

EE-527: MicroFabrication

Vacuum Systems

Outline

- Vacuum principles
- Vacuum pumps
- Vacuum materials and components
- Vacuum instrumentation
- Vacuum systems

Uses of Vacuum in Microfabrication

Rough Vacuum

wafer chucks

load locks

sputtering

reactive ion etching
(RIE)

low pressure chemical
vapor deposition
(LPCVD)

High Vacuum

evaporation

ion implantation

Ultra-High Vacuum

surface analysis

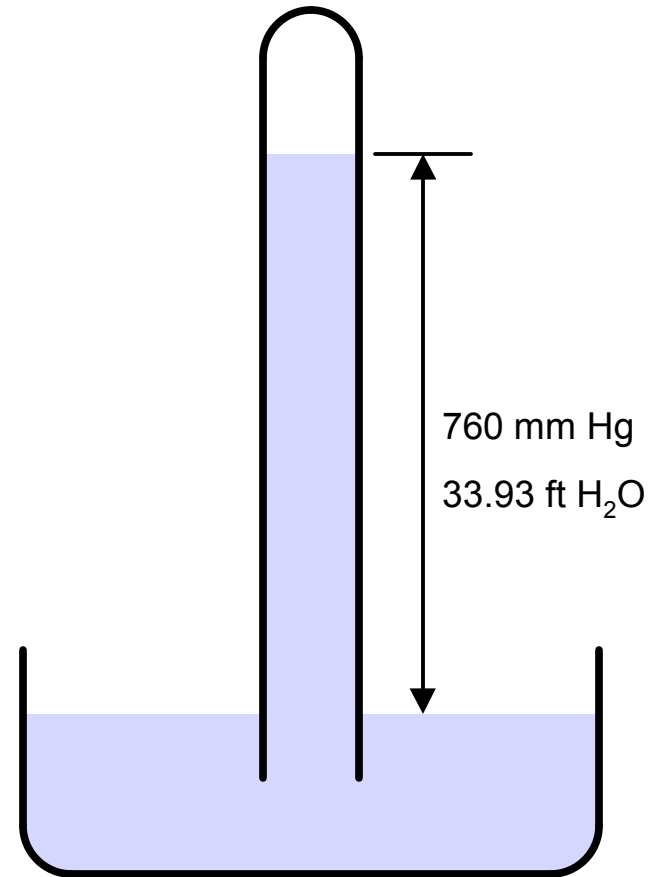
molecular beam

epitaxy (MBE)

Units of Pressure Measurement

- 1 atmosphere =
 - 760 mm Hg = 760 torr
 - 760,000 millitorr or microns
 - 29.9213 in. Hg
 - 14.6959 psi
 - 1.01325 bar
 - 1013.25 millibar
 - 101,325 pascals (Pa)
 - 407.189 in. H₂O
 - 33.9324 ft. H₂O

1 Pascal = 1 N/m ²
1 Torr = 1 mm Hg
1 micron = 1 μm Hg



Vacuum Ranges

- Low or Rough Vacuum (LV)
 - 760 to 10^{-3} torr
- High Vacuum (HV)
 - 10^{-3} to 10^{-8} torr
- Ultra-High Vacuum (UHV)
 - 10^{-8} to 10^{-12} torr

Partial Pressures of Gases in Air at STP

Gas	Symbol	Volume Percent	Partial Pressure, Torr
Nitrogen	N ₂	78	593
Oxygen	O ₂	21	159
Argon	Ar	0.93	7.1
Carbon Dioxide	CO ₂	0.03	0.25
Neon	Ne	0.0018	1.4 x 10 ⁻²
Helium	He	0.0005	4.0 x 10 ⁻³
Krypton	Kr	0.0001	8.7 x 10 ⁻⁴
Hydrogen	H ₂	0.00005	4.0 x 10 ⁻⁴
Xenon	Xe	0.0000087	6.6 x 10 ⁻⁵
Water	H ₂ O	Variable	5 to 50, typ.

