

F.1

Understanding Vacuum and Vacuum Measurement





Understanding Vacuum and Vacuum Measurement

Written By: Reál J. Fradette, Senior Technical Consultant, Solar Manufacturing, Inc.

Contributors: William R. Jones, CEO, The Solar Atmospheres Group of Companies Trevor Jones, Principal Engineer, Solar Atmospheres, Inc.

Editor: Patricia Niederhaus, Executive Technical Administrator, Solar Atmospheres, Inc.

> Layout & Illustrations: Andrew Nagy, Graphic Designer, Solar Atmospheres, Inc.





The purpose of this paper is to provide a better understanding of vacuum, including an explanation of vacuum, a definition and description of vacuum measuring instrumentation and an explanation of their application to vacuum furnace operation.

Explaining Vacuum

Vacuum can be defined as a space that is empty of matter; however, achieving such an empty space is essentially impossible on earth. Instead, vacuum is best described as a space with gaseous pressure much less than atmospheric pressure. Physicists and vacuum scientists describe this lack of a "perfect vacuum" in manmade chambers, such as production furnaces, as partial pressure or partial vacuum.¹

The quality of a vacuum is indicated by the amount of matter remaining in the system, so that a high quality vacuum is one with very little matter left in it. Vacuum is primarily measured by its absolute pressure.

At room temperature and normal atmospheric pressure, one cubic foot (0.03 cubic m) of air contains approximately 7×10^{23} molecules moving in random directions and at speeds of around 1,000 miles per hour.² The momentum exchange imparted to the walls is equal to a force of 14.7 (psia) pounds for every square inch of wall area.² This atmospheric pressure can be expressed in a number of units, but until relatively recently it was commonly expressed in terms of weight of a column of mercury 760 mm high.² Thus, one standard atmosphere equals 760 mm Hg.

Air Composition

at 50% Relative Humidity

Gas	Percent
N ₂	78.08
02	20.95
Ar	0.93
CO ₂	0.033
Ne	1.8×10 ⁻³
He	5.24×10 ⁻⁴
CH ₄	2.0×10 ⁻⁴
Kr	1.1×10 ⁻⁴
H ₂	5.0×10 ⁻⁵
N ₂ O	5.0×10 ⁻⁵
Xe	8.7×10 ⁻⁶
H ₂ 0	1.57

Table 1

Creating a Vacuum -The Pumpdown

The pumpdown process begins with air at atmospheric pressure in a chamber attached to a vacuum pump. The vacuum pump removes gas molecules from the chamber to reach the desired vacuum. Air at atmospheric pressure is a combination of gasses as shown in Table 1. The relative gas composition will be important later on in this paper.

Gas molecules are always moving and colliding, molecule to molecule. Gas molecules at atmospheric pressure are very close together, so the collisions are very short.

The distance between molecules is a function of pressure and is known as the mean free path (MFP).³ As the chamber is pumped down into vacuum and molecules are removed, the MFP becomes greater and greater.

As pressure decreases in a chamber, fewer molecules are present and the mean free path increases. Similarly, as the gas density reduces, there are fewer chances of molecular collision. This correlation between the MFP and pressure is shown in Figure 1. Air molecules are usually removed from the chamber through a type of positive displacement pump such as an oil-sealed rotary pump.



Figure 1 - Mean Free Path Vs Pressure

Vacuum Units of Measurement

Measuring vacuum, as with any kind of measuring, requires standard units of measure. Inches or millimeters of mercury, torr, and micron are three units of measure typically associated with the vacuum furnace industry. Other fields of vacuum use Pascals (Pa or kPa.)

