LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-BOOK-207375

# Vacuum Technology

P. J. Biltoft

October 20, 2004

Semiconductor Manufacturing Handbbook, 1 edition

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

**Chapter 15**
**Vacuum Technology**

**Pete Biltoft**
**Lawrence Livermore National Laboratory**
**Livermore, California**

## 15.1 Vacuum Technology Overview

- What is vacuum?
  The environmental condition called vacuum is created any time the pressure of a gas is reduced compared to atmospheric pressure. On earth we typically create a vacuum by connecting a pump capable of moving gas to a relatively leak free vessel. Through operation of the gas pump the number of gas molecules per unit volume is decreased within the vessel. As soon as one creates a vacuum natural forces (in this case entropy) work to restore equilibrium pressure; the practical effect of this is that gas molecules attempt to enter the evacuated space by any means possible. It is useful to think of vacuum in terms of a gas at a pressure below atmospheric pressure. In even the best vacuum vessels ever created there are approximately 3,500,000 molecules of gas per cubic meter of volume remaining inside the vessel. The lowest pressure environment known is in interstellar space where there are approximately four molecules of gas per cubic meter.
  -
- A Very Brief History of Vacuum technology
  The recorded history of vacuum dates back to 150 BC. Hero of Alexandria wrote *Pneumatias*[1] in which the function of siphons and pumps were discussed. Advances in the basic understanding of the behavior of gases took place in Europe between AD 1500 and 1800. Notably, Galileo Galilei studied the function of pumps, Evangelista Torricelli studied both pressure gauges (the barometer) and gas pumps and Otto von Guericke produced pumps specifically designed for creating vacuum. Englishman Robert Boyle published his scientific findings on the behavior of gases as a function of pressure. Devices invented between 1800 and 1900 such as the light bulb, X-ray tube and cathode ray tube required reliable methods for producing, measuring and maintaining vacuum and provided the motivation for development of better vacuum equipment. As early as 1936 vacuum tube integrated circuits were built. The growing electronics industry, the Manhattan Project, and exploration of outer space provided the drive for many of the advancements in vacuum technology made between 1930's and today including development of the turbomolecular pump, the ion pump and the partial pressure analyzer.
- The Composition of Atmospheric Gases
  The air we breathe is composed of approximately 78% nitrogen and 20.1% oxygen, the balance being argon, carbon dioxide, water vapor and other trance gases. Dalton's law of partial pressure describes the relationship between the total pressure and the partial pressures of gases in a gaseous mixture.

---
[1] Source: www.avs.org/information/timeline.pdf

$$P_{tot} = \sum_{1}^{i} P_i$$

where

$P_{tot} =$ total pressure of all gases in the mixture

$P_i =$ partial pressure of gas $i$

At sea level the approximate pressure of atmosphere exerts on all surfaces it contacts is 14.7 pounds per square inch (psi). Other units of measurement used include the Torr, mBar, and Pascal (Pa). Unit conversion calculators for pressure are available on the following website: http://www.avs.org/

Table 1 Atmospheric pressure expressed in a set of units

| psi | Torr | mBar | Pa | Kg/cm^3 | inches of Hg |
|---|---|---|---|---|---|
| 14.7 | 760 | 1013 | 101,300 | 1.033 | 29.92 |

- Typical applications of Vacuum technology
  Vacuum technology is essential to the micro-electronics industry as many of the processes involved in the fabrication of micro circuits require a controlled environment in which thin films can be deposited with minimal interference from atmospheric gas molecules. Other industries that rely on vacuum technology include the food processing and pharmecetical industries (products are freeze dried under vacuum).

**15.2 Methods For Measuring Sub-Atmospheric Pressure**

15.2.1 Force displacement gauges

These pressure gauges rely upon the physical displacement of a solid or liquid surface by an applied pressure as a means to measure the magnitude of the applied pressure. This family of pressure gauges will give an accurate reading of pressure within their range of operation for all gases independent of the composition of the gas. As such these gauges are referred to as being *gas species insensitive*.

- Liquid level barometer
  One of the earliest pressure gauges developed, the water barometer and later the mercury barometer were used to measure the pressure of the earth's atmosphere. Early barometers were made by filling an long glass tube open at only one end (the tube being approximately 33 feet long if water was the fluid being used and ~ 30 inches long for mercury), capping the open end of the tube, inverting the tube and placing the capped end under the surface of the same liquid used to fill the tube in a secondary container and then removing the cap. The column of liquid inside the inverted tube would drop under the force of gravity until the pressure on the top surface of the liquid in the secondary container was equal to the gravitational load of the column of liquid in the inverted tube. As external atmospheric pressure changed, the height of the supported column of liquid in the barometer would be observed to change. A reproduction of the barometers made in the 1600's is shown on the following website:http://www.barometers.com/torricel.htm

Measurement of pressure by this method is accurate only to approximately +/- 1 Torr.