Ideal Gas Law - 1

- V = volume of enclosure
- N = number of molecules
- N_m = number of moles = N/N_A
- n = particle density = N/V
- P = pressure
- T = absolute temperature
- k_B = Boltzmann's constant = 1.381×10^{-23} J/K
- N_A = Avogadro's number = 6.022×10^{23} particles/mole
- R = Gas constant = $N_A k_B = 8.315$ J/mole-K

$$PV = N_m RT$$

$$PV = Nk_B T$$

$$P = nk_B T$$

Ideal Gas Law - 2

- Historical Laws:
 - Boyle's Law: $P_1V_1 = P_2V_2$ at constant T
 - Charles' Law: $V_1/T_1 = V_2/T_2$ at constant P
 - Gay-Lussac's Law: $V = V_0(1 + T/273)$

Kinetic Gas Theory

- Velocity of a molecule is $\vec{v} = v_x \hat{x} + v_y \hat{y} + v_z \hat{z}$
- Mean square velocity is $\overline{v^2} = \overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2}$
- Pressure exerted on a wall in the x-direction is $P_x = nm\overline{v_x^2}$
- If velocities for all directions are distributed uniformly, $\overline{v^2} = 3\overline{v_x^2}$
- Thus, $P = \frac{1}{3}nm\overline{v^2} = nk_B T$ $\frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B T$
- Each molecular DOF has an average excitation of $k_B T/2$.

Distribution Functions - 1

- Boltzmann's postulates for an ideal gas:
 - The number of molecules with x -components of velocity in the range of v_x to $v_x + dv_x$ is proportional to some function ϕ of v_x^2 only:

$$\frac{dN_{vx}}{N} = \phi(v_x^2) dv_x \quad \frac{dN_{vy}}{N} = \phi(v_y^2) dv_y \quad \frac{dN_{vz}}{N} = \phi(v_z^2) dv_z$$

- The distribution function for speed v must be the product of the individual and identical distribution functions for each velocity component:

$$\frac{dN_{vx,vy,vz}}{N} = \psi(v^2) dv_x dv_y dv_z = \phi(v_x^2)\phi(v_y^2)\phi(v_z^2) dv_x dv_y dv_z$$

Distribution Functions - 2

- A mathematical solution to the above equations has the form of (A and v_m are constants):

$$\phi(v_x^2) = Ae^{-v_x^2/v_m^2}$$

- Normalization of the distribution functions:

$$\int_{-\infty}^{\infty} dN_{vx} = \int_{-\infty}^{\infty} NAe^{-v_x^2/v_m^2} dv_x = NA\sqrt{\pi}v_m^2 = N \quad A = (\pi v_m^2)^{-1/2}$$

$$\overline{v^2} = \frac{1}{N} \int_0^{\infty} v^2 dN_v = \int_0^{\infty} \frac{4v^4}{v_m^3 \sqrt{\pi}} e^{-v^2/v_m^2} dv = \frac{3}{2} v_m^2 = \frac{3k_B T}{m}$$

$$dv_x dv_y dv_z = 4\pi v^2 dv \quad v_m = \left(\frac{2k_B T}{m} \right)^{1/2}$$

Distribution Functions - 3

- Normalized distribution function for a single velocity component (Gaussian):

$$\phi(v_x^2) = \left(\frac{m}{2\pi k_B T} \right)^{1/2} \exp\left(-\frac{mv_x^2}{2k_B T} \right)$$

- Normalized distribution function for velocity magnitude (Gaussian):