Because of the work of 17th century scientist Evangelista Torricelli, we know that the atmosphere generally exerts enough pressure at sea level to support about a 30-inch (760mm) column of mercury. From that foundation, we can measure decreases in atmospheric pressure in terms of inches or millimeters of mercury. Thus, a 10% drop in atmospheric pressure would indicate a 3-inch fall in the height of our column of mercury. In this way, vacuum came to be measured by the difference between normal atmospheric pressure and pressure in the system

Units of Vacuum Measurement						
inHg (abs.) Torr Microns						
1 inHg	1	25.4	2.54 x 10 ⁴			
1 Torr	3.937 x 10 ⁻²	1	1000			
1 Micron	3.937 x 10⁻⁵	1 x 10 ⁻³	1			

Table 2

being measured. Thus, a 10% decrease in gas density from atmospheric pressure would be measured as a 3-inch vacuum. For everyday vacuum measurements such as in weather forecasting, inches of mercury function well, but for measurements on a finer scale, other units are needed. One "torr," a unit named in honor of Torricelli, is equivalent to one millimeter of mercury, yielding the figure of 760 torr as normal atmospheric pressure at sea level. Torr as units of measure are typically used for vacuums in the 1 to 760 Torr range. For measurements of vacuum on an even smaller scale, the "micron" is the term of use. One micron is equal to 0.001 Torr (10^{-3} Torr). Microns (represented by the symbol μ) are typically used to measure vacuums in the range of 10^{-3} to 1 Torr. For heat treating purposes, torr and micron are the most commonly used units of measure. Table 2 gives conversion factors for the three units discussed above.

Vacuum Levels

Vacuum quality is subdivided into ranges according to the technology required to achieve it or measure it. A typical distribution of the universally accepted ranges can be found in Table 3.¹

Atmospheric Pressure - is variable but is standardized at 760 Torr or 101.325 kPa.

Low Vacuum – also called rough vacuum, is a vacuum that can be achieved or measured by basic equipment such as a vacuum cleaner.

Medium Vacuum – is a vacuum that is typically achieved by a single pump, but the pressure is too low to measure with a mechanical manometer. It can be measured with a McLeod gauge, thermal gauge, or a capacitance gauge. (Instrumentation to be discussed later.)

High Vacuum – is vacuum where the MFP of residual gasses is longer than the size of the chamber or of the object under test. High vacuum usually requires multistage pumping and ion gauge measurement. NASA has revealed that the vacuum level recorded on the moon was 1×10^{-9} Torr.¹

Ultra-High vacuum – requires baking the chamber to remove trace gasses and other special procedures. Most standards define ultra-high vacuum as pressures below 10⁸ Torr.

Deep Space – is generally much emptier than any artificial vacuum.

Vacuum Level Ranges

Atmospheric Pressure	760 Torr
Low Vacuum (Rough)	760 to 25 Torr
Medium Vacuum (Rough)	25 to 1 x 10 ⁻³ Torr
High Vacuum (Hard)	1×10^{-3} to 1×10^{-9} Torr
Ultra High Vacuum	1 x 10 ⁻⁹ to 1×10 ⁻¹² Torr
Extremely High Vacuum	<1 x 10 ⁻¹² Torr
Outer Space	1 x 10 ⁻⁶ to <3×10 ⁻¹⁷ Torr

Table 3

Perfect Vacuum – is an ideal state of no particles at all. It cannot be achieved in a laboratory, although there may be small volumes which, for a brief period, happen to have no particles of matter in them.

Types of Vacuum Measuring Instruments

As it has become practical and desirable to create higher and higher vacuums, it has also become necessary to assess the level of those vacuums accurately.

Absolute pressure is measured relative to perfect vacuum (0 psia) with zero as its zero point. Gauge pressure is relative to ambient air pressure (14.5 psia), using atmospheric pressure as its zero point (0 psig = 14.5 psia).

Many gauges are available to measure vacuum within a vacuum furnace chamber. These gauges vary in design based on the particular range of vacuum they are analyzing. Table 4 shows the various gauges that we will be discussing in the following pages and their respective range of performance (shaded area).

