A Primer on Vacuum Pressure Measurement

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It's often said that we live at the bottom of a sea of air. Looking more closely at the atmosphere around us it is composed of a variety of molecules such as nitrogen, oxygen, water vapor, carbon dioxide, argon and a host of other natural and manmade substances. The density of this mixture of molecules is determined by such factors as the total depth of the atmosphere, ambient temperature, altitude and meteorological conditions. At the microscopic level, the molecules are in motion and the combined force exerted by this vibrating mass of molecules on a surface is something we call pressure.

Vacuum technology is concerned with reducing the density of molecules to some predetermined level in a contained environment and, more often than not, replacing the mixture that we call air with some other mixture of gases. The resulting environment: gas composition and density (pressure), is dictated by what we want to do in that environment, be it operating a surface analysis instrument, depositing films, or making a neon sign. That being said, the ability to accurately and reproducibly measure pressure is key to operating a successful vacuum application.

Pressure Measurement - The Beginnings

Ask a variety of people what "normal" sea-level atmospheric pressure is and you will get answers such as 14.7 pounds per square inch, 760 Torr, 29.92 inches of mercury, 1 bar, 100,000 Pascal, etc. What do these units mean and where do they come from?

In the middle of the 17th century, Evangelista Torricelli (1608-1647) was the first person to "measure" atmospheric pressure. He did this will his invention, the mercury barometer. This device consists of a glass tube, about a meter in length, that is sealed at one end. To set up the barometer, the tube is first filled with mercury and then inverted with the open end placed in a cup of mercury. What is observed is that the mercury column drops to some level in the tube. Since the space at the top of the tube was originally full of mercury (that is, free of air), the space now contains a reasonably good vacuum. The actual height of the mercury column in the tube then represents the weight of mercury that can be lifted by the difference in pressure between the pressure exerted on the mercury in the cup by the atmosphere and the pressure at the top of the tube (close enough to zero for the Renaissance vacuum experimenter).

At sea level, Torricelli observed that the typical height of the mercury column was about 760 millimeters. This would rise or fall depending upon the weather (hence the application of the barometer in meteorology). Other investigators found that the height of the column decreased when a barometer was carried up a hillside.

Analyzing this a bit more, we can observe three things (see **Figure 1**):

The barometer is measuring the pressure difference between the ambient atmosphere and a zero pressure reference. (Of course, the reference is not quite at zero pressure but it is at a pressure that is negligible as compared to what is being measured.) Thus, the pressure measurement is termed *absolute* because it is referenced to zero. If the barometer were carried toward space, the column height would drop to zero as the earth’s atmospheric pressure dropped to zero.

It is the force of the atmosphere on the mercury as applied over the surface area of the cup i.e. force per unit area that is holding the mercury column up. This is the proper definition of pressure. Devices such as barometers where the pressure is measured by the action of the gas on a moveable element are termed direct gauges. The moveable element can be a liquid column, a diaphragm, a bellows, a coiled tube or anything else that will move in response to the pressure of the gas.

The reading is the height of the column (length) for the particular working material (mercury). The proper way of expressing the reading is mmHg for millimeters of column height for the given working fluid. If water, which has a specific gravity 13 times lower than mercury were used, the column height for the same pressure would be that much more, i.e. about 30 feet. That brings us to the issue of pressure measurement units. We'll examine these in the next section.