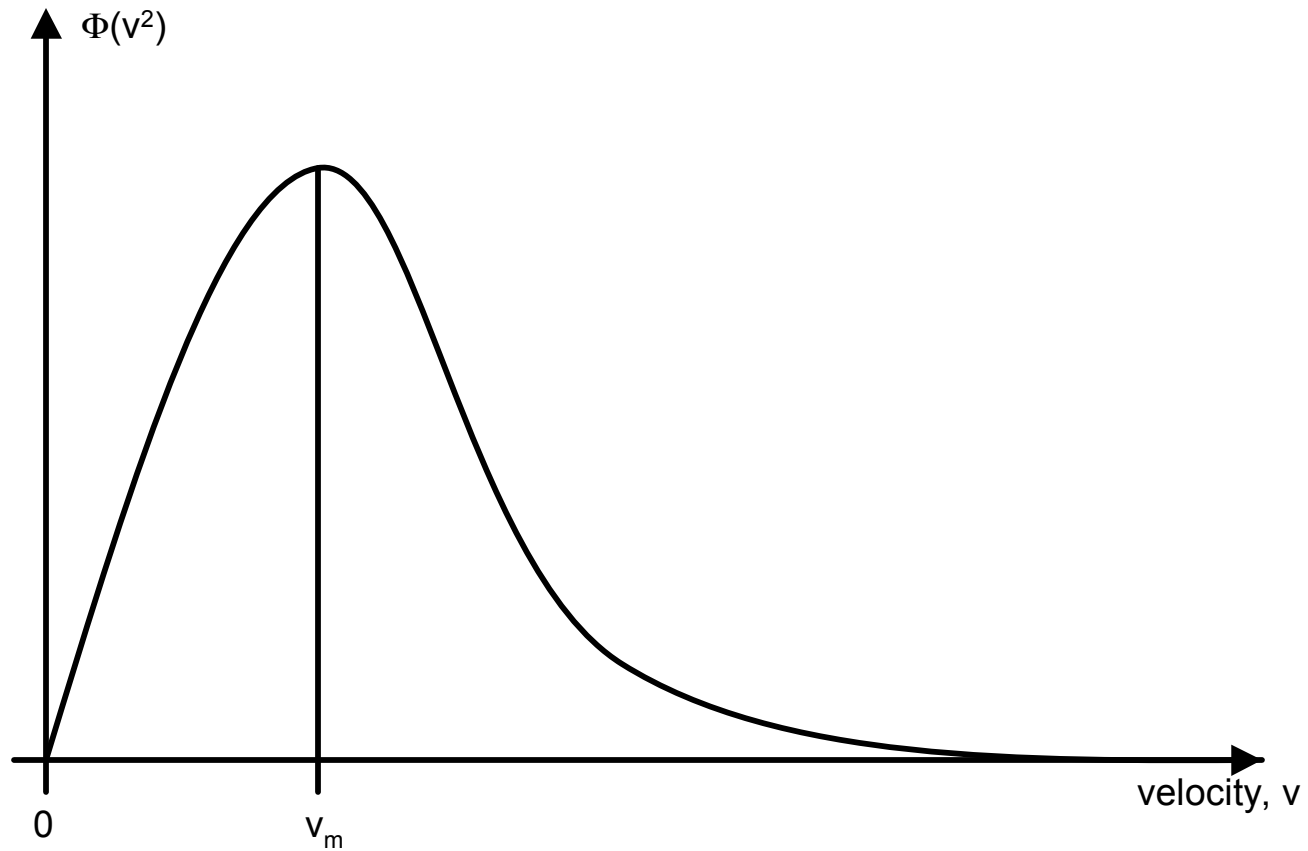
$$\psi(v^2) = \left(\frac{m}{2\pi k_B T} \right)^{3/2} \exp\left(-\frac{mv^2}{2k_B T} \right)$$

- Normalized distribution function for a randomly directed velocity (Maxwellian):

$$\Phi(v^2) = 4\pi \left(\frac{m}{2\pi k_B T} \right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2k_B T} \right)$$

Distribution Functions - 4

Maxwellian Distribution of Randomly Oriented Velocities:



Impingement Rates

- The number of molecules with a velocity from v_x to $v_x + dv_x$ is $dN_{vx} = N\phi(v_x^2) dv_x$.
- A = area under consideration.
- Only those molecules within striking distance $v_x dt$ will hit the wall after dt seconds.
- The number of molecules with velocities from v_x to $v_x + dv_x$ impinging upon the wall per time dt is

$$d^2 N_{vx} = \frac{N}{V} A v_x \phi(v_x^2) dv_x dt \quad \text{integrate:} \quad \int_0^{\infty} v_x \phi(v_x^2) dv_x = \left(\frac{k_B T}{2\pi m} \right)^{1/2}$$

$$\img alt="A large green arrow pointing to the right." data-bbox="146 765 242 825"/> \quad \frac{dN_i}{A dt} = \frac{N}{V} \left(\frac{k_B T}{2\pi m} \right)^{1/2} = (2\pi m k_B T)^{-1/2} P$$

Gas Flow - 1

- **Viscous Flow**
 - occurs for pressures greater than 10^{-2} torr
 - gas molecules constantly collide with one another
 - collisions with each other are more frequent than wall collisions
 - gas behaves like a coherent, collective medium; it acts like a fluid
- **Free Molecular Flow**
 - occurs for pressures less than 10^{-2} torr
 - gas molecules travel for large distances between collisions
 - collisions with walls are more frequent than with each other
 - gas molecules fly independently of each other