Vacuum Range	Bourdon Gauge	Capacitance Monometer	Pirani Gauge	T/C Gauge	Hot Cathode Gauge	Cold Cathode Gauge	McLeod Gauge
10 ³ Torr							
10 ² Torr							
10 ¹ Torr							
10° Torr							
10 ⁻¹ Torr							
10 ⁻² Torr							
10 ⁻³ Torr							
10 ⁻⁴ Torr							
10 ⁻⁵ Torr							
10 ⁻⁶ Torr							
10 ⁻⁷ Torr							
10 ⁻⁸ Torr							
10 ⁻⁹ Torr							
10 ⁻¹⁰ Torr							
10 ⁻¹¹ Torr							

Effective Operating Ranges of Vacuum Instrumentation

Table 4

Hydrostatic Gauges

Torricelli's Discovery

Instruments for measuring the emptiness of a given space have been used for hundreds of years, making use of the properties of gases to determine their relative absence. The barometer, a device used for measuring air pressure, was invented in 1643 by the Renaissance Florentine scientist Evangelista Torricelli. Because we are living submerged in an ocean of air, the atmosphere is pressing down on us. Due to local heating and cooling, areas of lower and higher atmospheric pressure periodically sweep over us. The areas of lower pressure are in a sense areas of vacuum, as the gasses of the air around us are relatively less dense there. Torricelli found that the pressure of the atmosphere at sea level pressing down on a well of mercury would support a nearly 30-inch column of mercury in a tube upended in the reservoir of mercury. The mercury in the column would not flow down into the well because of the counterbalancing atmospheric pressure on the surface of the mercury in the well.

From that beginning, more sophisticated and precise devices have been designed to measure lower and lower masses of gas in a given volume.

Two of the most common hydrostatic measuring devices are the Bourdon gauge in Figure 2 and the McLeod gauge in Figure 3.

The Bourdon Gauge/Diaphragm Gauge

The Bourdon gauge, also known as the diaphragm gauge, shown in the Figure 2, accurately and continuously indicates the pressure from approximately atmospheric pressure (760 Torr) to 20 Torr.

The pressure gauge uses the principle that a flattened tube tends to straighten or regain its circular form in cross-section when pressurized. Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses



Figure 2 - Bourdon Tube Gauge

within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized. Eugene Bourdon patented his gauge in France in 1849, and it was widely adopted because of its superior sensitivity, linearity, and accuracy. ⁵

In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a segment of a gear by a connecting link that is usually adjustable. A small-diameter pinion gear is on the pointer shaft, so the motion is magnified further by the gear ratio. The positioning of the indicator card behind the pointer, the initial pointer shaft position, the linkage length and initial position all provide means to calibrate the pointer to indicate the desired range of pressure for variations in the behavior of the Bourdon tube itself. Differential pressure can be measured by gauges containing two different Bourdon tubes, with connecting linkages. ⁶

Bourdon tubes measure gauge pressure relative to ambient atmospheric pressure, as

opposed to absolute pressure; vacuum is sensed as a reverse motion. Some barometers use Bourdon tubes closed at ends (but most use diaphragms or capsules, see below.) When the measured pressure is rapidly pulsing, such as when the gauge is near a reciprocating pump, an orifice restriction in the connecting pipe is frequently used to avoid unnecessary wear on the gears and provide an average reading. When the whole gauge is subject to mechanical vibration, the entire case including the pointer and indicator card can be filled with an oil or glycerin. Tapping on the face of the gauge is not recommended as it will tend to falsify actual readings initially presented by the gauge. The Bourdon tube is separate from the face of the



Figure 3 - McLeod Gauge

gauge and thus has no effect on the actual reading of pressure. Typical high-quality modern gauges provide an accuracy of $\pm 2\%$ of span, and a special high-precision gauge can be as accurate as 0.1% of full scale.⁶



McLeod Gauge

This gauge is a modification of a manometer that can measure *absolute pressure* of gasses quite accurately. 7