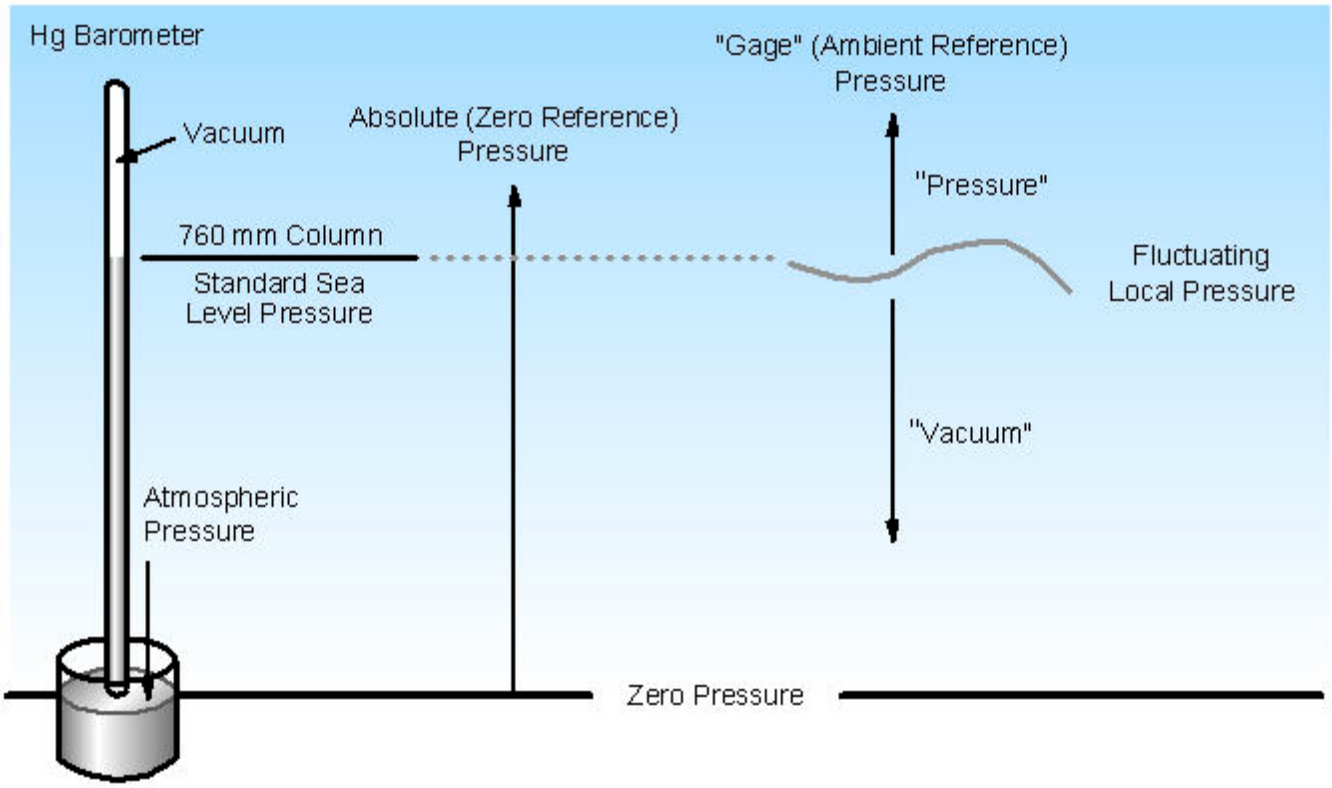

Figure 1. Absolute and atmosphere (gage) referenced pressures.

Pressure Units

For the reasons noted above, the traditional way to express pressure in a vacuum system is in terms of the height of a column of mercury that may be supported by the pressure in the system. This developed from the use of the barometer and later mercury column manometers (such as the McLeod gauge) as the primary way of measuring sub-atmospheric pressures. To summarize, one standard atmosphere of pressure will support a mercury column 760 millimeters (29.92 inches) high. One millimeter of mercury (mmHg) is the same as 1 Torr, a unit named in honor of Torricelli. A thousandth of 1 mm Hg is referred to as 1 micron Hg or, in more current terminology, 1 milliTorr (mTorr). But, none of these is actually a measure of pressure.

As stated before, pressure is properly defined as the force per unit area that the gas exerts on a surface. Depending upon what set of units we are working with or are accustomed. For example we can express

760 Torr as equivalent to 14.7 pounds per square inch (psi). If we are using the metric system the same pressure is about 1.03 bar (units of dynes/sq. cm) in cgs (centimeter-gram-second) units. In the professional scientific literature and in Japan the *SI* (*Système International)* units that are based on the meter and kilogram are normally used. Here, pressure is stated properly in terms of newtons/sq. meter or Pascal (Pa). In this system, 1 standard atmosphere is expressed as 101,300 Pa.

So, in the US we tend to stay with torr as the unit has a long history and people are familiar with it. Just remember that, properly speaking, the torr isn't really a unit of pressure.

Pressure References

Since we live our lives at this thing we call atmospheric pressure, we have a perception that vacuum is anything less than 1 atmosphere and pressure is anything above. Thus, to a person who lives in Boston, anyone who lives in Denver is living in a vacuum. (Normal atmospheric pressure at Denver's mile-high altitude is about 660 Torr.) This atmospheric reference that we have produces some difficulties when we talk about measuring vacuum and we have to be careful about what the reference is against which we are measuring pressure.

As we've seen, the barometer measures absolute pressure. The perfect zero pressure reference would be a vessel with absolutely no gas molecules in it. Once even one molecule is introduced, we have some pressure, albeit very small. Then, for every doubling of molecular density, we have a doubling of pressure. (See Table 1.)

Pressure (Torr)	Molecules/Liter
760	2.7×10^{22}
1	3.5×10^{19}
1×10^{-3}	3.5×10^{16}
1×10^{-8}	3.5×10^{11}
1×10^{-12}	35 million

Table 1. Pressure expressed as molecular density (at $0\ ^{0}C$).

Absolute pressure is generally used when it is important to know exactly how much "stuff" is in a given volume. Molecular densities, hence absolute pressure, are very important in vacuum apparatus and process tools as critical parameters such as mean free path and vapor pressures are related directly to absolute pressure.

Another way of expressing pressure is with reference to our normal, but varying, atmospheric pressure. This is often called *gage* pressure. Gage pressure simply tells you how far away you are from the ambient reference. Common dial gauges are an example of a gage, or atmosphere referenced gauge. In process systems, gage pressure is useful in applications such as loadlock monitoring and control where it is important or necessary to open the chamber right at the prevailing atmospheric pressure.

Differential pressure is another term that is often encountered. This is simply the pressure difference that exists between any two points in a system. For example, the differential pressure across an in-line filter might be monitored to insure proper air flow or to provide a warning in the even of clogging.

Direct and Indirect Gauges

While the barometer will provide an absolute pressure indication, its resolution is low. Most vacuum processes operate at pressures below 1 Torr and you simply can't measure such a minuscule column height. As vacuum technology improved during the 19th century it was necessary to develop gauges that could accurately indicate lower and lower pressures. After all, how can you brag about the quality of your pump if you don't have a way of telling how good a vacuum it will produce? The answer to the gauging problem was a sort of amplifying barometer that was developed by Herbert McLeod (1841–1923) in 1874. The McLeod gauge is a mercury manometer in which the gas whose pressure you are trying to measure is compressed by a known amount, usually in the range of ten to one hundred-thousand fold. By compressing the gas the height of the mercury column is correspondingly increased, providing a visually observable reading. Good McLeod gauges could provide accurate gas pressure measurements to the 10^{-5} Torr range providing there were no condensable gases (such as water vapor) in the sample. (The compression action will turn these condensables to liquid and therefore will not be part of the pressure measurement.)