Gas Flow - 2

- Pipe of radius r and length l :
- Viscous Flow

– Poiseuille's equation:

$$\eta = \frac{2f}{\pi \sigma^2} \left(\frac{mk_B T}{\pi} \right)^{1/2}$$

$$Q = C_{vis} (P_2 - P_1) = \frac{\pi r^4}{16\eta l} (P_2^2 - P_1^2)$$

- Free Molecular Flow
- Knudsen's equation:

$$Q = C_{mol} (P_2 - P_1) = \frac{2}{3} \pi \frac{r^3}{l} \left(\frac{8k_B T}{\pi m} \right)^{1/2} (P_2 - P_1)$$

Mean Free Path

- MFP is the average distance a gas molecule travels before colliding with another gas molecule or the container walls.
- σ is the diameter of the particles
- $\pi\sigma^2$ is the cross-sectional area for hard-sphere collisions

$$\text{MFP} = \frac{V}{N\pi\sigma^2\sqrt{2}} = \frac{k_B T}{P\pi\sigma^2\sqrt{2}}$$

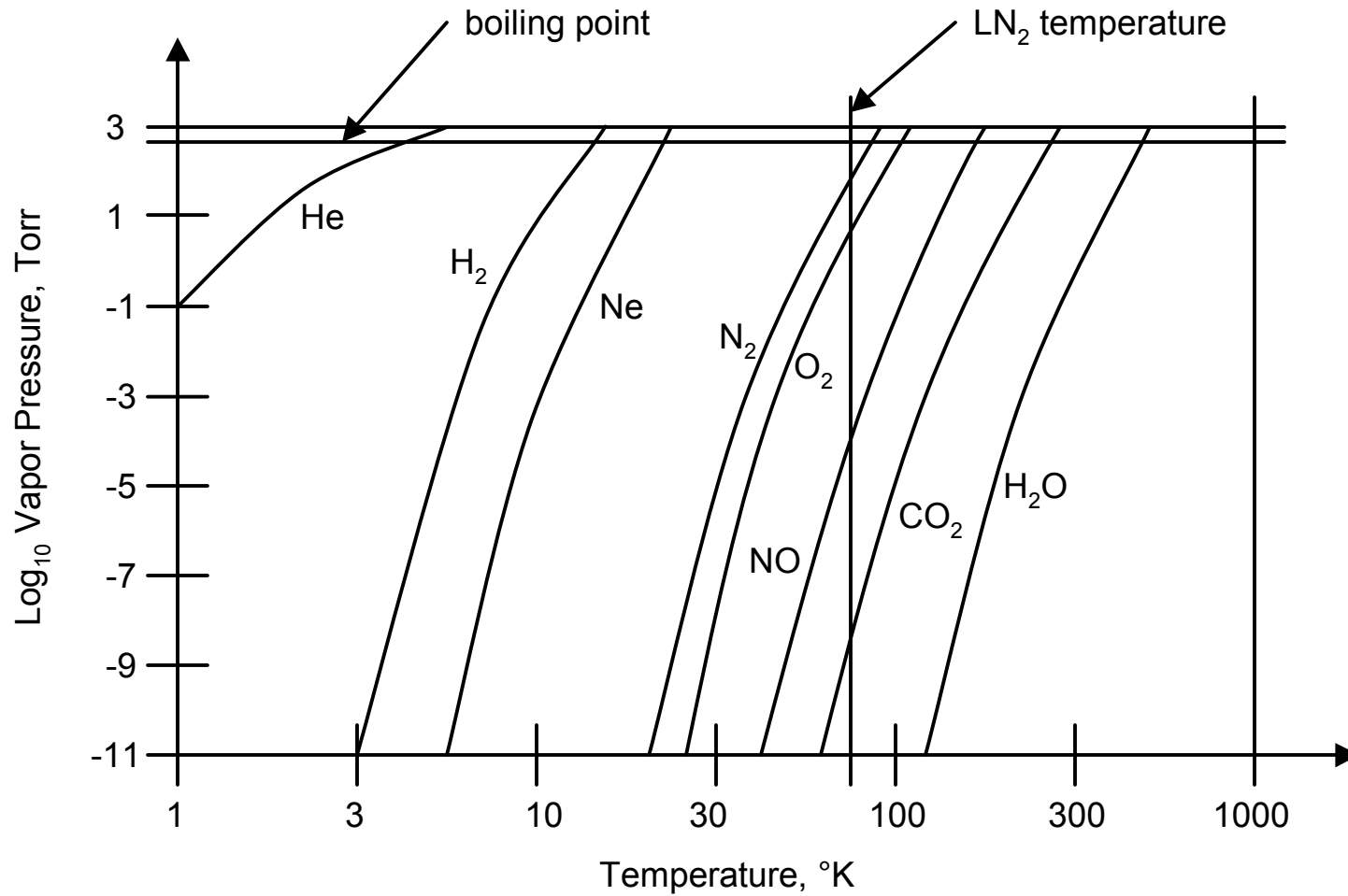
For common gases, {H₂O, He, CO₂, CH₄, Ar, O₂, N₂, H₂}, at T = 300 K:

