
Lecture 2

L2a:

Fundamentals of Vacuum Science and Technology



Basics of Vacuum System

Ventilation:

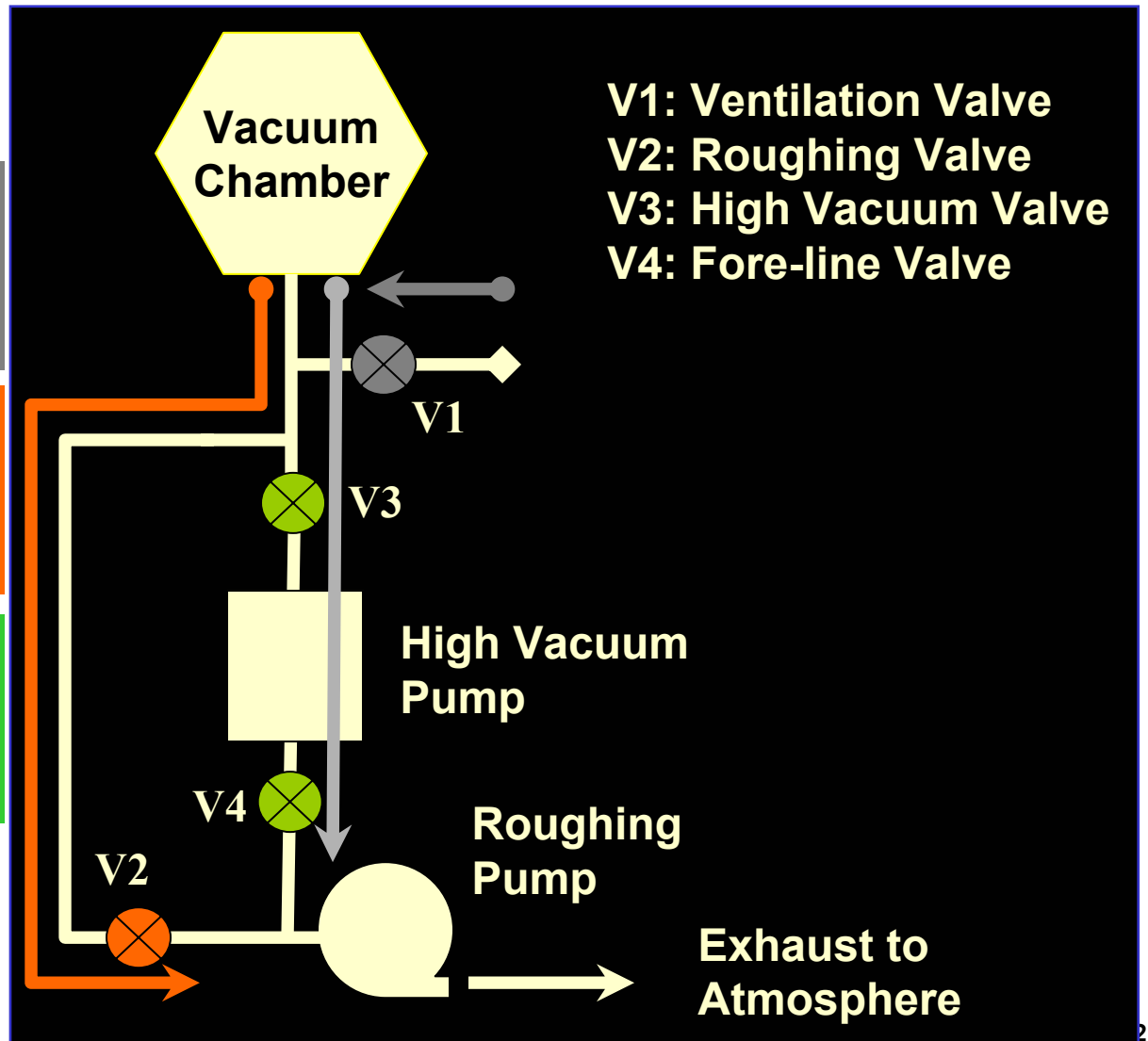
V1: On
V2, V3, V4: Off

Roughing:

V2: On
V1, V3, V4: Off

High Vacuum:

V3, V4: On
V1, V2: Off



A vacuum pump may operate by:

- **Capturing, compressing and expelling the gas molecules:
(Positive displacement pump)**
 - Mechanical pumps.
- **Giving the gas molecule a preferential direction:
(Momentum transfer pump)**
 - Diffusion pump,
 - Turbo-molecular pump,
 - Aspiration pump.
- **Capturing and keeping the gas molecules:
(Adsorption pump, adsorption or reaction pump)**
 - Cryopump,
 - Sorption pump,
 - Ion pump,
 - Evaporative getter pump,
 - Absorption pump,
 - Getter pump.



Operation Ranges of Vacuum Pumps

- **Mechanical Pumps:** atmospheric – 10^{-2} Torr
- **Sorption (Adsorption) Pumps:** atmospheric – 10^{-3} Torr
- **Molecular Drag Pumps:** 1 – 10^{-2} Torr
- **Turbomolecular Pump:** 10^{-2} – 10^{-8} Torr
- **Diffusion Pump:** 10^{-3} – 10^{-7} Torr
- **Cryopump:** 10^{-3} – 10^{-8} Torr