McLeod and similar mercury manometers were difficult to fabricate, temperamental in operation, and fragile. These negatives led to the rise of another class of vacuum gauge that could be quite simple in construction and yet provide fairly good measurements. The trick in these gauges was not to measure pressure (force/area) but some property of the gas that predictably varies with pressure.

These gauges are termed *indirect* gauges. Many 20th century researchers have spent a good part of their careers developing pressure gauges that measure anything but pressure.

A large class of indirect gauge are those that depend upon the variation of thermal conductivity of the gas whose pressure is being measured. The specific quantity being measured is the molecule to molecule heat transfer from a heated element to the shell of the gauge tube. It turns out that thermal conduction is essentially constant in the higher pressure viscous flow regime (i.e. at pressures in excess of a few Torr) so these gauges have a high pressure limit. It also turns out that gases become very effective thermal insulators in the molecular flow regime (i.e. at pressures below about 10^{-3} Torr). However, in the region between these pressures, thermal conductivity will vary with pressure.

So, if one has a heated filament within an envelope, at higher pressures there will be some level of heat transfer from the filament causing it to operate at some temperature, assuming a given power input to the filament. Then, as the pressure is lowered, the thermal conduction of the gas decreases and the filament will tend to increase in temperature.

The temperature of the filament can be sensed with a thermocouple element that contacts the filament wire. This type of gauge is therefore termed a thermocouple gauge. Alternatively, the filament's temperature may be determined by the resistance of the filament wire: as the filament heats up, its resistance will also increase. This type of gauge is termed a Pirani gauge after its inventor, Marcello Pirani (1880-1968). Pirani's gauges were based on electric light bulb technology and indeed, Pirani was the laboratory head at Siemens & Halske AG’s bulb factory in Berlin.

Simple and relatively inexpensive, the thermocouple gauge has some deficiencies. One is the mode of operation: as the pressure changes, the filament and thermocouple have to arrive at a new temperature.

Since these elements have some amount of mass, the reading will lag the actual pressure by as much as several seconds. As a result, this type of gauge will not sense fast changes in pressure.

Although the principle is the same, the Pirani gauge has followed a different evolutionary path. Most notably, the filament is operated at a constant temperature. As the pressure changes, a bridge circuit varies the amount of power delivered to the filament in order to hold its resistance, hence its temperature, at a given value. Since there is no thermal time lag, the response of a Pirani gauge is quite fast, usually on the order of a tenth of a second or less. Other niceties in the Pirani gauge include temperature compensation to adjust for changing ambient temperature and a low filament temperature that helps to prevent contaminants that might be in the vacuum system from baking on to the filament. These provide for a more stable, repeatable gauge. Finally, the parameters associated with the Pirani filament (dimensions, temperature, electrical characteristics, etc.) permit usable pressure measurements up to about 100 Torr.

Thermocouple and Pirani gauges are most frequently seen in pressure monitoring applications: indicating proper pump down performance, foreline pressures and so forth.

As the pressure in the Pirani gauge approaches its upper limit, its sensitivity declines as a hot, stationary boundary layer forms around the filament. However, if the tube is properly constructed, as the pressure further increases strong convection currents of air will start to flow around the filament. The convection, as it gets stronger at higher pressures, will have a cooling effect on the filament. This convection cooling is exploited in a special form of the Pirani gauge, called the convection enhanced Pirani. With two modes of heat conduction, molecular at lower pressures and convection at higher pressures, a convection Pirani can provide continuous measurements over a 6-decade range, 1000 Torr down to 1 milliTorr. (In some cases these gauges can measure to about 0.1 milliTorr.) This type of gauge is frequently used to monitor the pump down of chambers from atmosphere.

It must be noted that convection Pirani gauges must be mounted in a given orientation in order to work properly in the convection mode.

Figure 2 shows a convection Pirani gauge and a typical pressure vs output curve. Note the non-linearity of the curve.