- U-Tube manometer
  Developed following the liquid barometer the U tube manometer allows one to measure pressure in two vessels or between a vessel and atmospheric pressure. The difference in height of liquid in the U-tube's two columns provides a direct reading of the pressure difference in the two sides of the U-tube. Measurement of pressure by this method is accurate only to approximately +/- 1 Torr.
- McLeod Gauge
  The McLeod gauge was developed to extend the range of pressures that could be measured using liquid displacement gauges. In this device, a known volume of gas is isolated from the vacuum vessel under study by tipping the McLeod gauge such that liquid mercury traps the gas in a bulb of known volume. As the McLeod gauge is turned upright the trapped gas in compressed a known amount and the pressure of the compressed gas is measured by comparing levels of mercury in the tubes of the device and applying Boyles law ($P_1 x V_1 = P_2 x V_2$). Pressure readings using a McLeod gauge can be accurate to pressures as low as $10^{-7}$ Torr
- Bourdon Tube Gauge
  This gauge design uses the elastic deformation of a thin-walled formed metal tube to sense pressure and display on a circular dial. The sensing element is not unlike a popular party favor that unravels as one exhales into the mouthpiece. The interior of the Bourdon tube is connected to the interior volume of a vacuum vessel; as pressure in the vessel increases the Bourdon tube responds by elastically deforming; this motion is translated into rotation of a dial indicator on the gauge face.
- Diaphragm gauge
  This gauge design utilizes the elastic deformation of a diaphragm to measure pressure. As the pressure inside the gauge tube is reduced, the diaphragm is elastically deformed; this deformation is translated via an electrical signal or mechanical mechanism to a pressure reading. Gauges of this type typically can read pressure from atmospheric down to 1 Torr.

### 15.2.2 Capacitance Manometers

The capacitance manometer gauge contains a diaphragm that is elastically deformed as pressure in the gauge tube changes. This diaphragm is one electrode of a capacitor, and as the diaphragm is displaced relative to a fixed electrode the capacitance of the assembly changes yielding an electrical signal that can be used to infer pressure. These gauges are referred to as being *gas species insensitive*. Capacitance manometers are typically manufactured to accurately measure pressure across a span of 3 to 4 decades below the rated pressure. For example, a 1000 Torr capacitance manometer can typically read pressures as low as 0.5 Torr with an accuracy of +/- 0.25%. Additional accuracy can be obtained if the gauge is equipped for temperature stabilization.

### 15.2.3 Thermal transfer gauges

The property of thermal conductivity of a gas is utilized in this family of gauges to infer the pressure of the gas being measured. The thermal conductivity of a gas is a function of its molecular weight and other gas characteristics, therefore pressure gauges based on thermal conductivity must be calibrated for the gas of interest. These gauges are referred to as being *gas species sensitive*.

- Thermocouple gauge
  This gauge uses a thermocouple junction to measure the temperature of a wire heated by an applied constant electric current which is exposed to the environment of the vacuum vessel interior. As pressure is reduced in the thermocouple gauge tube interior fewer gas molecules per unit time are available to remove heat from the thermocouple gauge heated filament. The temperature rise in the filament of the gauge tube is sensed by the thermocouple; this signal is sent to the gauge controller that computes the corresponding pressure based upon an algorithm in the controller for a specified gas.
- Pirani gauge
  The Pirani gauge uses two heated electrodes, each made from platinum to sense pressure inside the gauge tube. One of the electrodes is the reference and is encapsulated in an evacuated glass tube, the other electrode is the sensor and is enclosed in a similar glass envelope that is open to the interior of the Pirani gauge tube volume. These two electrodes are connected to a Wheatstone bridge circuit. As pressure in the Pirani gauge tube is decreased, the temperature of the sensor filament increases due to fewer collisions with gas molecules. The electrometer in the Wheatstone bridge circuit senses the change in resistance of the sensor filament and increases current to that leg of the circuit to maintain current balance in the Wheatstone bridge. The current applied to the sensor filament is used as to infer pressure. Typical operating range for a Pirani gauge is from approximately 1 Torr down to $10^{-5}$ Torr.
- Convection-enhanced Pirani Gauge
  In this gauge technology the range of a typical Pirani gauge is extended by adding a resistively heated coil that creates an environment in which induced convection occurs in the viscous flow regime. Under these conditions the range of operation of the gauge is from atmospheric pressure down to approximately 1 mTorr.