Turbomolecular Pump



Mechanical Pump



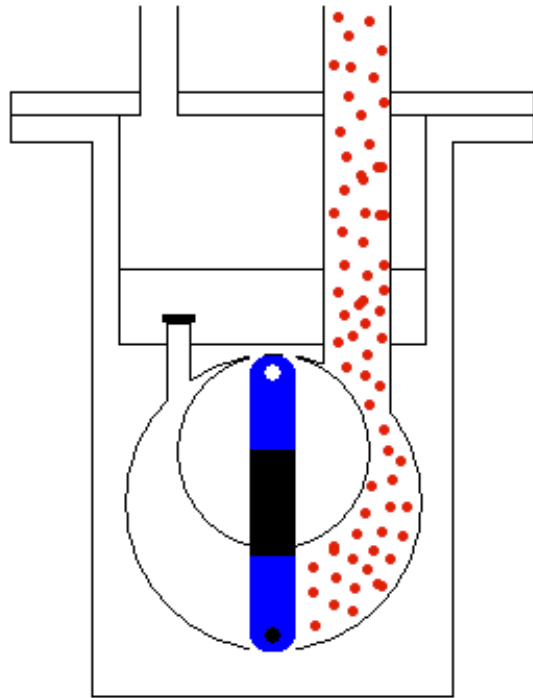
Diffusion Pump



Cryopump

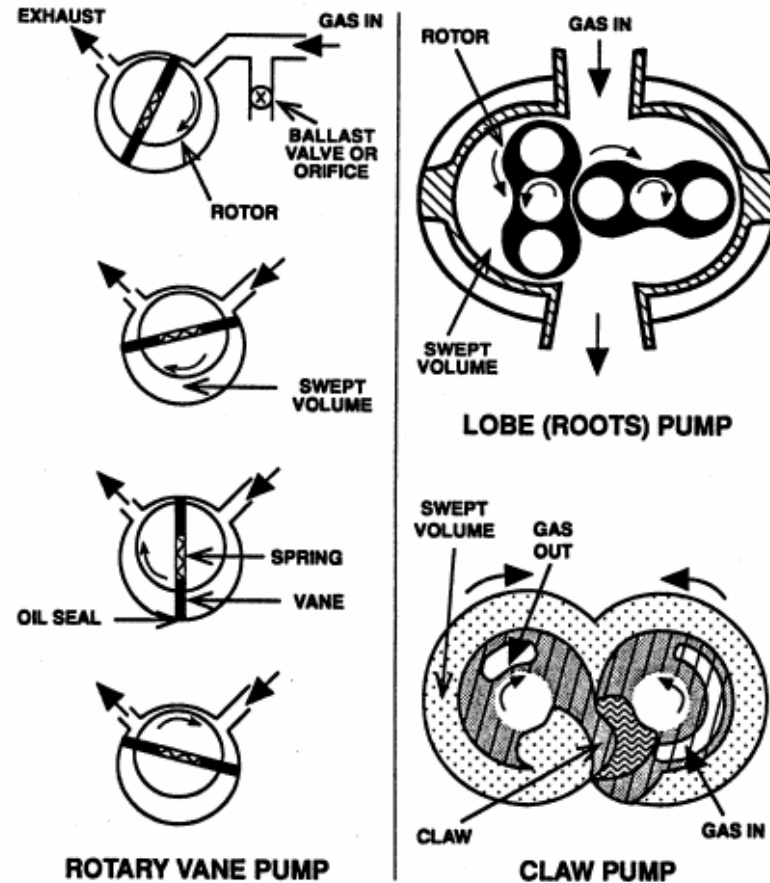


Mechanical Pump



<http://accept.la.asu.edu/PiN/rdg/vacuum>

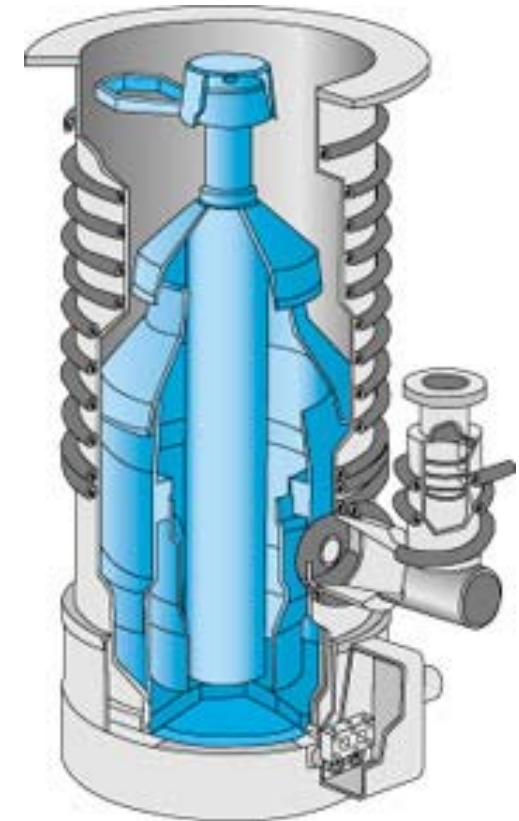
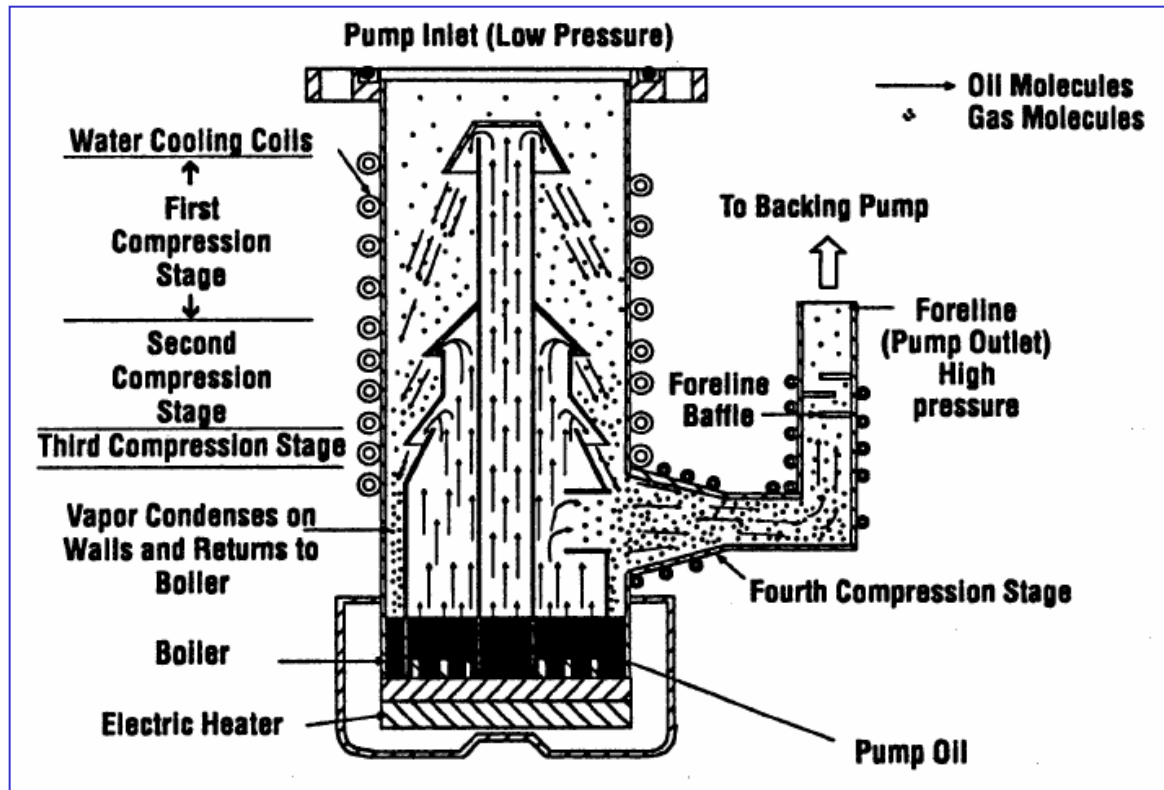
Oil Sealed and Dry Mechanical Pumps



* Donald M. Mattox, Handbook of Physical Vapor Deposition (PVD) Processing, Noyes Publications, 1998.