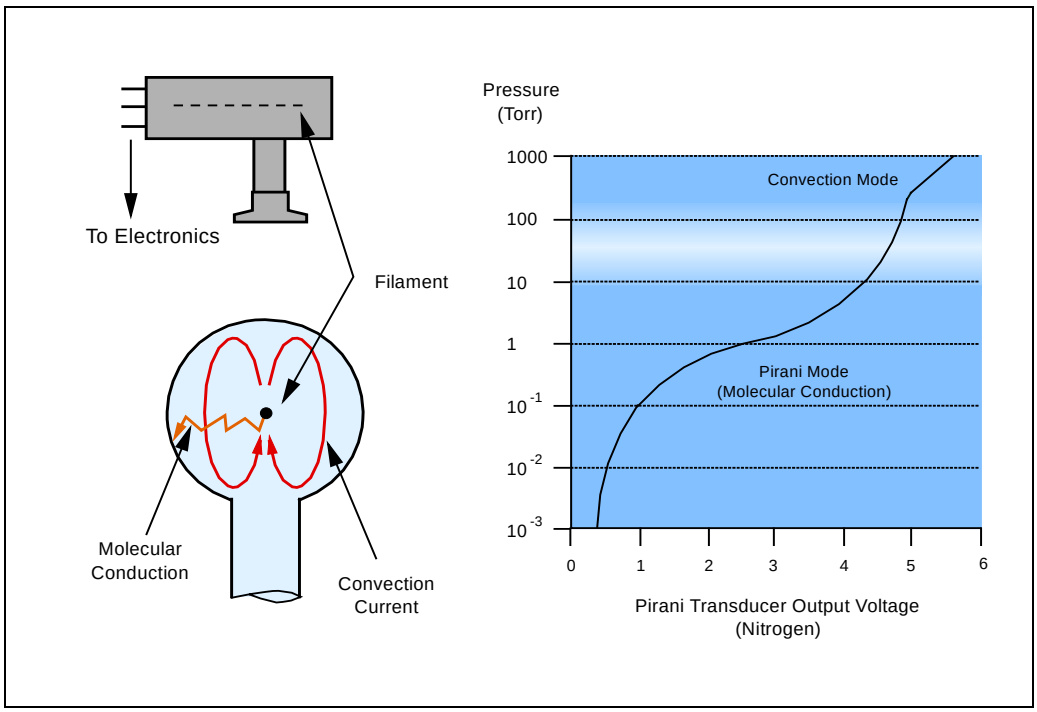

Figure 2. Schematic of a convection Pirani gauge with pressure vs voltage relationship. Illustration courtesy of MKS Instruments, Inc.

Figure 3. Convection Pirani sensor and controller. Photo courtesy of MKS Instruments, Inc.

Measuring Lower Pressures - Ion Gauges

While the thermal conductivity gauges provided a good solution to the measurement of pressures down to the upper end of the high vacuum realm, it won't work at lower pressures because the physical basis upon which the gauge works simply ceases to operate. The early researchers had to find another gas property that varies with pressure, one that would work at lower pressures. This lead to the development

of the ion gauge. Ion gauges developed from early vacuum tube technology where it was observed that the current drawn from the positive element (called the plate in a vacuum tube and a collector in a gauge tube) in a triode tube was related to the gas pressure in the tube, other conditions being constant.

Figure 4 illustrates the principle. Here we have an electron tube with three elements: an incandescent filament of refractory metal (pure tungsten or coated iridium) which provides a source of electrons through the process of thermionic emission, a positively biased fine wire grid that accelerates the electrons to a fixed energy though the volume of the tube, and a negatively biased collector. Some of the electrons that are passing through the tube will interact with the gas molecules, producing positive ions through a process called electron impact ionization. If the electron flux is held constant (done by controlling the current between the filament and the grid), the number of ions that are generated will be directly related to the density of gas molecules within the tube, that is, the collector current is directly related to the pressure.

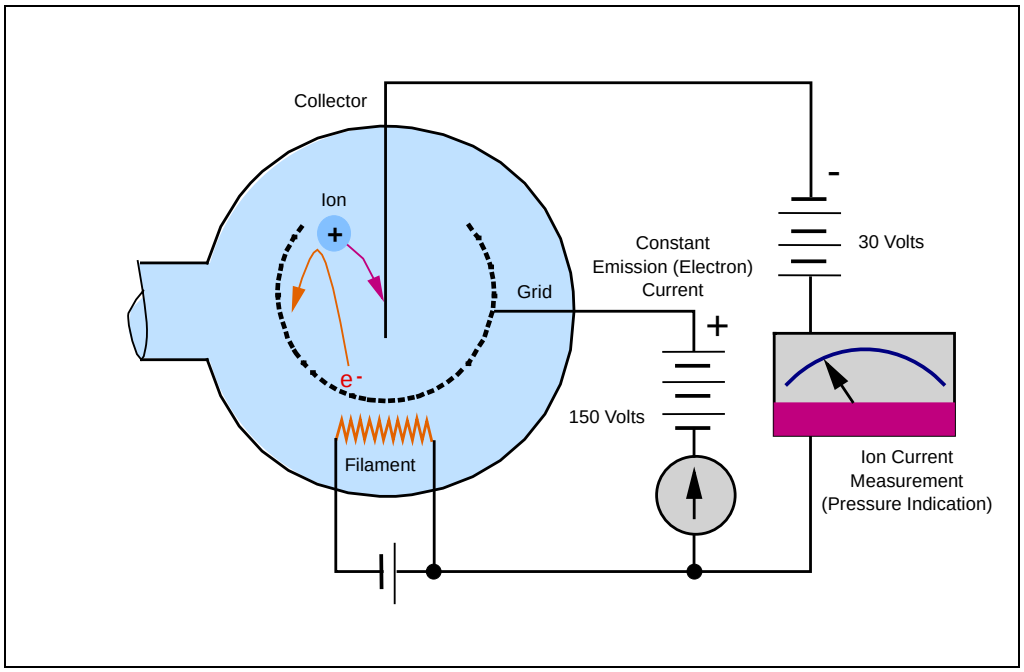

Figure 4. Schematic of a hot cathode ion gauge. Bias voltages are typical values.

A number of ion gauge configurations are in use with most being based upon the geometry of Bayard and Alpert where the collector is a fine wire that is located along the central axis of the sensor. The collector is surrounded by a helical grid and the filament is located outside the grid. This configuration was introduced to eliminate spurious signals that interfered with measurements below about 10^{-7} Torr. The common configurations include glass envelope tubes and "nude" gauges where the electrodes are mounted to a vacuum flange. An example of a nude gauge is shown in Figure 5. Ion gauges of the Bayard-Alpert configuration can measure pressures over the range of 10^{-10} to 10^{-3} Torr. The upper limit is determined by the short mean free path which limits the free movement of the electrons and ions. The lower limit is determined by a variety of noise sources.