15.2.4 ionization gauges

Gauges that infer pressure from ionization events are *gas specie sensitive.*

- Hot Cathode ionization Gauge
  The basic hot cathode ionization gauge has three electrodes: an electron emitter (often referred to as the filament), an electron collector (referred to as the grid) and the ion collector (referred to as the cathode). Following evacuation of the internal volume of the hot cathode ionization gauge tube to a pressure of less than $10^{-4}$ Torr current is provided by the gauge controller to the filament which becomes heated to a temperature of approximately 2000 C. At this operating temperature the tungsten or thoria coated iridium filament glows white hot and emits electrons. These electrons are electrostatically attracted to the electron collector that has a positive bias of approximately 150 to 180 V DC. Enroute to the electron

collector these electrons are likely to collide with neutral gas molecules inside the gauge tube body; these collisions often result in the ejection of an electron (or two) from the gas molecule resulting in the creation of ionized gas molecules. These ionized gas molecules are electrostatically attracted to the ion collector by a bias applied to the collector by the gauge controller. As ionized molecules impinge upon the ion collector, they extract an electron to become neutral once again. This extracted current (ion current) is used to infer pressure. Two factors that influence the observed reading for a specific gas specie are the physical size of the gas molecule (cross section) and its ionization potential.

- Cold Cathode ionization Gauges
  As with the hot cathode ionization gauge described above the cold cathode gauge must be internally evacuated to a pressure of less than $10^{-4}$ Torr prior to operation. In the cold cathode gauge a high voltage (up to approximately +6 kV) is applied the anode inside the gauge. This bias causes spontaneous electron emission from the cathode inside the cold cathode gauge tube body. These electrons traversing the space between the anode and cathode can strike neutral gas molecules and may create gas-phase ions. These ions will move under the applied bias towards the cathode. Once the ions impact the cathode they will extract an electron and result in a net ion current that may be used to infer pressure inside the gauge tube. Often a strong permanent magnet is placed outside the cold cathode gauge tube body to cause the electrons to travel in a helical path thus increasing the probability of an impact with a gas phase molecule. A variety of designs for cold cathode gauge tubes are commercially available including an inverted magnetron design.

15.2.5 Partial Pressure measurement

It is often useful to know not only the total pressure of gases remaining in a vacuum vessel after evacuation, but to also know the composition of the gas mixture and the relative amounts of each gas specie in the mixture. Partial pressure analysis (PPA) also known as Residual gas analysis (RGA) is the method used to obtain this kind of information. Most commercial partial pressure analyzers have three functional components: an ionizer, a mass selector and a detector. In the ionizer neutral gas molecules that randomly enter the detector inlet are bombarded with energetic electrons that have sufficient energy to ionize the gas molecules. In addition to ionizing the energetic electrons may break the gas molecules into fragments consisting of one or more of the atoms in the original molecule. Thes fragments are often also ionized. All of the gas phase ions created in the ionizer are electrostatically attracted to the mass selector by an applied electric field. Based upon the mass and charge (single or multiple) on the ion its trajectory through the magnetic field of the mass selector will determine if the ion completes its journey all the way to the charged particle detector to be counted. ions that reach the detector extract one or more electrons at the detector thus creating a current that is a function of the number and charge (single or multiple) of the ions impacting the detector. In practice the control system for the partial pressure analyzer (PPA) creates a set of operating conditions (accelerating voltage for the ions entering the mass selector and magnetic field strength of the mass selector) such that at any one time only one mass to charge ratio (M/z) is allowed to pass through the mass selector and continue to the detector to be counted. ions having a M/z other than the value prescribed by the mass selector are neutralized or otherwise prevented from being counted by the detector. After a signal for a specified M/z has been collected the controller will adjust the operating parameters of the PPA for another M/z and will collect data for ions having this new M/z. In this manner the PPA scans through a range of M/z and records data for each ionized gas species. The Data from the PPA is typically plotted as detector current as a function M/z.

## 15.3 Methods for Creating a Vacuum

15.3.1 Primary Vacuum Pumps

These pumps are used for reducing pressure in a vacuum vessel from an initial state of atmospheric pressure (760 Torr) to a reduced pressure (typically in the range of 10 mTorr). The principles of operation and operating ranges for a variety of commercially-available pups are covered in the following subsections.

- Oil Sealed Rotary Vane mechanical Pumps

  These pumps move gases by isolating a small volume of gas from the vacuum system, compressing this isolated volume to atmospheric pressure and then exhausting this gas to the atmosphere. The mechanisms of the oil sealed rotary vane pump include: a rotor with sliding vanes, a stator, inlet and exhaust ports a means for rotating the stator and the pump oil. In operation the rotor, which is smaller in diameter than the bore of the stator and offset concentrically from the stator bore is caused to rotate by the drive mechanism. As the rotor spins within the stator the sliding vanes maintain intimate contact with the inside surface of the rotor. As a sliding vane passes by the pump's inlet orifice which connects to the bore of the stator a crescent shaped volume of increasing size is created by the surfaces of the rotor, stator and sliding vane. The oil serves to help create a seal between the rotor, stator and sliding vane. As the rotor continues to rotate the next sliding vane passes by the pump inlet port; as this happens the gas which has expanded into the crescent-shaped volume is isolated from the vacuum system. Continued rotation of the rotor causes the crescent shaped volume to reduce in size thus compressing the isolated gas. Compression continues until the pressure is just above atmospheric pressure and through an exhaust valve and port the compressed gas is released to the atmosphere. Each rotation of the rotor continues to isolate, compress and exhaust gas in this manner to reduce pressure at the inlet of the pump. The oil in pumps of this type in addition to forming a tight seal serves to remove the heat generated by compression of gas, to lubricate the sliding surfaces of the pump and to help remove wear particles and other debris during maintenance cycles.
- Dry Pumps
  - Diaphragm Pumps