Diffusion Pump



* Donald M. Mattox, Handbook of Physical Vapor Deposition (PVD) Processing, Noyes Publications, 1998.

http://www.lesker.com/newweb/Vacuum_Pumps

Diffusion Pump

- **A high speed jet of fluid directs gas molecules in the pump throat down into the bottom of the pump through a multistage jet assembly and out the exhaust.**
- **The high speed jet is generated by boiling the fluid (typically silicone oil)**
- **Unlike mechanical pumps, diffusion pumps have no moving parts and as a result are quite durable and reliable.**
- **They can function over pressures ranging from about 10^{-10} torr to about 10^{-2} torr.**
- **Diffusion pumps cannot discharge directly into the atmosphere, so a mechanical fore-pump is typically used to maintain an outlet pressure around 0.1 torr.**
- **One major disadvantage of diffusion pumps is the tendency to back-stream oil into the vacuum chamber contaminating surfaces inside the chamber**
- **Upon contact of back-streaming oil with hot filaments or electrical discharges may result in carbonaceous or siliceous deposits.**
- **Due to back-streaming, diffusion pumps are not suitable for use with highly sensitive analytical equipment or other applications which require an extremely clean vacuum environment.**
- **Often cold traps and baffles are used to minimize back-streaming, although this results in some loss of pumping ability**



Diffusion Pump

Advantages

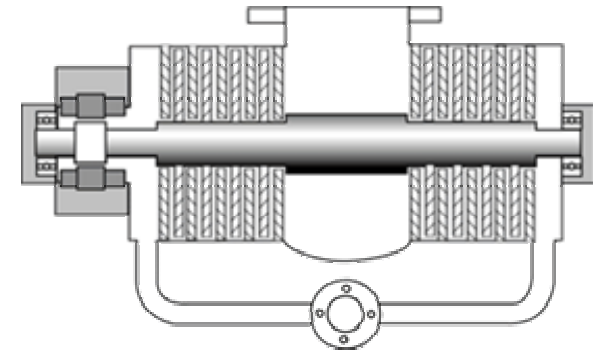
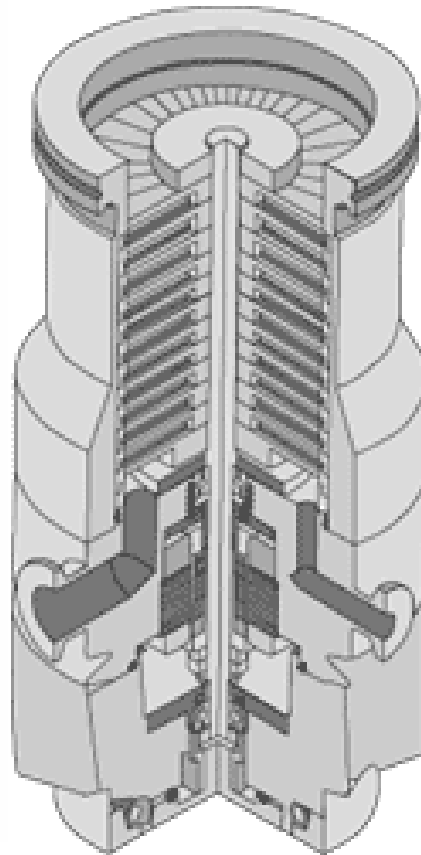
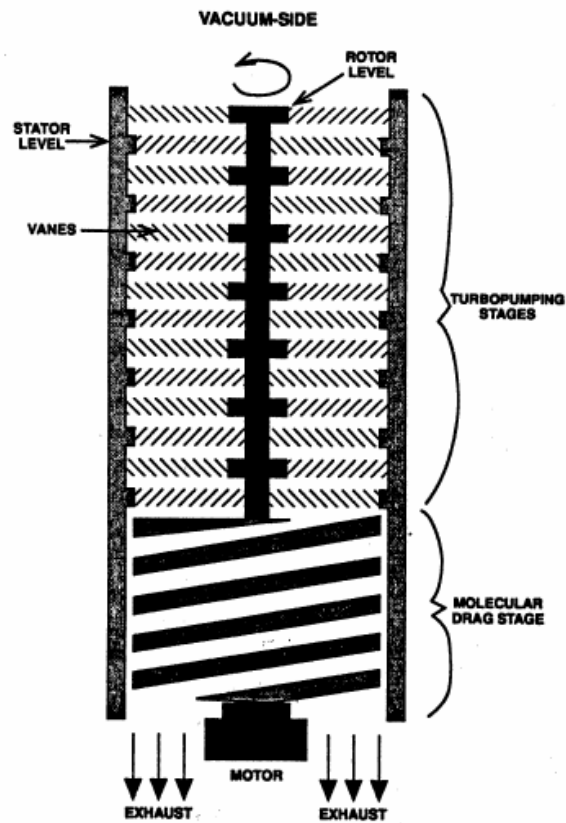
- **Simple part geometry**
- **Cheaper than other pumps**
- **Nearly linear pumping rate**
- **Tolerant of particles**

Disadvantages

- **Contamination of the chamber with hydrocarbons**
- **Heating and cooling time**
- **Needs coolant**



Turbo-Molecular Pump



http://www.lesker.com/newweb/Vacuum_Pumps

* Donald M. Mattox, Handbook of Physical Vapor Deposition (PVD) Processing, Noyes Publications, 1998.



