of the gases inside the confined cathode. The ions are accelerated by the magnetic field towards the charged cathode. The impact of the ions with the cathode is measured and reported by the gauge's electronics.

Penning and Ion gauges are significantly affected by the gas composition in the vacuum system and cannot be used with reactive gases. Some ion gauges are constructed from glass, and once the gauge's glow discharge starts, the heat can cause the gauge to become very brittle (and fragile). The glow discharge that is required for the gauge to operate is also the reason that these gauges cannot operate at pressures above one Pal (1 x 102 Torr).

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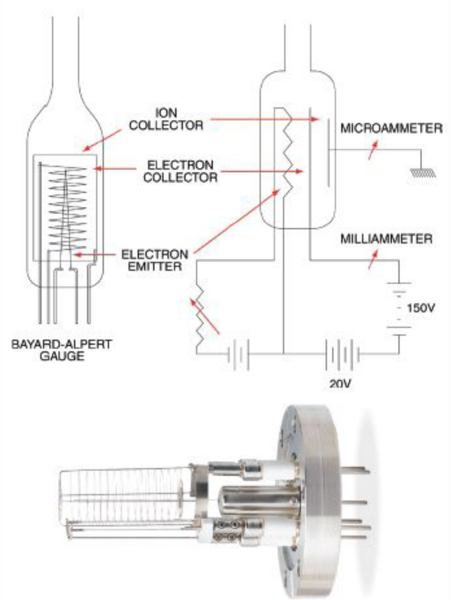

***Figure 5.** Penning and Ion gauges.*

Capacitance Manometer

This direct-pressure gauge typically operates from atmosphere to 1 x 102 Pa (1 x 104 Torr). The gauge contains a small metal diaphragm (disk) with one side of the diaphragm exposed to the vacuum chamber and known pressure on the backside. The pressure in the vacuum chamber either compresses or allows the expansion of the metal diaphragm. The gauge's electronics measures the movement of the metal diaphragm as a function of capacitance of the metal diaphragm with a fixed "parallel" electrode.

When the metal disk and the housing are constructed from stainless steel, this type of gauge is very resistant to corrosive or reactive gases. The range of the gauge can be changed to a degree by changing trapped pressure. A very small trapped volume and pressure allows the gauge to measure small differences in chamber pressure. The small gap between the metal diaphragm and the fixed electrode makes this type of gauge especially susceptible to vibration, temperature and any electrical field changes.

Most operators are unaware of the fact that the zero and span of the electronics must be reset every time the sensor head is changed, bumped or otherwise moved.

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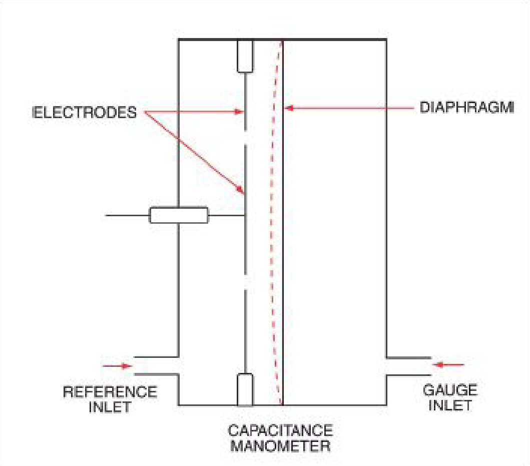

Figure 6. *Capacitance manometer.*

Summary

Vacuum technology provides controlled environments for scientific experiments and production lines. It is the basis for almost all areas of science and technology, materials, semiconductor, display production, surface analysis, space study, and in most R&D equipment. As science and technology develops, the importance of good vacuum technology has increased dramatically. In the processes where each unwanted molecule can ruin the whole process, the precise control of the environment, processing gases, materials and surface treatments producing little particles and gases from all the moving parts are crucial.

A basic understanding of what a vacuum is, how it is measured, and where each type of measurement is applied is essential to understanding how and when each can be applied most effectively and economically.