    In these pumps a diaphragm (usually made from thin stainless steel or polymer sheet) is flexed by the rocking motion of a eccentric connecting rod and rotating shaft. The motion of the diaphragm opens an inlet port, isolates a volume of gas, compresses the gas and then expels this gas to the atmosphere. These pumps are available as multiple stage units that can attain pressures as low as 1 Torr. Diaphragm pumps are well suited for intermittent use applications and can be oil-free.
  - Scroll Pumps

In this pump design there are two interleaved helical scrolls: one that is stationary and one that moves in a circular oscillation relative to the stationary scroll. During each oscillation of the moving scroll a crescent-shaped volume is created at a port connected to the pump inlet. As oscillation of the moving scroll continues the crescent shaped volume increases in size thus locally reducing pressure and gas flows into this volume from the pump inlet. With further travel of the oscillating scroll the volume of gas drawn into the crescent-shaped volume is isolated from the pump inlet and is compressed. In the last stage of the pump cycle the size of the crescent shaped volume is reduced, compressing the gas to slightly above atmospheric pressure and the gas is exhausted through a spring loaded valve. Scroll pumps use no lubricant in the swept volume and are well suited for use in primary evacuation of vacuum vessels and load vacuum locks.

- Screw Pumps

The concept of moving fluids using a screw mechanism dates back over 2000 years and is attributed to Archimedes. In the modern implementation of this design for vacuum applications two parallel counter-rotating close tolerance screws are fitted within a stator housing. As the screws rotate at approximately 6000 RPM gas is drawn into the pump inlet and forced along the axis of the pump by the screw threads. Most of the compression occurs at the exhaust end of the pump and gas temperatures can rise to 300 C. The screws of these pumps are often coated with Teflon (PTFE) to reduce friction and to protect the base metal of the pump internal components from chemical attack by the gases being pumped. Screw pumps are used for primary evacuation of a vessel from atmospheric pressure to a base pressure of approximately 10 mTorr.

- Sorption Pumps

Sorption pumps remove gases from a vacuum vessel by cryo-sorption and cryo-condensation. These pumps typically consist of an aluminum cylinder internally filled sorbent such as zeolite. The exterior of the pump body is cooled to below room temperature often through immersion in a cryogenic fluid such as liquid nitrogen. The cooled sorbent material will cryo-condense gases that have a boiling point above that of liquid nitrogen; other gases are cryo-sorbed onto the very fine pore structure of the zeolite. In either case, the gas molecules entering the cryosorption pump are effectively removed from the vacuum vessel thus reducing pressure in the vessel. Gases not efficiently pumped using a cryo-sorption pump are helium, hydrogen and neon. Sorption pumps are used for primary evacuation of a vessel from atmospheric pressure to a base pressure of approximately 100 mTorr.

15.3.2 Secondary Vacuum Pumps

Secondary vacuum pumps are used to further reduce pressure in a vacuum vessel following the primary evacuation from 760 Torr to approximately 10 mTorr. Secondary vacuum pumps if operated correctly can routinely achieve pressures in the range of $10^{-8}$ Torr and with extra care and good vessel design pressures as low as $10^{-11}$ Torr.

- Momentum Transfer Pumps

Momentum transfer vacuum pumps reduce pressure in a vacuum vessel by compressing gas and expelling it to the inlet of a primary vacuum pump which further compresses the gas and expels it to the atmosphere. During operation momentum transfer pumps require the pressure at their exhaust port (also called the foreline) to be maintained at a pressure below their *critical foreline pressure*. The value of the critical foreline pressure is a function of pump design; manufacturers clearly state the value of the critical foreline pressure for each pump in the published specifications.

- Oil Vapor Diffusion Pumps

In the oil vapor diffusion pump a supersonic speed jet of vapor is created by controlled boiling of the pump fluid inside the pump body. The oil vapor rising up the internal stack of the diffusion pump body is forced out of jets that are directed downwards and towards the inner surface of the water-cooled pump body. Gas molecules that randomly enter the diffusion pump inlet are intercepted by the high speed oil vapor jet. This collision with a high speed and relatively high molecular weight oil vapor molecule produces a net downward trajectory for the gas molecule impacted. Through the use of multiple stages of jets gas molecules are compressed and forced to the foreline port of the diffusion pump. At the foreline sufficient pumping speed applied by the primary roughing pump (in this case functioning as the foreline pump) causes the gas ejected from the diffusion pump foreline to be compressed and expelled to the atmosphere. Often a liquid nitrogen cold trap is installed at the inlet of the diffusion pump to reduce the amount of pump oil that can migrate from the diffusion pump into the vacuum vessel. The operating range of most commercial diffusion pumps is from $10^{-4}$ Torr to $10^{-10}$ Torr.