Turbomolecular Pumps

- **Turbomolecular pumps use a rapidly spinning turbine rotor to push gas from the inlet of the pump towards the exhaust,**
- **Most turbomolecular pumps employ multiple stages consisting of rotor/stator pairs mounted in series,**
- **Gas captured by the upper stages is pushed into the lower stages and successively compressed to the level of the fore-vacuum pressure,**
- **As with the diffusion pump a mechanical vacuum pump is usually employed to reduce the exhaust pressure.**
- **In order to obtain extremely low pressures on the order of 10^{-10} Torr, rotation rates of 20,000 to 50,000 revolutions per minute are often necessary**
- **Heavy molecules are pumped much more efficiently than light molecules in contrast to diffusion pump (e.g. hydrogen and helium are not pumped efficiently.)**



Turbomolecular Pump

Advantages

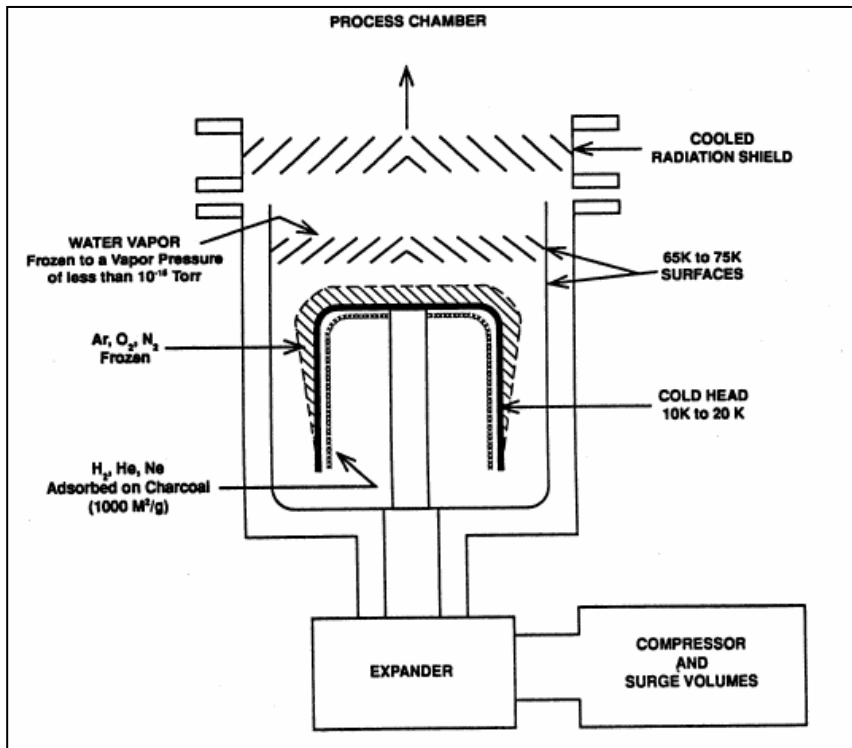
- **Clean comparing to diffusion pump**
- **No need to warm up or cool down**
- **High vacuum**
- **High pumping speed**

Disadvantages

- **Expensive**
- **Can fail catastrophically and expensively**
- **Pumping speed varies with gas type**
- **Problem with particles**



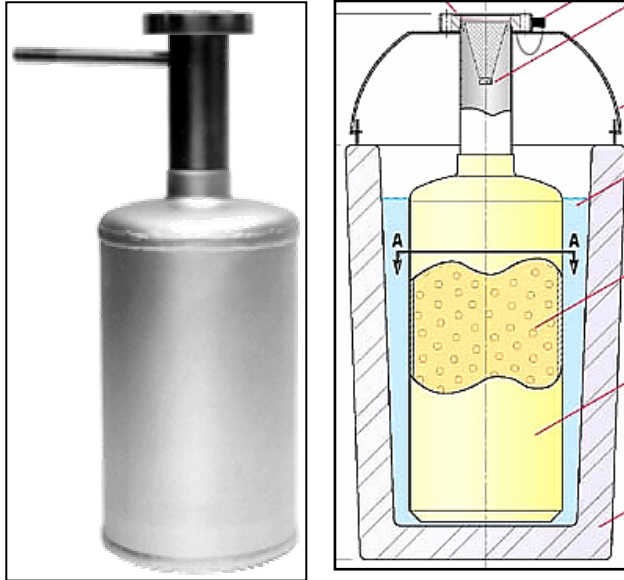
Cryo-Pump



* Donald M. Mattox, Handbook of Physical Vapor Deposition (PVD) Processing, Noyes Publications, 1998.

- consists of a vacuum-tight vessel with a valved inlet, containing a highly absorbent material such as a synthetic zeolite microporous on the scale of 1 to 10 Å and an enclosing cryogenic vessel.
- compressed helium is used to cool a cold head,
- can remain cold for months or even years in normal high and ultrahigh vacuum operation.
- At some point, the pump is shut down, and allowed to heat up. The trapped gasses evaporate and are flushed out, a process know as regeneration.
- Since cryopumps don't use any oil in the vacuum side, they are used when very clean pumping is needed.

Sorption Pumps



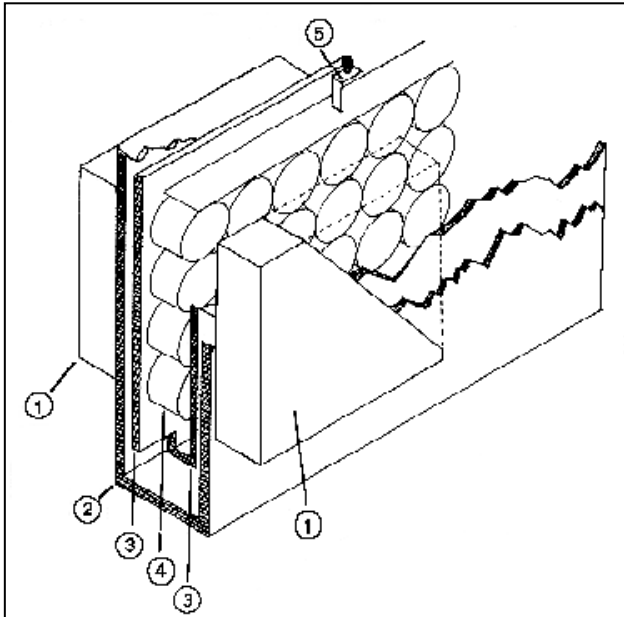
Evacuate gas molecules from a volume by cryosorption, adsorbing them on a chilled Surface.

- Sorption pumps are a type of cryopump that is often used as roughing pumps
- They reduce pressures from the range of atmospheric to 10^{-3} Torr
- As the sorbent saturates, the efficiency of a sorption pump decreases
- They can be recharged by heating the zeolite material (preferably under conditions of low pressure) to a temperature near but below the breakdown point of the zeolite material's porous structure.