The main advantage of the McLeod gauge is that its calibration is unaffected by the type of gas in the system. Many gasses such as hydrogen, helium, carbon dioxide, and many other gasses in a vacuum system will wreak havoc with the calibration of most other types of vacuum gauges. However, as long as the condensable vapors are trapped out, readings from the McLeod gauge can be used to calibrate other gauges. ⁸

As shown in Figure 4, it traps a fixed volume 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. A vacuum is established with the mercury level shown in dark gray (Figure 4(B)). The mercury is raised

until the level in the tube connected to the vacuum is equal to the top of the sealed capillary. The reading difference now indicates the vacuum measurement. The McLeod gauge was invented by H.G. McLeod in 1974 to measure gas pressure of or between 10⁻² and 10⁻⁷ Torr. ⁹

Capacitance Manometer Gauges

The capacitance manometer gauge is a pressure gauge used to measure vacuum from atmospheric pressure to 10⁻⁵ Torr dependent on the given sensor applied. ¹¹

A capacitance sensor operates by measuring the change in electrical capacitance that results from the movement of a sensing diaphragm relative to some fixed capacitance electrodes (Figure 5). The higher the process vacuum, the farther it will pull the measuring diaphragm away from the fixed capacitance plates. In some designs, the diaphragm is allowed to move. In others, a variable DC voltage is applied to keep the sensor's Wheatstone bridge in a balanced condition. The amount of voltage required is directly related to the pressure.

The great advantage of a capacitance gauge is its ability to detect extremely small diaphragm movements. Accuracy is typically 0.25 to 0.5% of reading. Thin diaphragms can measure down to 10^{-5} Torr, while thicker diaphragms can measure in the low vacuum to atmospheric range. To cover a wide vacuum range, one can connect two or more capacitance sensing heads into a multi-range package.





The capacitance diaphragm gauge is widely used in the semiconductor industry, because its Inconel body and diaphragm are suitable for the corrosive services of this industry. They are also favored because of their high accuracy, immunity to contamination, and gas type species.

Pirani Gauges

The Pirani gauge is a thermal conductivity gauge used to measure pressure in a vacuum. The gauge is able to give a pressure reading due to a heated metal wire suspended in the vacuum system to be measured as shown in Figure 6b. Gas molecules in the system collide with the wire allowing it to emit heat and cool. As the vacuum is pumped down, there are fewer gas molecules to affect the wire and the wire heats up. When the wire is heated, the electrical resistance increases and a circuit attached to the wire detects the change in resistance. Once the circuit is calibrated, it can directly correlate the amount of resistance to the pressure in the vacuum chamber.



There are two types of Pirani gauges: constant current

and constant resistance. Each refers to how the electrical measurement of the wire is controlled. The constant current gauge has a power supply giving off a consistent amount of energy to the metal filament. The current is the control and the resistance is the variable. The varied resistance is proportional to the pressure in the vacuum. The constant resistance gauge has a power supply which varies the current based on the constant resistance. The variation in the current is proportional to the pressure in the vacuum.

The Pirani gauge is used to measure pressures between 0.5 Torr to 10⁴ Torr. Before using the gauge, the apparatus may need calibrating to obtain accurate readings depending on the thermal conductivity and the heat capacity of the gas.

Thermocouple Gauges

A thermocouple (T/C) gauge works very similarly to a Pirani gauge. The difference is that the temperature of the wire is measured precisely by the T/C, which is attached to the wire. The current is determined based on the resistance. This gauge is normally used for comparison purposes and the sensitivity varies based on the pressure and the strength of the current. The reading is on a minivolt meter calibrated to show pressure,

high vacuum relies on some form of ionization gauge

for pressure measurements under 10⁻³ Torr. There

are two competing ionization gauge technologies to choose from which are viable means for pressure measurements between 10⁻² and 10⁻¹⁰ Torr. They

sense pressure indirectly by measuring the electrical

Fewer ions will be produced by lower density gasses.