Another type of ion gauge was developed by F.W. Penning in 1937. The Penning gauge consists of just two electrodes that are immersed in a magnetic field. With about 2,000 volts placed across the electrodes, a glow discharge is formed in the gap. The magnetic field causes the electrons to move in a spiral trajectory, increasing the probability of electron-ion collisions, even at very low pressures. In this de-

vice, the pressure is related to the current flowing between the electrodes. Because there is no filament, this type of gauge is called a cold cathode ion gauge. These are often used where the chamber gases might attack the filament of a hot cathode tube. Properly designed cold cathode gauges are also more immune to some of the noise sources that occur with hot cathode gauges, permitting operation to even lower pressures.

Figure 5. Nude hot cathode ion sensor and controller. The sensor elements are mounted on a 2-3/4 inch CF flange. Photo courtesy of MKS Instruments, Inc.

Trends in Indirect Vacuum Gauges

While the traditional pairing of sensor/readout is still very popular there has been a trend toward integrated transducers where a scalable output is available directly from the gauge. In addition to analog voltage outputs, a variety of digital interfaces have been incorporated in these transducers.

Miniaturization has been part of this transformation. Most of the sensor technologies have remained the same, just made more compact. An exception to this is the introduction of the micromachined Pirani sensor. The integrated/miniature nature of these transducers has further led to the combining of sensors within a single package. For example, a Pirani sensor can be combined with an ion gauge to provide continuous wide range coverage. Furthermore, the menu of indirect sensors may also be coupled with strain gauge (piezoresistive) diaphragm gauges to extend reading ranges to atmospheric pressure and above.

Typical combinations include:

- Pirani and hot cathode or cold cathode ion gauge for wide range measurement (UHV to low vacuum)
- Pirani and absolute strain gauge for medium vacuum to positive pressure measurement
- Pirani and atmosphere referenced strain gauge for loadlock control

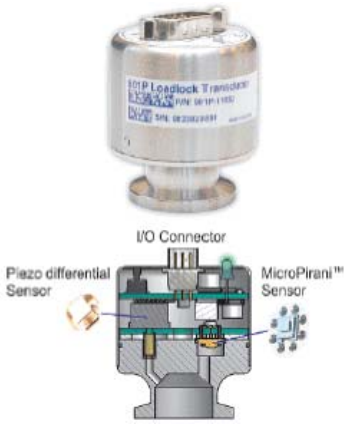

Figure 6. Integrated piezo differential and Pirani sensors in a loadlock gauge. Illustration courtesy of MKS Instruments, Inc.

Accuracy in Indirect Gauges

While simple and relatively inexpensive, the indirect gauges discussed above have some performance limitations that must be taken into account when they are used.

A major factor is gas sensitivity. In the case of thermal conductivity gauges, different gases have varying thermal conductivities. Gases that are lighter than air, such as helium, are better thermal conductors because the molecules travel faster. Gases that are heavier than air, such as argon and xenon, are relatively poor thermal conductors. Since thermocouple and Pirani gauges work on the principle of thermal conductivity, their readings will change with gas type.

The errors are particularly large at higher pressures. Some gauges, usually Piranis, will have calibration curves for various pure gases and corrections for a few common gases (helium, argon) may be incorporated in the electronics of the controller. When calibrating a thermal conductivity gauge (or any other kind of indirect gauge) the gauge must be calibrated with the gas that the gauge will be used with.

With regard to ion gauges, as we have seen, the pressure indication produced by an ion gauge is dependent upon the quantity of ions that are produced and the ion yield is proportional to pressure. However, for a given electron energy, it is more difficult to ionize the smaller atoms which have tightly bound electrons than it is to ionize heavier atoms. Thus a given density of helium atoms will produce fewer ions than the same density of argon atoms.

Another general issue with most of the commonly used indirect gauges is the fact that the gauges are not individually calibrated. Thus the calibration curve that is imbedded in the readout is a typical calibration curve for that make and model of gauge. Manufacturing tolerance, handling issues, etc. will cause gauge to gauge variations as well as variations over time. For the most part, manufacturers will not specify absolute accuracy values for these gauges. Repeatabilities may be specified and the better thermal and ionization gauges can achieve repeatabilities in the 5% range.

In the earlier days of vacuum, indirect gauges were usually adequate because the variety of gases used was fairly minimal and great precision was generally not required. In the few critical applications a McLeod manometer could be used.

The situation changed with the advent of wide ranging microelectronics and thin film vacuum processes. Process pressure measurement and control became a major issue and a host of exotic gas mixtures came into use. The old style direct reading mercury manometers simply could not adapt to this new environment. To address this situation, the capacitance manometer (also called a capacitance diaphragm gauge) was developed.

The Capacitance Manometer

The requirements that are placed on a process control gauge are as follows: made of non-corrosive materials, providing accurate pressure readings independent of gas type, a wide range of pressure ranges, highly accurate and stable, high resolution, fast response and providing an electrical (analog or digital) output in order to integrate the gauge into pressure control systems.