$$\text{Mean Free Path (cm)} = \frac{5 \times 10^{-3} \text{ torr-cm}}{\text{Pressure (torr)}}$$

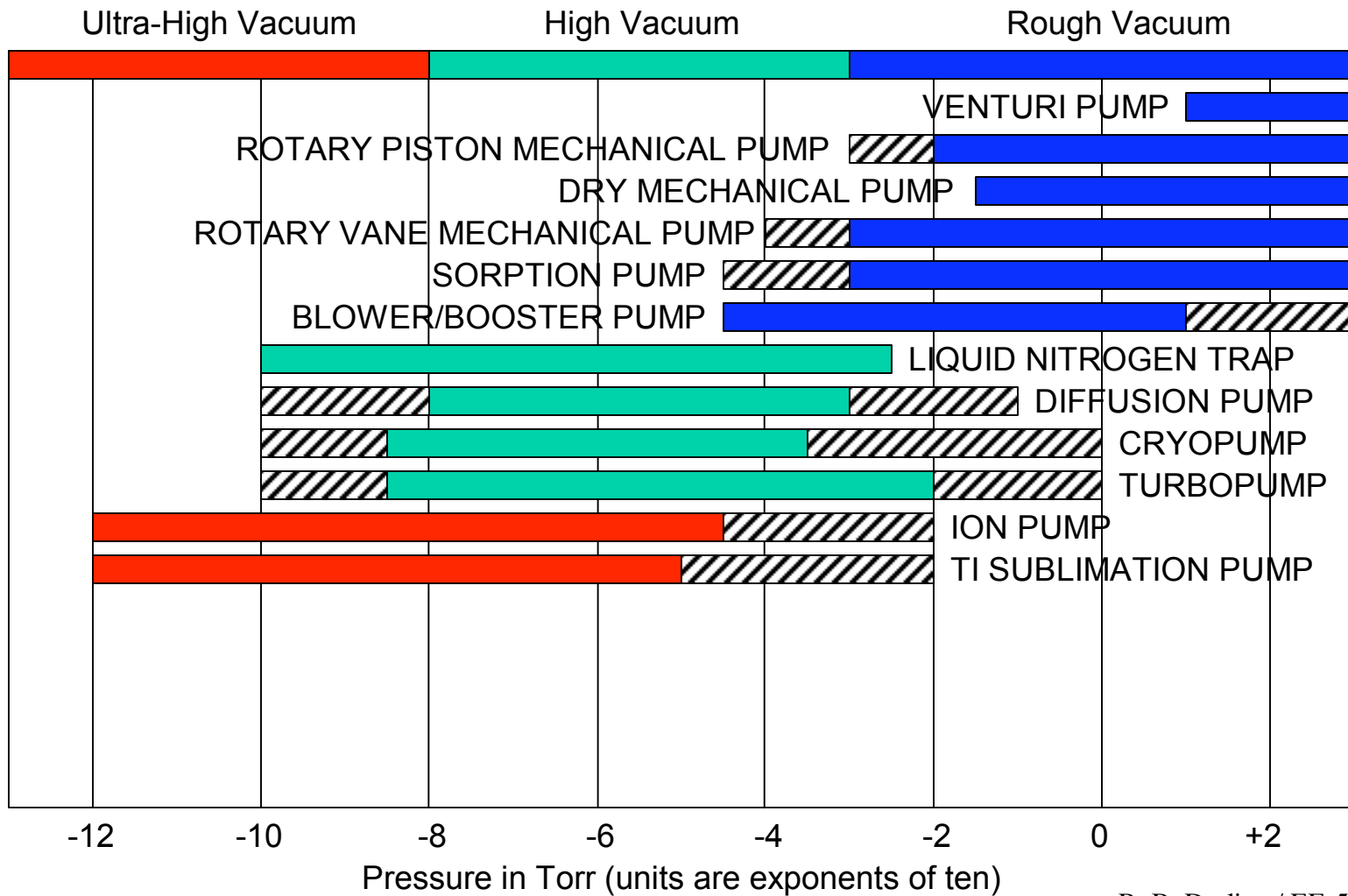
Gas Throughput

- $Q = PS$
- P = gas pressure in torr
- S = pumping or leaking speed in liters/second (L/s)
- Q = gas throughput in torr-liters/second (torr-L/s)