Sputter ion pumps

Sputter ion pumps operate by ionizing gas within a magnetically confined cold cathode discharge



1. Permanent magnets
2. Pump envelope
3. Titanium cathodes
4. Anode cell array
5. Positive high voltage lead

http://www.thermionics.com/ip_too.htm

The events that combine to enable pumping of gases under vacuum are:

- *Entrapment of electrons in orbit by a magnetic field.*
- *Ionization of gas by collision with electrons.*
- *Sputtering of titanium by ion bombardment.*
- *Titanium gettering of active gases.*
- *Pumping of heavy noble gases by ion burial.*
- *Diffusion of hydrogen and helium into titanium.*
- *Dissociation of complex molecules into simple ones for pumping ease, e.g., CH_4 breaks down into C and 2H_2 . Hydrogen is pumped separately. Carbon is no longer part of the residual gas and resides in solid form.*



Vacuum Chambers



**Glass and Metal
Bell Jars**



**Spherical
Chamber**



**Standard Box
Chamber**

**Feed-through
Collars**



http://www.lesker.com/newweb/Vacuum_Pumps

Main Characteristics of Vacuum Chambers

- **Standard Box Chambers** with
 - large entry doors
 - linings to prevent deposition or out-gassing products sticking to the chamber walls
 - short cycle times and quick product turn-around
- **Spherical chambers** are frequently chosen for high vacuum or UHV applications where:
 - The center lines of many attached instruments cross at a common point—for gas, laser, electron, or ion beam interactions with each other or with a sample surface
 - Short, convenient access to a point-in-space needed—for thermal, electrical, or mechanical control for heaters, coolers, signals, thermocouples, rotary and linear movement devices
 - Simple rotation aligns the center-mounted sample with a number of ports
- **Glass Bell Jars** can withstand thermal shock and chemical attack but is fragile.





Vacuum Chamber Configurations

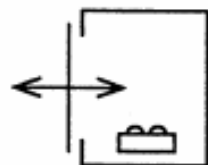
- **Direct Load System:** The processing chamber is opened to the ambient for loading or unloading the parts.
- **Load-Lock System:** The processing chamber remains isolated from the ambient.
- **In-Line System:** Several load-lock processing modules are in series so that the substrate passes sequentially from one to the next process.
- **Cluster Tool System:** A central introduction chamber is used so that the substrate may be moved into separate processing modules through load-locks and transferring tooling.
- **Web Coater (Roll Coater):** The system allows coating of a flexible materials (“web”) in the form of roll (coating of polymers and paper materials etc.)
- **Air-To-Air Strip Coater:** A continuous strip of material passes into and out of the deposition chamber through several differentially-pumped slit or roller valves.



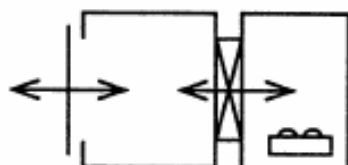
Vacuum Deposition Chamber Configurations

 = Isolation Valve with Transfer Tooling
 = Motion of Fixturing

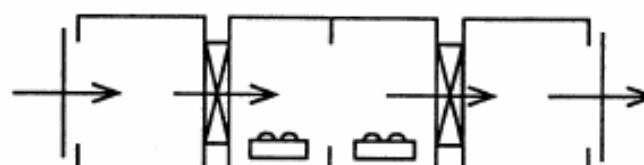
 = Access Door



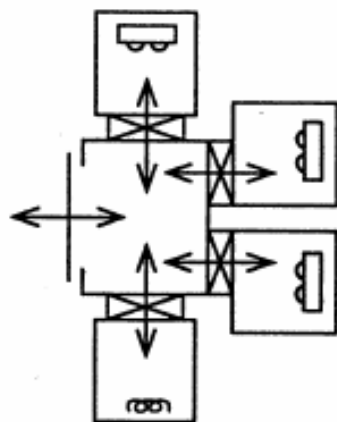
Direct-Load Coater



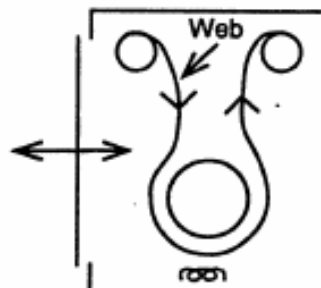
Load-Lock Coater



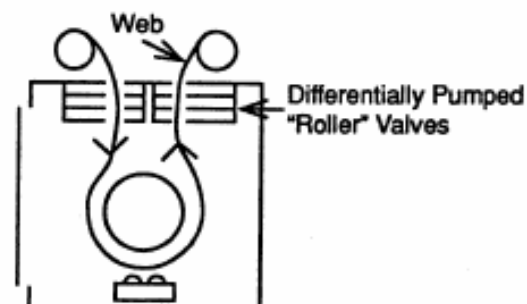
In-Line Coater



Cluster Tool



Roll Coater
(Batch)



Roll Coater
(Air-To-Air)

Vacuum Measurement Units and Classification of Vacuum Levels

- **Torr (or millimeters of mercury, mmHg),**
- **milliTorr (or micron),**
- **Inches of mercury (in. Hg),**
- **Pascal**
- **Millibar**

- **760 – 10^{-2} Torr : Low Vacuum**
- **10^{-2} – 10^{-4} Torr : Medium Vacuum**
- **10^{-4} – 10^{-8} Torr : High Vacuum**
- **$>10^{-9}$ Torr : Ultrahigh Vacuum**

Conversion of Units Used for Pressure Measurements

- Torr (or millimeters of mercury, mmHg),
- milliTorr (or micron),
- Inches of mercury (in. Hg),
- Pascal
- Millibar

To Convert...	Pascal	bar	atm	Torr (mmHg)	psi
1 Pa (= 1 N/m ²)	1	10 ⁻⁵	9.8692x10 ⁻⁶	750.06x10 ⁻⁵	1.4504x10 ⁻⁴
1 bar (= 0.1 MPa)	10 ⁵	1	0.98692	750.06	14.5032
1 atm (= 760 Torr)	101325	1.013	1	760	14.6972
1 Torr (= 1 mmHg)	133.322	≈ 0.00133	1.3158x10 ⁻³	1	0.01934
1 psi	6894.8	0.06895	0.06804	51.715	1



Vacuum gauges can function by one of the following mechanisms:

- **Pressure exerted on a surface with respect to a reference (e.g. capacitance manometers)**
- **Thermal conductivity of system gases (e.g. thermocouple and Piriani gauge)**
- **Ionization and collecting of ions (e.g. hot and cold cathode ionization gauges)**



Choosing a Gauge

When choosing a gauge, the following should be considered:

- **Interaction with the chamber environment:**
 - magnetic fields
 - working temperature
 - mechanical vibration
 - corrosive gases
- **Pumping speed and how it will affect the measurement of the pressure**