In a capacitance manometer, the pressure that the gas exerts is applied to a thin tensioned diaphragm. The thickness and diameter of the diaphragm are specified to permit the gauge to respond over a

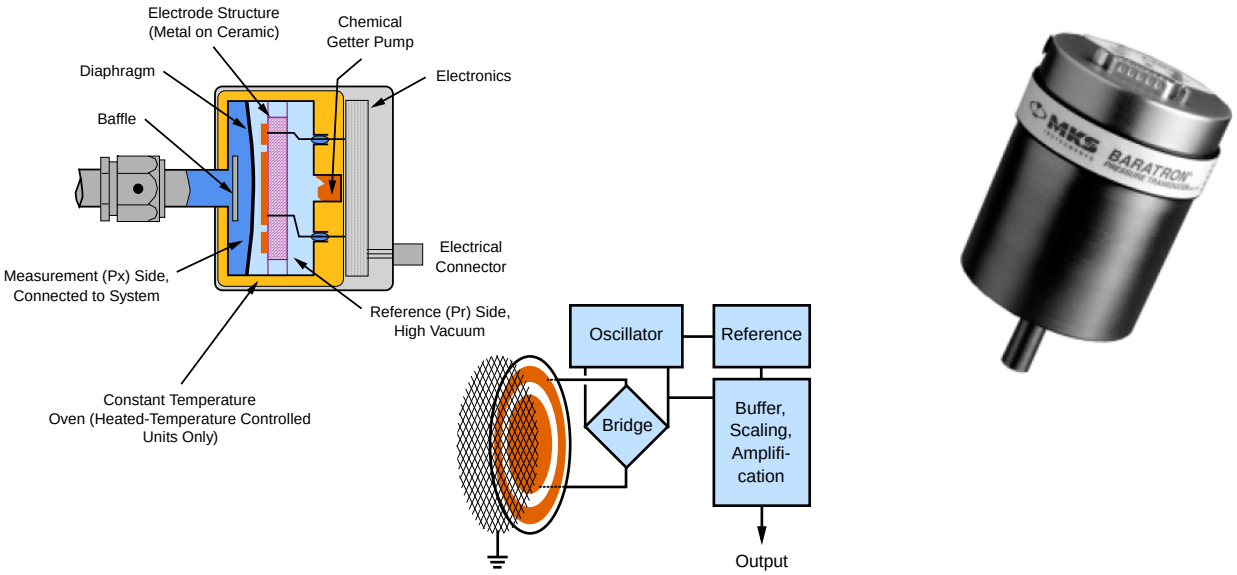

Figure 7. Schematic depiction of a capacitance manometer for absolute pressure measurement and a representative process manometer. Illustration and photo courtesy of MKS Instruments, Inc.

particular range of pressures. It turns out the motions of the diaphragm are exceedingly small and therefore the bending of the diaphragm is sensed electrically by means of a capacitance bridge.

Figure 7 shows the concept. The sensor consists of a sealed capsule that is divided by the diaphragm. Behind the diaphragm is a ceramic disk upon which there is a metal pattern in a form similar to that of a circular bull's eye surrounded by a ring. As a result of this geometry, between each electrode and the

diaphragm there is a capacitance that is defined by the areas of each electrode, the dielectric constant of the intervening gas (a constant since the capsule is sealed), and the separation of the each electrode from the diaphragm. Each of these variable capacitors is a leg in a bridge circuit. When the diaphragm is flat, the bridge is balanced and there is an output of 0 volts. However, as the diaphragm becomes curved as pressure is applied, the bridge becomes unbalanced and the degree of imbalance is reflected in the output voltage.

The configuration shown in the figure represents an absolute gauge. The backside of the diaphragm is evacuated and maintained at a very low reference pressure. In order to maintain a high vacuum reference over the life of the instrument, a getter material is fired during the evacuation process. The getter is a chemical that scavenges any gases that may evolve.

When the measurement port is open to any environment where the pressure is greater than that of the reference pressure, the diaphragm will curve and there will be a positive output voltage. The signal conditioning electronics then translates this to an output that is linear with pressure.

Each capacitance manometer is specified according to its full scale (FS) range and it will be able to measure pressure for some number of decades below that full scale value. In the case of a 10 Torr FS manometer, the output at 10 Torr will be 10 volts. At 1 Torr it will be 1.0 volts, at 0.1 Torr it will be 0.1 volts and so forth.

Needless to say, as the pressure goes to, say, a hundredth of a percent of the full scale rating, the output voltage will be exceedingly small and will hinder measurements. To measure lower pressures, one would use a lower full scale instrument. By varying the dimensions of the diaphragms, currently offered manometers have full scale ranges from 1000 Torr down to 20 milliTorr. High pressure capacitance manometer have also been introduced that will measure pressures to 3000 psi.

The materials that are used in the construction of capacitance manometers are crucial to accuracy and stability. Inconel^{R} (Inconel^{R} is a registered trademark of Inco Alloys International, 3200 Riverside Dr., Huntington, WV) diaphragms have been in continuous use since the introduction of commercial capacitance manometers in 1961. This material offers great chemical resistance and thermal-mechanical stability and is used in all of the high resolution and high accuracy manometers. Ceramic diaphragm instruments, first introduced about 20 years ago, have been in and out of production but have found some ongoing success in general purpose applications.

For some applications the instrument may incorporate a temperature regulated oven to improve stability or to prevent the condensation of process gases on the diaphragm.

Concerning accuracy, all capacitance manometers are individually calibrated and are traceable to national standards laboratories. They are available with guaranteed accuracy specifications of 1% of reading to 0.12% of reading. Premium capacitance manometers are available with 0.05% of reading accuracies.

The Capacitance Manometer Enters the 21st Century

Digital Capacitance Manometers

The past decade has seen a steady increase in vacuum gauges with digital interfaces. This has been driven by the need to reduce the bulk of interconnect wiring, to improve noise immunity and to enhance diagnostics capabilities.

The first generation of digital capacitance manometers consisted of an analog to digital module that was added to the standard analog circuitry. These instruments were calibrated as standard analog gauges by adjusting the span and linearity pots to match as much as possible the readings of the calibration standard.