but it must be calibrated for each different gas other than air and nitrogen. Another disadvantage is that it is not marked in a linear order. At low pressures, the scale markings are spread apart and in higher ranges, the marks are closer together. For the most part, the thermocouple gauges have the same advantages and disadvantages as the Pirani gauge although the thermocouple gauge is considered to be less expensive and more user friendly. Figure 7 is an example of a typical





Hot Cathode Ionization Gauge

A hot cathode ionization gauge like the one in Figure 8 is composed mainly of three electrodes acting together in a triode, wherein the cathode is the filament. The three electrodes are a collector or plate, a filament and a grid. Electrons emitted from the filament move several times in back and forth movements around the grid before finally entering the grid. During these movements, some electrons collide with a gaseous molecule to form a pair of an ion and an electron. The number of these ions is proportional to the gaseous molecule density multiplied by the electron current emitted from the filament, and these ions enter into the collector to form the ion current. Since the gaseous molecule density is proportional to the pressure, the pressure is estimated by measuring the ion current.¹⁶

thermocouple gauge.

Ionization Gauges





Cold Cathode Gauge

A cathode is an electrode that emits electrons, that is not electrically heated by a filament.¹⁸ There are two types of cold cathode ionization gauges: the Penning gauge and the inverted magnetron, also known as the redhead gauge.¹⁹

This gauge, like the one in Figure 9, makes use of the fact that the rate of ion production by a stream of electrons in a vacuum system is dependent on pressure and the ionization probability of the residual gas. $^{\rm 20}$

Two parallel connecting cathodes and the anode is placed midway between them. The cathodes are metal plates or shaped metal bosses. The anode is a loop of flattened metal wire, the plane of which is parallel to that of the cathode. A high voltage potential is maintained between the anodes and the cathodes. In addition, a magnetic field intensity is applied between the elements by a permanent magnet, which is usually external to the gauge tube body.





Figure 9 - Cold Cathode Gauge

anode, thus increasing the amount of ionization occurring within the gauge. Normally the anode is operated at about 2kV, giving rise to a direct current caused by the positive ions arriving at the cathode. The pressure is indicated directly by the magnitude of the direct current produced. The pressure range covered by this gauge is from as low as 10^{-7} Torr. It is widely used in industrial systems because it is rugged and simple to use.

Vacuum Levels in Production Vacuum Furnaces

In discussing vacuum furnace operation and performance, vacuum levels are usually defined by the capabilities of the vacuum pumps included on the vacuum furnace system.

A typical vacuum pump arrangement might look like Figure 10. Basically, there are three pumps to provide the following practical vacuum level ranges shown in Table 5.

Understanding the Use of Partial Pressure

The use of partial pressure is required in many heat treating and brazing cycles in a vacuum furnace. It is very important to understand how the vapor pressure of the materials being processed can be affected by the process temperature and furnace vacuum level.



Figure 10 - Typical Vacuum Furnace Pump Configuration

Flactical vacuum Fump Levels					
Vacuum Pump	Achievable Range (Torr)	Achievable Range (Microns)			
Mechanical Pump	0.050	50			
Vacuum Booster Pump	0.010	10			
Oil Vapor Diffusion Pump	1 x 10 ⁻⁷	0.0001			
Table 5					

Practical Vacuum Pump Levels

Understanding Vacuum and Vacuum Measurement

As a material is processed in vacuum, the temperature at which the material will vaporize reduces as the vacuum level is lowered. In vacuum furnaces, metals tend to volatize at temperatures below their melting point. Table 6 illustrates the effect of vacuum levels as related to the reducing vapor pressure temperatures.

Vapor Pressure Chart of Certain Metals (°F)

When the particular metal is part of an alloy, the vapor pressure temperature of the alloy changes based on the various metals included. It has been established that the total vapor pressure of the alloy is the sum of the vapor pressures of each component times its percentage in the alloy.