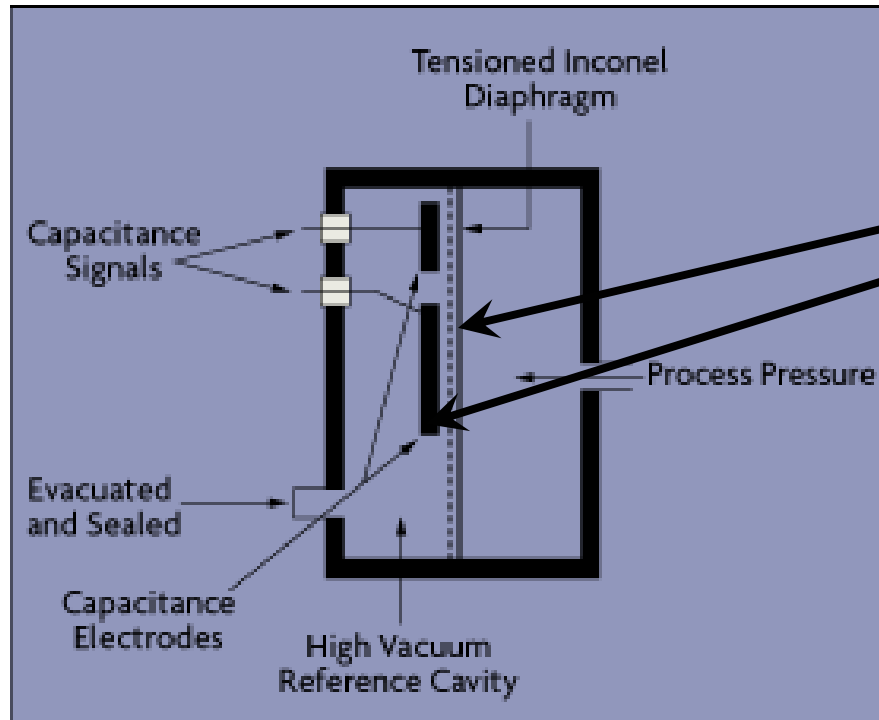


Pressure Ranges of Various Gauges

Gauge Type	Pressure Range (Torr)	Accuracy
Capacitance Diaphragm (CDG)	Atmosphere to 10^{-6}	± 0.02 to 0.2%
Thermal Conductivity (Piriani)	Atmosphere to 10^{-4}	$\pm 5\%$
Hot cathode Ionization (HCIG)	10^{-1} to 10^{-9}	$\pm 1\%$



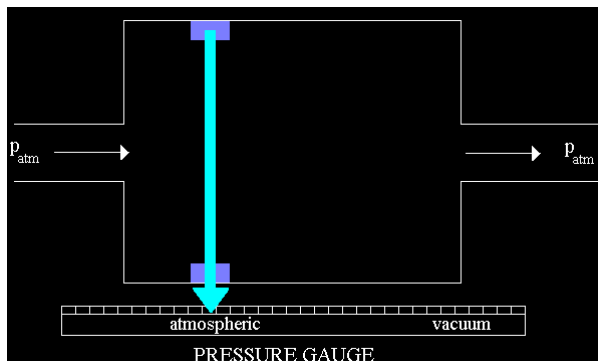
Capacitance Manometers



The electrical capacitance between the diaphragm and the fixed electrodes gives an accurate measurement of the distance between them

High accuracy for measuring the absolute pressure and differential pressure

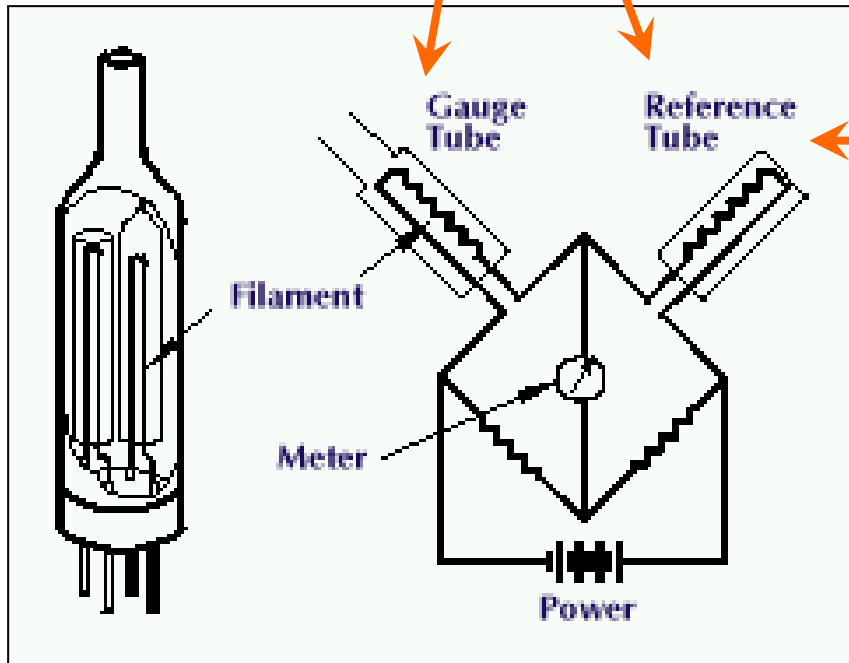
They measure all gases and materials vaporizing at the gauge's operating temperature.



<http://accept.la.asu.edu/PiN/rdg/vacuum>

Operation of Piriani Gauge

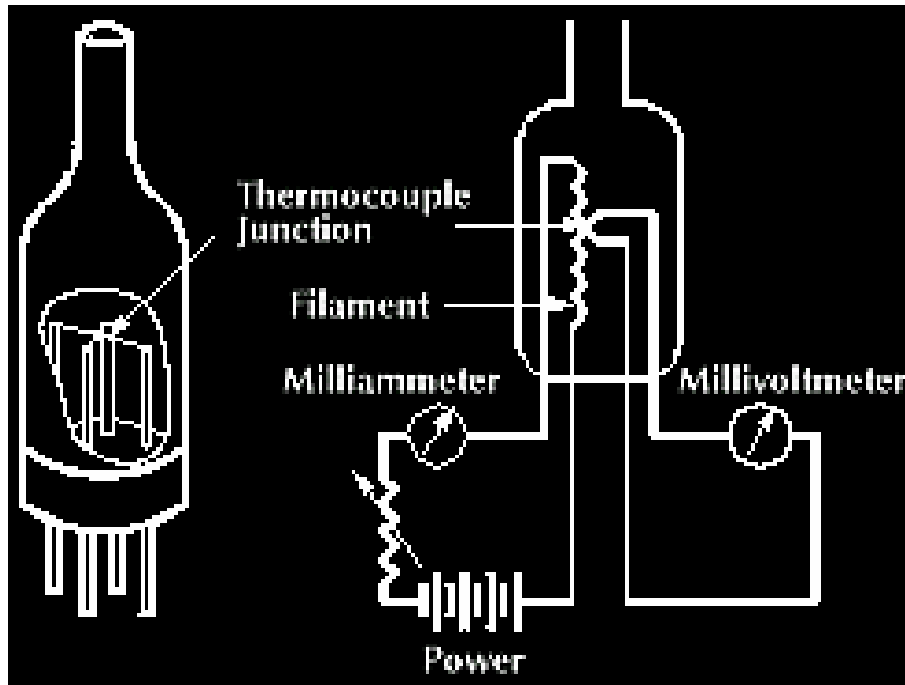
Two filaments (platinum alloy in the best gauges), act as resistances in two arms of a Wheatstone bridge.