In the latest generation of digital instruments the digital section is integral to the manometer's functionality, not just an interface. **Figure 8** shows the architecture along with a representative product. Note that both analog and digital connections may be made to the gauge. Many options are available for digital interfaces including DeviceNet, Profibus, RS-485 and ethernet protocols.

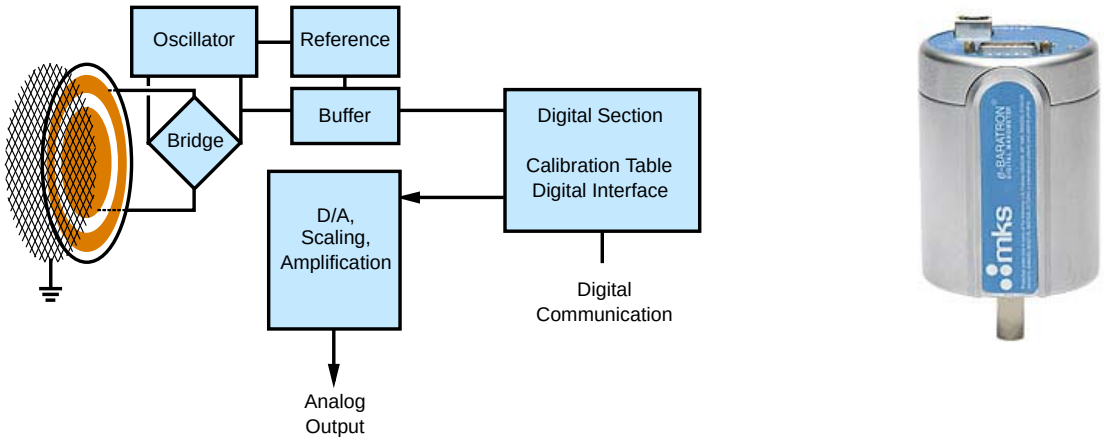

Figure 8. Digital capacitance manometer architecture and a representative instrument with analog and ethernet connectors. Photo courtesy of MKS Instruments, Inc.

Note that the digital block contains a calibration table. As noted previously analog instruments are calibrated by adjusting 3 pots (zero, span, linearity) to match, as closely as possible, the readings of the calibration standard. With true digital instruments, the internal calibration table is populated with as many as 20 pressure points between zero and full scale. Because of the number of calibration points the linearity (and accuracy) of the instrument is improved. This improvement is generally in the range of 20%. This is depicted in **Figure 9**.

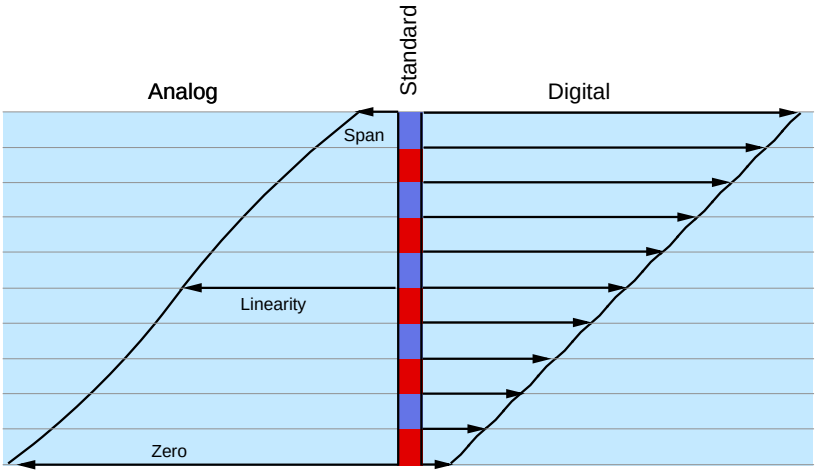

Figure 9. Analog vs digital capacitance manometer calibration.

Contamination Control

Capacitance manometers are directly exposed to the process conditions and are therefore subject to by-product and/or particle build up on the diaphragm. As material accumulates on the diaphragm, the zero will shift and eventually it will be impossible to zero the gauge. The only remedy at this point is to have the sensor replaced.

Using a heated manometer is a primary method to mitigate the effects of condensable gases. However, in some cases (especially some etch processes) these contaminants are still difficult to control.

Figure 10 shows a variety of features that may be incorporated into process manometers to insulate the diaphragm from contaminants. The features shown include long/narrow passageways and particle "sumps." The inlet screens and traps are usually replaceable elements whereas the internal baffles are integral to the sensor design.

For the most part, these features will lengthen (often substantially) the life of a manometer but they may not render the instrument immune from contamination.