- Turbomolecular Pumps

In Turbomolecular vacuum pumps the random trajectory of gas molecules entering the pump inlet is influenced by the high velocity surfaces of the rotating turbine blades. Gas molecules impacted by the blades stay on the surface of the blades for a brief period called the *residence time*. During this period gas molecules lose any directional identity they had and assume the trajectory of the blade (not unlike a bug interacting with the windshield of a car traveling at 60 miles per hour!). At the end of the residence time gas molecules leave the surface of the turbine blade following the *Cosine Law*. According to this law, gas molecules are most likely to leave a surface in a direction normal to the plane of the surface and are least likely to follow a trajectory parallel to the surface. The combination of these two effects cause gas molecules to be forced from the inlet of the turbomolecular pump to the exhaust. Most modern turbomolecular pumps are of the axial flow design, which bears similarity to the engines on commercial jet aircraft. The rotors of most turbomolecular vacuum pumps are precision machined and carefully balanced for operation at rotational velocities ranging from 30,000 to 90,000 RPM depending on the pump size and model. Rotors of turbo pumps often are designed with several "stages". At the inlet of the pump the rotor blades are wide, have a steep pitch and form a relatively open blade structure. This design is optimized for high pumping speed at the pump inlet with relatively modest compression. At the middle of the rotor, blades are often more closely spaced, and the pitch of the blades is reduced compared with blades at the inlet. At the output or exhaust of the turbo pump the blades are very closely spaced and the pitch of the blades is optimized to achieve high compression of gas and relatively modest pumping speed. The critical foreline pressure of may turbomolecular pumps is approximately 100 mTorr. A suitable foreline pump is required for proper operation of a turbo pump. Some turbo pumps have an integrated molecular drag stage that further compresses the gas before exhausting it to the foreline of the pump. These hybrid pumps are often called "turbo-Drag" pumps. The critical foreline pressure of many commercial turbo-drag pumps can be as high as 1 Torr, allowing for evacuation of the foreline by a diaphragm pump. In either design care should be taken to prevent objects from entering the inlet of a turbo pump during operation. Were this to occur, almost certainly the pump would be damaged, and in some cases a hazard to personnel would be created.

- Gas Capture Pumps

Unlike the momentum transfer pumps discussed previously, gas capture pumps reduce pressure in a vacuum vessel by removing gas molecules from the gas phase. In cryogenic pumps gas molecules are *cryo-condensed* or *cryo-sorbed*, while in sputter-ion pumps gas molecules are chemically reacted to form solid by-products or are otherwise immobilized.

- Cryogenic Vacuum Pumps

There are generally two types mechanisms used in cryogenic vacuum pumps: direct cooling via the use of cryogenic liquids or cooling by a mechanical compressor. One of the oldest cryogenic pump designs is the *Meissner Coil*. In this design a helical coiled tube (usually copper) is placed inside the vacuum vessel, both ends of the helical coil pass through and are tightly sealed to a flange attached to the vacuum vessel. After primary evacuation of the vacuum vessel to a pressure of approximately 100 mTorr, liquid nitrogen is flowed through the inside of the copper coil. Gas molecules randomly striking the cooled surface of the Meissner coil will be cryo-condensed if the gas specie has a boiling point above that of liquid nitrogen. Gas species with boiling points below that of liquid nitrogen will be removed from the gas phase for a *residence time* which is a function of the temperature of the Meissner coil and the molecular weight of the gas specie.

- Sputter ion pumps

These pumps reduce the pressure inside a vacuum vessel by removing molecules from the gas phase. There are three methods by which sputter-ion pumps remove gas molecules from a vacuum vessel: gettering, ion burial and physical burial. Gettering is a chemical process in which a gas molecule reacts with an active metal to form a solid product. In most sputter ion pumps the active metal that is utilized is titanium. During operation of the sputter ion pump a thin film of titanium is deposited onto the internal surfaces of the pump. Titanium is a chemically reactive metal that will readily react with atmospheric gases to form stable solid compounds such as titanium dioxide, titanium hydride and titanium nitride. In addition to gettering sputter ion pumps can also remove noble gases such as helium, neon, argon, krypton, Xenon and radon. These gases tend not to from chemical compounds with reactive metals. During operation of the sputter ion pump all gases, including the noble gases may be ionize by the electrons traversing the space between the cathode and anode. If a collision between an electron and a gas molecule occurs the gas molecule may become ionized. This ionized gas molecule will then move under the applied electric field of the pump towards the cathode. Upon impact with the cathode the ion will lose its electric charge and

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

may have sufficient kinetic energy to become implanted within the bulk of the cathode. This process is called ion implantation. It should be noted that as pump operation continues the exposed surface of the cathode will continue to be eroded and some of the implanted gas molecules may be liberated. The last process by which sputter ion pumps can remove molecules from the gas phase is called physical burial. In this process gas molecules that land on the internal surfaces of the sputter ion pump body and remail on that surface for a residence time may be overcoated with titanium.