The reference filament is immersed in a fixed-gas pressure, while the measurement filament is exposed to the system gas.

http://www.lesker.com/newweb/Pressure_Measurement

Thermocouple Gauges



http://www.lesker.com/newweb/Pressure_Measurement

These gauges are used extensively in foreline monitoring to switch the main chamber from backing to high-vacuum pumps

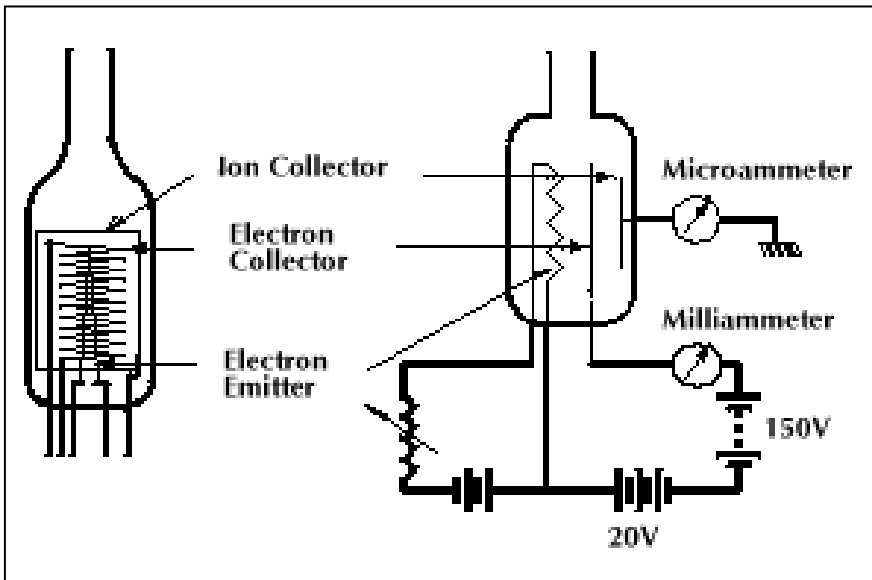
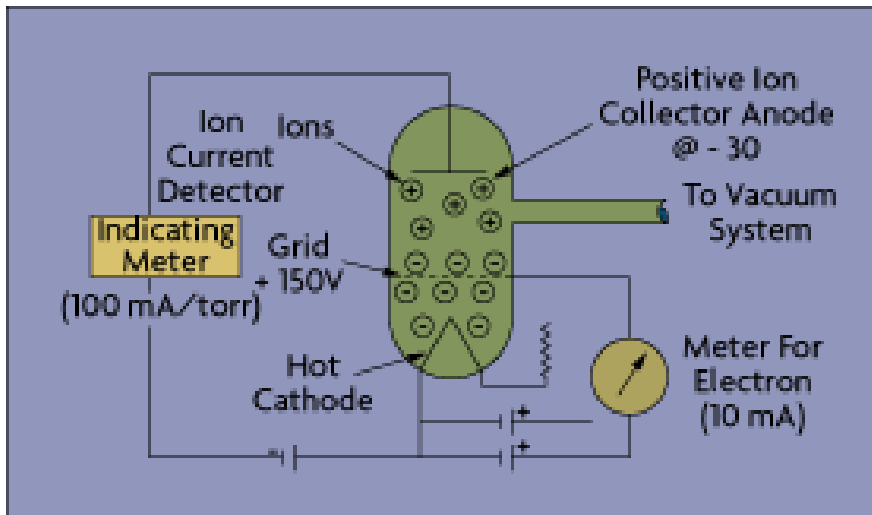
- Operation: Measuring the voltage of a thermocouple spot-welded to a filament which is exposed to the system gas
- The filament's temperature depends on thermal losses to the gas
- At higher pressure, more molecules hit the filament removing more heat energy and changing the thermocouple voltage
- Working pressure range: between 10 and 10^{-3} Torr

Comparison of Piriani Gauge and Thermocouple Gauge

- **Piriani gauge measurement principle allows these gauges to cover a greater total range (from 20 Torr to 10^{-5} Torr)**
- **Any particular Piriani gauge has roughly the same dynamic range as a thermocouple gauge**
- **Piriani gauges and their circuitry are typically ten times faster than thermocouple gauges.**

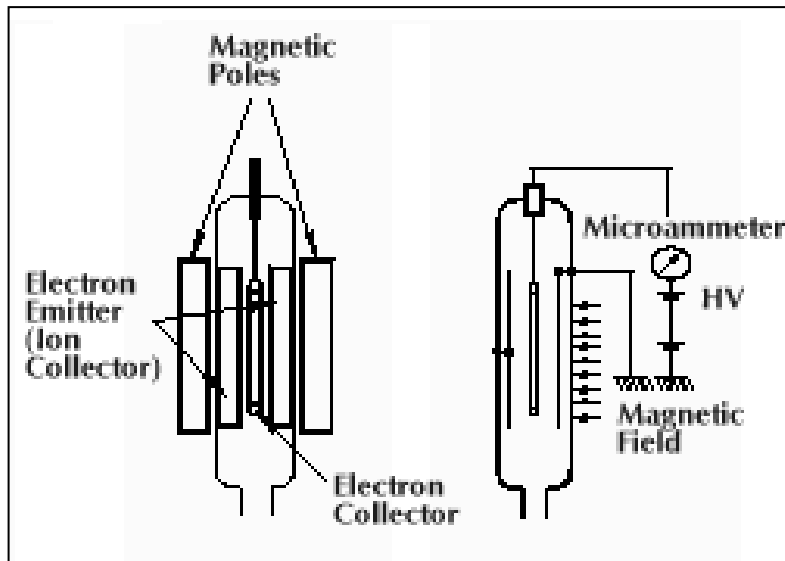
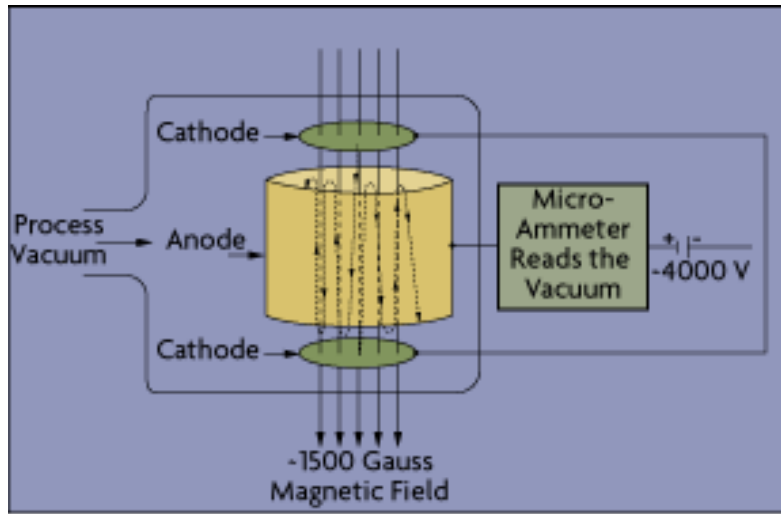