Partial Pressure and Vacuum Furnace Brazing

One of the most critical processes performed in a vacuum furnace is the brazing of materials. As an example, copper is commonly used as the brazing filler material for brazing steel components. Copper brazing (shown in Figure 11) is typically performed at a high temperature of about 2025-2050°F. If we look at our above chart for copper, the vapor pressure at 760 Torr is about 4700°F so that at atmospheric pressure, it would require this temperature to start to vaporize. However, if we look at the chart at a vacuum pressure of 10⁻⁴ Torr, copper begins vaporizing at about 1895°F. Since we must raise the process temperature to 2025-2050°F, Table 6 tells us that we must be above 10⁻³ Torr (1 micron) to control the vaporization.



Figure 11 - Copper Brazed Assembly

Partial pressure systems are normally incorporated into the vacuum furnace controls to allow for clean, inert gas to be introduced into the vacuum chamber during a cycle in order to build the pressure in the chamber to levels high enough to suppress the vaporization of a particular metal or group of metals. Such partial pressure systems are quite effective. However, it becomes quite difficult to accurately control at 0.1 Torr or lower, so a typical partial pressure is usually controlled in the 0.5 Torr to 5.0 Torr range to provide more than adequate vaporization suppression while not affecting the process conditions.

Although this is directed toward brazing, there are other vacuum cycles that must be run in partial pressure to minimize possible material vaporization. Stainless and tool steels are now normally

vapor Pressures of Certain Metals								
Element	10 ⁻⁴ Torr	10 ⁻³ Torr	10 ⁻² Torr	10 ⁻¹ Torr	1.0 Torr	10 ¹ Torr	10 ² Torr	760 Torr
Aluminum	1486	1632	1825	2053	2334	2709	3180	4473
Beryllium	1884	2066	2275	2543	2853	3249	3087	4545
Boron	2084	2262	2471	2712	2998	5486	6260	4581(s)
Cadmium	356	428	507	610	741	903	1132	1409
Calcium	865	982	1121	1292	1503	1801	2205	2709
Carbon	4150	4480	4858	5299	5817	7135	7903	8721
Cerium	1996	2174	2381	2622				6199
Cesium	165	230	307	405		703	955	1274
Chromium	1818	1994	2201	2448	2739			4031
Cobalt	2484	2721	3000	3331	3732	4316	4928	5607
Copper	1895	2086	2323	2610	2962	3414	4005	4703
Gallium	1578	1769	1999	2278	2629	2806	3243	4400
Germanium	1825	2034	2284	2590	2975	3416	4010	4905
Gold	2174	2401	2669	2995	3393	3909	4570	5371
Iron	2183	2390	2637	2916	3241	3702	4280	4941
Lead	1018	1148	1324	1508	1787	2133	2583	3159
Magnesium	628	716	829	959	1121	1296	1668	2059
Manganese	1456	1612	1796	1868	2284	2741	3257	3807
Mercury		64	118	180	259	363	421	682
Molybdenum	3809	4163	4591	5216	5616	6395	7428	8679
Neodymium		2177	2448	2799	3227	3803	4586	5594

Table 6 - Part 1

Vapor Pressures of Certain Metals

Element	10 ⁻⁴ Torr	10 ⁻³ Torr	10 ⁻² Torr	10 ⁻¹ Torr	1.0 Torr	10 ¹ Torr	10 ² Torr	760 Torr
Nickel	2295	2500	2750	3054	3423	3645	4287	5139
Niobium	4271	4602						8568
Palladium	2320	2561	2851	3198	3632	4136	5036	5732
Phosphorus		320	374	437	509	590	698	808
Platinum	3171	3459	3794	4150	4680	5695	6717	6921
Potassium	253	322	405	509	640	829	1078	1434
Rhenium		5054	5540	6152	6890			10166
Rhodium	3299	3580	3900	4274	4725	5216	6138	7011
Selenium		392	455	536	662	806	1022	1265
Silicon	2041	2233	2449	2705	3038	3430	3781	4491
Silver	1558	1688	1917	2163	2467	2867	3389	4013
Sodium	383	460	556	673	819	1018	1285	1677
Sulfur		151	207	275	361	475	631	831
Tantalum	4710	5108	5565	6098	6764			10881
Tin	1692							
Titanium		2523	2815	3168	3569	3956	4496	5661
Tungsten		5461	5988					10701
Uranium		3146	3448	3808	4240			6381
Vanadium		3137	3430	3774	4005	4665	5342	6116
Yttrium	2484	2721	3000	3331				6040
Zinc	478	558	649	761	907	1099	1357	1665
Zirconium	3020	3301	3634	4014	4458			6471