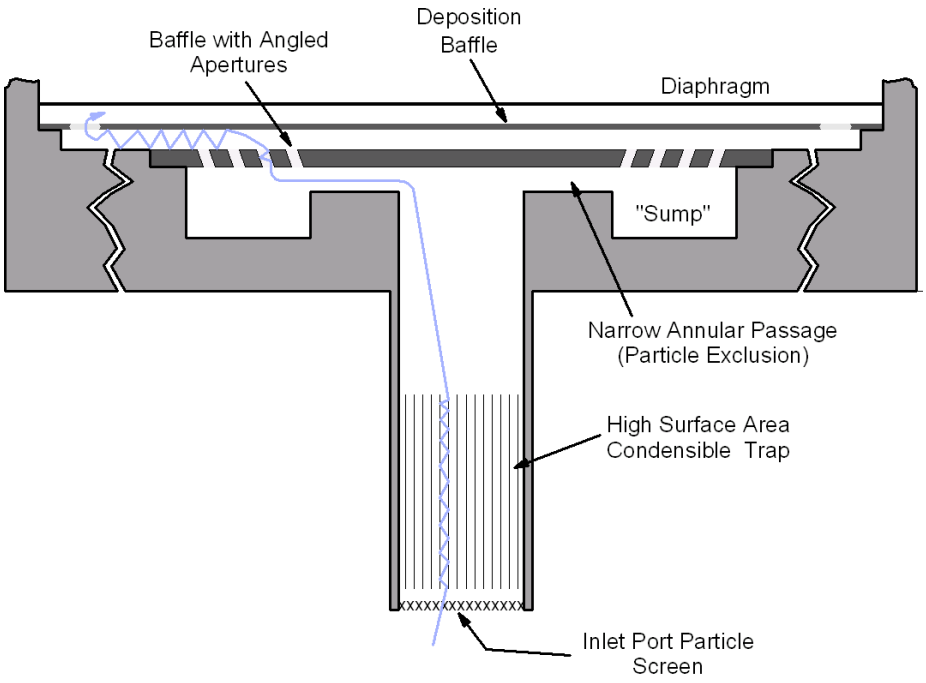

Figure 10. Features to shield the diaphragm from particulates and condensables.

Summary

Selecting a vacuum gauge for a particular application requires an understanding of how the gauge operates, what factors will cause erroneous readings, and what degree of accuracy and repeatability are required. The indirect gauges are generally economical and offer satisfactory performance for many monitoring applications. High precision capacitance manometers are used for critical control applications where known levels of accuracy and stability are required. **Figure 11** shows a vacuum system with a variety of gauges in appropriate locations.

This brief survey has only touched the surface of the more commonly encountered vacuum gauges. Please consult the references for articles that go into further detail or touch on other aspects of vacuum gauging.

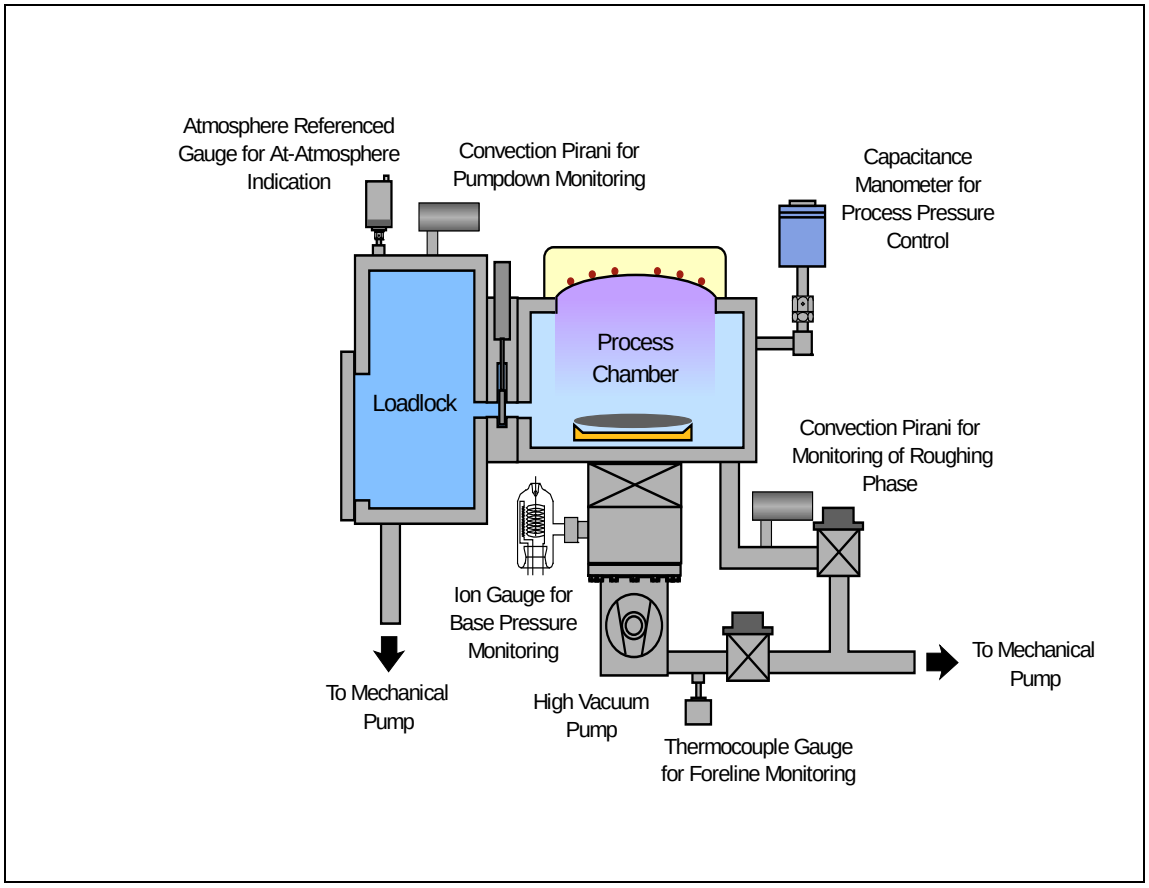

Figure 11. Vacuum system with a variety of gauges and the function of each. A single "combo" transducer could replace the two loadlock gauges.

Acknowledgements

Many aspects of this article are drawn from my years with MKS Instruments. I would also like to extend my thanks to Philip Sullivan of MKS for his input on the more recent innovations in capacitance manometers.

Further Reading

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