## 15.4 Vacuum System Components

- Flanges with Demountable Seals

Components such as vacuum pumps, pressure gauges and virtually every component of a vacuum system are typically connected to a vacuum vessel using a flange system incorporating some type of demountable seal. These joints are made up using mechanical devices such as threaded fasteners or clamps and form a relatively leak-tight seal that allows the vacuum system to achive its design base pressure. The seals used may be polymeric (O-rings) or metallic.

- Valves

Valves serve to control the flow of gas into or out of a vacuum vessel. While some vacuum systems are constructed without valves for simplicity, robustness or cost savings, most vacuum systems employ several types of valves. Isolation valves are generally placed between the primary roughing pump inlet and the vacuum vessel as well as between the inlet of a secondary vacuum pump and the vacuum vessel. If a process gas is used injected into a vacuum system a metering valve is often used to control the flow rate. either the flow rate or the pressure based upon feedback from a pressure gauge and flow controller. .

- Feedthroughs

Feedthroughs allow for the transmission of mechanical motion, radiation or fluids into or out of vacuum vessels. Mechancial feedthoughs allow us to manipulate objects inside a vacuum system under vacuum; examples of this are the multiple axis stages of electron microscopes that allow simultaneous tip, tilt translation and rotation of a sample under study. Viewports on a vacuum system are a type of optical feedthough. Viewports permit us to observe the vacuum environment inside a vessel or to transmit radiation such as a beam of laser light generated outside the vessel to the vessel interior while the vessel is evacuated. Electrical feedthroughs permit the transmission of electrical power into an evacuated vessel for the operation of devices such as deposition sources and detectors. Electrical feedthroughs also are used for transmission of data such as the signal from a thermocouple located inside an evacuated vessel to an electronics package located outside the vacuum vessel.

## 15.5 Leak Detection

15.5.1 Techniques for Locating and Quantifying Large Leaks

15.5.2 Rate of Rise test

This test measures the combined effects of gas loads to a vacuum system from outgassing sources internal to the vacuum system, gas loads due to permeation though vacuum seals and leaks in the vacuum system. To measure the rate of rise one typically evacuates a vacuum vessel to its base pressure, isolates the vacuum pump from the vessel, and records the pressure as a function of time. If a leak is present the rate of change in pressure is linear with time. If outgassing is the major source of gas load to the system the pressure will rise and eventually stabilize at the equilibrium vapor pressure for the materials internal to the vacuum system.

- 

15.5.3 Techniques for Locating and Quantifying Small Leaks

- Ultrasonic leak Detection

In this technique a microphone sensitive to the sound in the ultrasonic range is used to survey the external surfaces of an evacuated vacuum vessel. Leaks present may generate sound in the ultrasonic range that the microphone can detect.

- Helium Mass Spectrometer Leak Detector (HMSLD)

A mass spectrometer tuned to detect only helium gas is used to precisely locate leak paths in vacuum vessels. Helium is used as the tracer gas as it is in low abundance in the atmosphere, relatively inexpensive, non-toxic, non-flammable and has a high average velocity relative to other gas molecules in the atmosphere.

There are two modes of operation for a HMSLD: tracer probe and sniffer probe. In the tracer probe method the HMSLD is connected to an evacuated vessel at a pressure of less than $10^{-4}$ Torr. The point of connection of the HMSLD to the vessel may be at a port of the vessel or the foreline of a secondary vacuum pump. Helium gas is carefully applied using a wand to locations on the external surface of the vessel where leaks are suspected. Helium gas entering the vacuum vessel through a leak will likely be detected in the HMSLD, which will give a visual or auditory signal to the operator. As an alternative to using a probe to search for leaks as described, one may enclose the vessel in a plastic bag and flood the bag with helium. This method will test all of the vacuum system that is enclosed in the plastic bag at once.

## 15.6 Design of a Vacuum System

15.6.1 Flow Modes for gases

For the following discussion it is assumed the gas being pumped is atmospheric in composition (approximately 79% nitrogen and 19% oxygen, the balance being trace gases), the conductance elements through which the gases flow is circular in cross section and the internal surfaces of these conductance elements are relatively smooth. Gases move under the influence of pressure differentials As a vacuum pump operates it creates a reduced pressure environment at its orifice; gas molecules in a vacuum vessel connected to the pump by a conductance element move almost instantaneously to equilibrate pressure within their confined environment. Some resistance to flow of the gas molecules is provided by the conductance element(s). At near atmospheric pressure the flow of gases is well described by viscous flow. Viscous flow may be further broken down into turbulent flow and laminar flow. In turbulent flow the motion of gas molecules is characterized by disorganized eddies and currents not unlike a raging river rapids. Once pressure is further reduced gas flow shifts to laminar which is like that see in wind tunnels: orderly flow of gases in sheets. Further reduction in pressure results in a transition between viscous flow and molecular flow. Once the mean free path of molecules is approximately the same length as the inside diameter of the conductance element the trajectory of molecules is more strongly influenced by the inner walls of the vacuum vessel than by other gas molecules. The mean free path is the length on average a gas molecule travels between collisions with other gas molecules. For air, the mean free path is a function of pressure and is given by:

$$\lambda = \frac{5 \times 10^{-3}}{P}$$

where

$\lambda =$ mean free path [cm]

$P =$ pressure [Torr]

In molecular flow gas molecules travel in straight lines between collisions and their motion tends not to be influenced by pressure differentials.