Operation Principle of Hot Filament Ion Gauges



- Heated filaments are biased to give thermionic electrons which is energetic enough to ionize any residual gas molecules during collisions.
- The positive ions formed drift to an ion collector held at about 150V.
- The current measures gas number density, a direct measure of pressure.
- Measurement range is between 10^{-4} to 10^{-9} Torr.

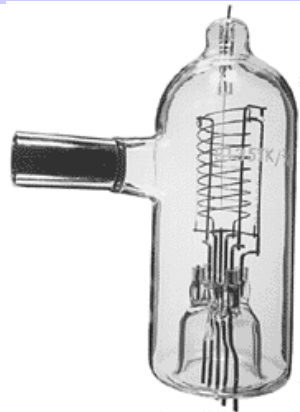
Operation Principle of Penning Cold Cathode Gauges



- Positive ions from a discharge bombard an active metal cathode (Zr, Th) to form secondary electrons.
- These electrons have a high probability of colliding with and ionizing residual gas molecules.
- The positive ions so formed complete the cycle by adding to the discharge.
- Measurement range is between 10^{-2} and 10^{-5} Torr

Piriani & Ion Guages

- Piriani Gauge
 - measures the heat conduction of gases
 - Operation: Low vacuum.
- Ion Gauge
 - measures the amount of thermionic current by a filament
 - Operation: High vacuum.

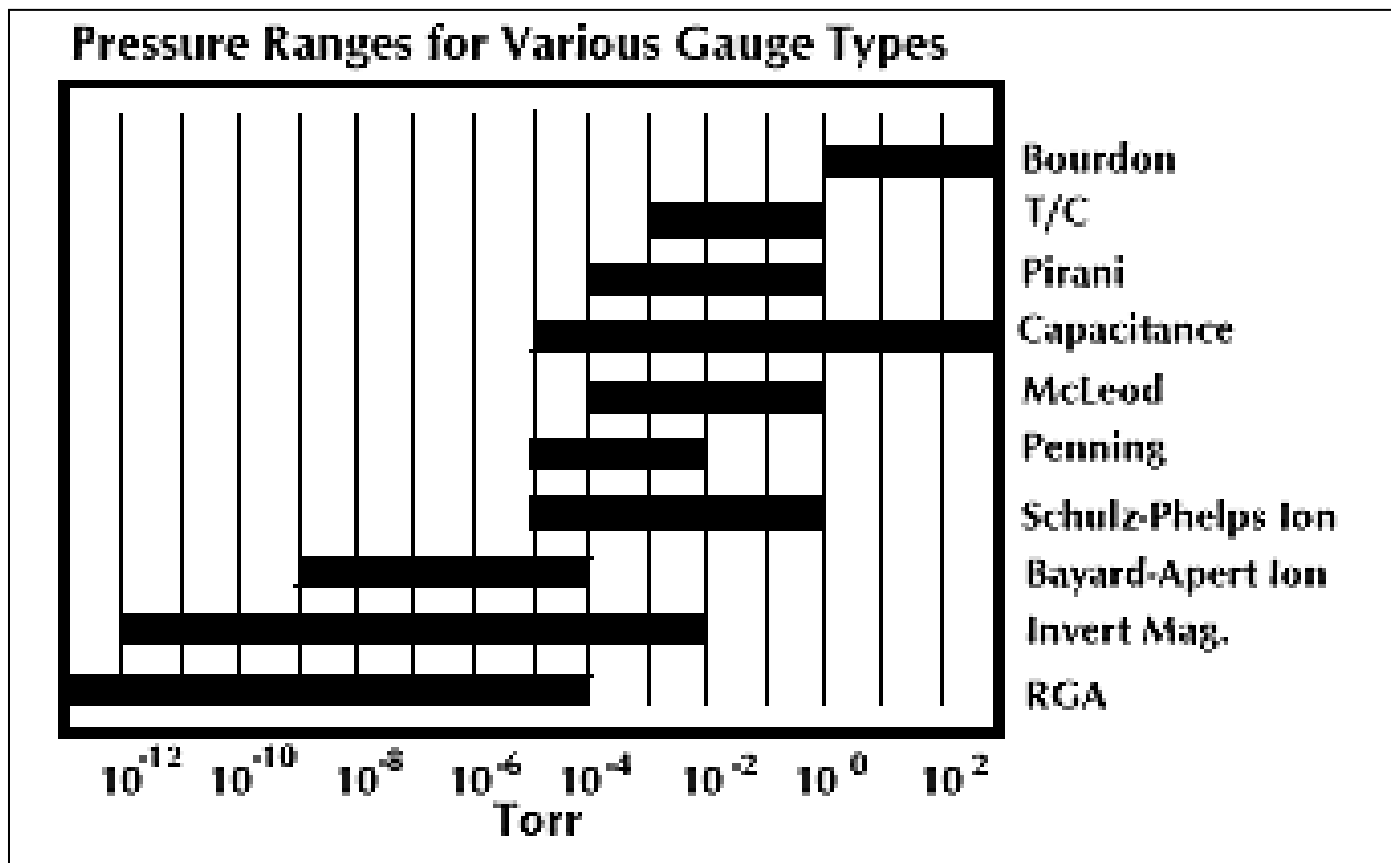


Ion Gauge



Pirani gauge

Pressure Range Coverage of Various Gauge Types



Selected References

- **Handbook of Vacuum Science and Technology** by D. M. Hoffman, B. Sing, J. H. Thomas, Academic Press, 1998.
- **A User's Guide to Vacuum Technology** by J. F. O'Hanlon, Wiley-Interscience, 2003.
- **High-Vacuum Technology: A Practical Guide** by M. Hablanian, Marcel Dekker, 1997.