Table 6 - Part 2

Understanding Vacuum and Vacuum Measurement

processed in vacuum. However, chromium that is present in these materials will evaporate noticeably at temperatures and pressures within normal heat treating ranges.

Chromium will begin to vaporize at approximately 1815° F and a vacuum of 1×10^{-4} Torr when parts are held for an extended time. To avoid this, again the furnace should be operated in a partial pressure in the 0.5 Torr to 5.0 Torr range.

Gas Correction Factors For Vacuum Gauges

Vacuum gauges are very sensitive to the type of gas being used for partial pressure. The reading on the gauge must be adjusted per the following studies that have been made for the various gauge types.

Thermocouple Gauges

The thermocouple gauge is typically very inaccurate when reading partial pressure gas levels above 1-2 Torr for different gasses. This is illustrated in Figure 12 below.

The T/C vacuum gauge used in the Figure 12 studies was a Granville Phillips Convectron gauge. Table 7 shows the true readings of the partial pressure gas versus the thermocouple gauge reading. This chart is based on actual testing results and can be used to provide the true readings at the various vacuum levels and can be used as guidance in actual operation.

Ionization Gauges

The values in Table 8 are the gas correction factors for various gases with respect to nitrogen for both hot cathode and cold cathode ionization vacuum gauges.

In a gauge calibrated for nitrogen, where the predominant gas being measured is other than nitrogen, divide the actual gauge reading by the appropriate gas correction factor to get the corrected pressure value for the specific gas. These are relative correction factors to be used in the high vacuum range of ionization gauges.

As shown in Table 8, helium is the most sensitive of the listed gasses and thus becomes very useful during leak checking of vacuum furnaces. Spraying a small amount of helium around a potential leaking area will be reflected quickly on the vacuum gauge should there be a problem.

Nominal relative sensitivity factors cannot be relied upon for accurate measurements since they are known to vary significantly between seemingly identical gauges and even more for different gauge types, filament materials, and operating potentials.

For general vacuum use, the discrepancy in reported measurements is not greater than 10% for the common gases, rising to a little above 20% for the less common gases, where less accurate information is available. Relative sensitivities are pressure dependent and become particularly unreliable above 10^{-5} Torr. Where greater precision is required, gauges must be calibrated individually against the specific gasses and under conditions as close as possible to the operating conditions of the vacuum system.²¹



Figure 12 - Gas Species Effect on T/C-Type Vacuum Gauges

T/C Gauge Readings Vs True Partial Pressure						
T/C Gauge Read- ing	True Nitrogen PP Gas Vacuum Level	True Argon PP Gas Vacuum Level	True Hydrogen PP Gas Vacuum Level			
1 x 10 ⁻¹ Torr	1 x 10 ⁻¹ Torr	1.4 x 10 ⁻¹ Torr	6 x 10 ⁻² Torr			
1 Torr	1 Torr	1.9 Torr	6 x 10 ⁻¹ Torr			
5 Torr	5 Torr	20 Torr	1.4 Torr			
10 Torr	10 Torr	400 Torr	1.8 Torr			
20 Torr	20 Torr	800 Torr	2 Torr			

Table 7

Gas Correction Factors for Ionization Gauges Relative to N₂

	Partial Pressure Gas	Symbol	Corrective Factor Relative to Nitrogen
	Nitrogen	N ₂	1.00
,	Air		1.00
	Helium	He	0.18
	Hydrogen	H ₂	0.46
	Argon	Ar	1.29
1		Table 9	

Table 8

Understanding Vacuum and Vacuum Measurement

Conclusions and Summation

This paper provided a better understanding of vacuum, the types of instruments that record and monitor vacuum levels, and how these devices relate to vacuum furnace operation.