### 15.6.2 Conductance of gases Through Tubes and Orifices

In the viscous flow regime conductance of gases is a function of the length and diameter of the conductance element as well as the average pressure of the gas in the element.

$$C = \frac{3000\overline{P}D^4}{L}$$

Where:

$C =$ conductance [l/s]

$\overline{P} =$ average pressure [Torr]

$D =$ inside diameter of conductance element [inches]

$L =$ length of conductance element [inches]

In the transition flow regime the conductance of gases is given by:

$$C = \frac{3000\overline{P}D^4 + 80D^3}{L}$$

and in the molecular flow regime the conductance of a straight tube is given by:

$$C = \frac{80D^3}{L}$$

Often conductance elements of different diameters are connected in series; the total conductance of a series connection of conductance elements is given by:

$$C_{tot} = \sum_{1}^{n} \frac{1}{C_n}$$

where

$C_{tot} =$ total conductance [l/s]

$C_n =$ conductance of element n [l/s]

$n =$ number of conductance elements

### 15.6.3 Delivered Pumping Speed

Conductance elements impede the flow of gas from a vessel to a pump and therefore reduce the effective (delivered) pumping speed. The delivered pumping speed is a function of the speed at the pump inlet and the total conductance of the conductance elements connecting the vacuum pump to the vessel.

$$\frac{1}{S_t} = \frac{1}{S_p} + \frac{1}{C_{tot}}$$

where

$S_t =$ delivered pumping speed [l/s]

$S_p =$ speed at vacuum pump inlet [l/s]

15.6.4 Time Required for Primary Evacuation of a Vacuum Vessel

The elapsed time required to evacuate a vacuum vessel from an initial pressure (generally 740 Torr) to a lower pressure (usually near the base pressure of a primary vacuum pump, approximately 10 mTorr) is given by:

$$t = \frac{V}{S_t} \ln(\frac{P_1}{P_2})$$

where

$t =$ time [s]

$V =$ vessel volume [l]

$P_1 =$ initial pressure [Torr]

$P_2 =$ final pressure [Torr]

15.6.5 Calculation of Base Pressure for a Vacuum System

Following primary evacuation of a vacuum vessel the primary pump is isolated from the vessel and the secondary pump is used to further reduce pressure in the vessel. The time required to reach the base pressure of the vessel by the secondary vacuum pump is a strong function of the internal environment of the vessel. Outgassing from components internal to the vacuum vessel, permeation of gases through the vessel walls and leaks all contribute significantly to the gas load the secondary pump works to remove from the vacuum vessel. At the base pressure an equilibrium is established between the delivered pumping speed of the secondary vacuum pump and the total gas loads as described above.

$$Q = S_t \times P$$

where

$Q =$ total gas load [Torr•liters/s]

- Outgassing

  Outgassing is the spontaneous vaporization of materials that is commonly observed in a vacuum vessel. The rate at which materials outgas tends to be a strong function of the material composition and the temperature of the material. Tables of outgassing rates for a wide variety of materials used in vacuum are available in the books listed in the references. Materials to avoid placing inside vacuum vessels intended to achieve pressures below $10^{-5}$ Torr include: high vapor pressure fluids (water, common hydrocarbon oils), and any solid materials that have a detectable smell (you can smell these materials because they have a high vapor pressure!). To achieve pressures below 10-7 Torr the following additional materials should be excluded from the internal volume of a vacuum vessel if possible: polymers such as polyvinyl chloride (PVC), high vapor pressure metal such as zinc, cadmium, mercury and lead.

To calculate the outgassing load for a given material one must know the outgassing rate (at the temperature it will experience inside the vacuum vessel) and the amount of surface area of the material inside the vacuum vessel.

$$Q_x = q_x \times A_x$$

where

$Q_x =$ outgassing load for material x [Torr • liters/s]

$q_x =$ outgassing rate for material x [Torr • liters/s • cm$^2$]

$A =$ area of material x exposed to the interior of the vacuum vessel [cm$^2$]

Note: Many reference books provide values for outgassing rates (q) in W/m$^2$. To covert from w/m$^2$ to Torr•l/sec•cm$^2$ divide by 1333.2.