- Measuring vacuum is a very complex subject requiring a good understanding of the best instrumentation available for the application.
- Vacuum instruments are very sensitive to the pressures being measured and to any contaminating particles that might be present within the chamber being measured.
- The type of partial pressure gas used to establish safe operating pressure can seriously affect the vacuum gauge reading if not properly referenced for accurate reading.
- Vacuum gauges must be properly calibrated periodically to maintain accuracy and prior to processing critical furnace cycles.
- Vapor pressures of materials are a serious consideration when establishing proper partial pressure operating levels.
- Thermocouple vacuum gauge readings vary significantly when measuring different partial pressure gasses above 1 Torr levels of vacuum.

References:

- 1 https://en.wikipedia.org/wiki/Vacuum
- 2 www.avs.org/AVS/files/c7/c7862e0a-c90e-428f-ab08-2651655b0f1a.pdf
- 3 http://hyperphysics.phyastr.gsu.edu/hbase/kinetic/menfre.html
- $4-http://instrumentation and controllers. blogs pot.com/2010/10/elastic-diaphragm-gauges. html \label{eq:controllers} with the second second$
- 5 https://en.wikipedia.org/wiki/Pressure_measurement
- 6-http://www.vizgep.bme.hu/letoltesek/targyak/BMEGEVGAG02-ENG/Measuring%20 devices.pdf
- 7 http://people.rit.edu/vwlsps/LabTech/Gauges.pdf (section 7.4)
- $8-https://en.wikipedia.org/wiki/McLeod_gauge$
- $9-http://physics.kenyon.edu/EarlyApparatus/Pneumatics/McLeod_Gauge/McLeod_Gauge.html$
- 10 http://encyclopedia2.thefreedictionary.com/mcleod+gauge
- 11 http://www.omega.com/literature/transactions/volume3/high3.html
- $12 \ \ http://www.mksinst.com/product/Product.aspx?ProductID=1426$
- 13 http://saba.kntu.ac.ir/eecd/ecourses/instrumentation/projects/reports/Vaccum/report/theory/pirani.htm
- 14 http://www.pchemlabs.com/product.asp?pid=1658
- 15 http://nau.edu/cefns/labs/electron-microprobe/glg-510-class-notes/instrumentation/
- 16 https://en.wikipedia.org/wiki/Hot-filament_ionization_gauge
- 17 http://thinksrs.com/downloads/PDFs/Manuals/igc100mApp.pdf (section A-4)
- 18 https://en.wikipedia.org/wiki/Cold_cathode
- 19 https://en.wikipedia.org/wiki/Pressure_measurement#Cold_cathode
- 20 http://www.britannica.com/technology/vacuum-technology
- 21 http://www.thinksrs.com/downloads/PDFs/ApplicationNotes/IG1BAgasapp.pdf

Additional References:

- Vacuum History and Technology McAllister Technical Services
- Understanding Vacuum Measurements Howard Twing
- Vacuum Heat Treatment Daniel H. Herring

Eastern Pennsylvania 1969 Clearview Road, Souderton, PA 18964 p. 800.347.3236

Western Pennsylvania 30 Industrial Road, Hermitage, PA 16148 p. 866.982.0660

California 8606 Live Oak Avenue, Fontana, CA 92335 p. 866.559.5994

South Carolina 108 Progressive Court, Greenville, SC 29611 p. 864.970.0111



www.solaratm.com



1983 Clearview Road, Souderton, PA 18964 p. 267.384.5040 www.solarmfg.com