The total outgassing load for all materials inside the vacuum vessel is given by:

$$Q_{tot}^{outgas} = \sum_{1}^{y} Q_y$$

where

$Q_{tot}^{outgas} =$ total outgassing load [Torr • l/s]

$Q_y =$ outgassing load for material y

It should be noted that for a vacuum system at equilibrium the relationship between pressure, volume temperature and amount of gaseous material inside the vacuum vessel is given by the Ideal gas law.

$$PV = nRT$$

where

$P =$ total pressure [atm]

$V =$ volume [l]

$n =$ amount of material [moles]

$R =$ Ideal Gas law constant [atm • l/k • mole]

$T =$ temperature [K]

The numeric value of the Ideal gas law constant, $R$, is 0.08206 l•atm/K•mole. One mole of material contains approximately 6.023x $10^{23}$

molecules of the material and weighs one gram atomic weight. For example, one mole of diatomic nitrogen gas weighs approximately 28 g and one mole of helium gas weighs 4 g.

- Permeation

Permeation is the transport of a fluid (in this case gas) through a contiguous solid. In order for gases to permeate through a solid material gas molecules must land on the outer surface of a solid material, become adsorbed, diffuse through the bulk of the solid and desorb from the inner surface. The driving force for permeation of gases through materials is the pressure differential for each gas specie. Tables of permeation rates ($K_p$) for a wide variety of materials used in vacuum are available in the books listed in the references. To calculate the permeation gas load one must specify the gas permeating through a solid, know the area the gas is permeating through and the thickness of the permeable solid. The equation for calculating permeation rate is:

$$q_x = \frac{K_{px} \Delta P_x}{d}$$

where

$q_x =$ permeation rate for a specified gas through a specified solid [W/m $^2$]

$K_{px} =$ permeation coefficient for a specified gas through a specified solid [m $^2/s$]

$\Delta P_x =$ pressure differential across solid interface for the specified gas [Pa]

$d =$ distance the gas must permeate through [m]

Permeation gas load is calculated in the same manner as the outgassing gas load.

$$Q_x = q_x \times A_x$$

where

$Q_x =$ permeation load for material x [Torr • liters/s]

$q_x =$ permeation rate for material x [Torr • liters/s • cm$^2$]

$A =$ area of material gas is permeating through [cm$^2$]

- Leaks

Leaks are accounted for by measuring the leak rate by the rate of rise method or using a helium mass spectrometer leak detector. It should be noted that if one measures the leak rate using helium as a tracer gas a conversion factor must be applied to relate that value to the leakage rate for the higher molecular weight atmospheric gases nitrogen and oxygen.

## 15.8 Future trends and conclusions

Researchers are currently developing vacuum technology components (pumps, gauges, valves, etc.) using micro electro mechanical systems (MEMS) technology[2]. Miniature vacuum components and systems will open the possibility for significant

---

[2] http://www.darpa.mil/mto/mems/index.html

savings in energy cost and will open the doors to advances in electronics, manufacturing and semiconductor fabrication.

In conclusion, an understanding of the basic principles of vacuum technology as presented in this summary is essential for the successful execution of all projects that involve vacuum technology. Using the principles described above, a practitioner of vacuum technology can design a vacuum system that will achieve the project requirements.

### 15.9 Reference Books and References on the Web

**Reference books:**

Hoffman, D.M., Singh, B., Thomas, J.H., 1998. *Handbook of Vacuum Science and Technology*. Academic Press, San Diego.

Lafferty, J.M. 1998. *Foundations of Vacuum Science and Technology*. John Wiley and Sons, New York.

O'Hanlon, John, 1987 *A User's Guide to Vacuum Technology Second Edition*, John Wiley and Sons, New York.

Harris, Nigel, 2004, *Modern Vacuum Practice, Third Edition*, BOC Edwards (Phone in the USA: (800)-848-9800)

**References on the web:**

The American Vacuum Society:
www.avs.org

The Association of vacuum Equipment Manufacturers International:
www.avem.org

Safety information relevant to vacuum and pressure systems:
http://www.llnl.gov/es_and_h/esh-manual.html

Homepage of the American Society of Mechanical Engineers: http://www.asme.org/

The University of Alberta Vacuum Website:
http://www.ee.ualberta.ca/~schmaus/vacf/

The Bell Jar:
http://www.belljar.net/

List of International Vacuum Societies:
http://www.sansalone.de/engl/LK_vacuum_associations.htm

List of Vacuum Industry Associations:
http://www.sansalone.de/engl/LK_vacuum_industry_associations.htm

Journals of vacuum science and technology:
http://www.sansalone.de/engl/lk_vacuum_journals.htm

Physics on the web:

http://physicsweb.org/

Keywords or phrases for Index

Vacuum
Valve
Gauge
Pressure
Ion
Gas
Pump
Atmosphere
Vessel
Residual gas analysis
Partial pressure analysis
Outgassing
Permeation
Ideal gas law
Boyles law
Flange
Safety