 - This is the quantity of gas moving through an orifice per unit time.
- Q is directly related to the power needed to move the gas:
 - 1 Watt = 7.50 torr-L/sec = 1000 Pa-L/sec
- C = gas conductance in liters/second (L/s)
- $Q = C(P_2 - P_1)$

Vapor Pressures of Gases



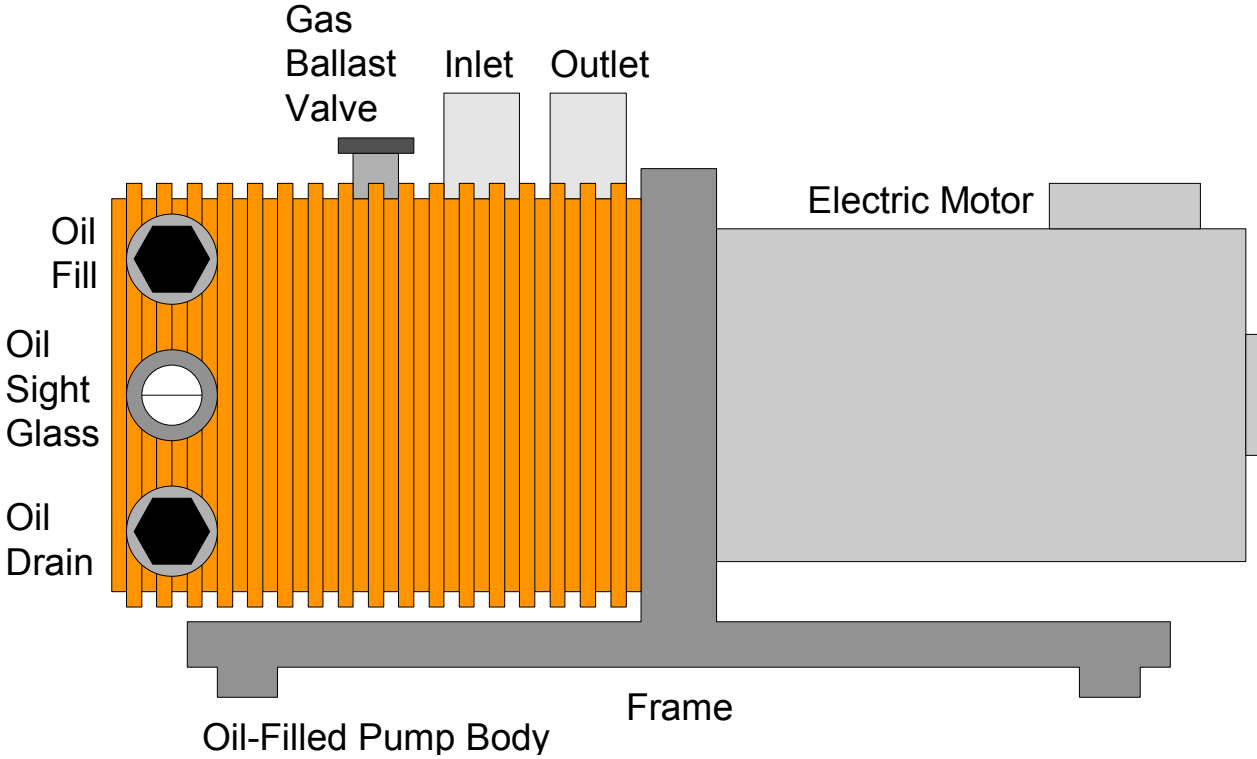
Vacuum Pump Pressure Ranges



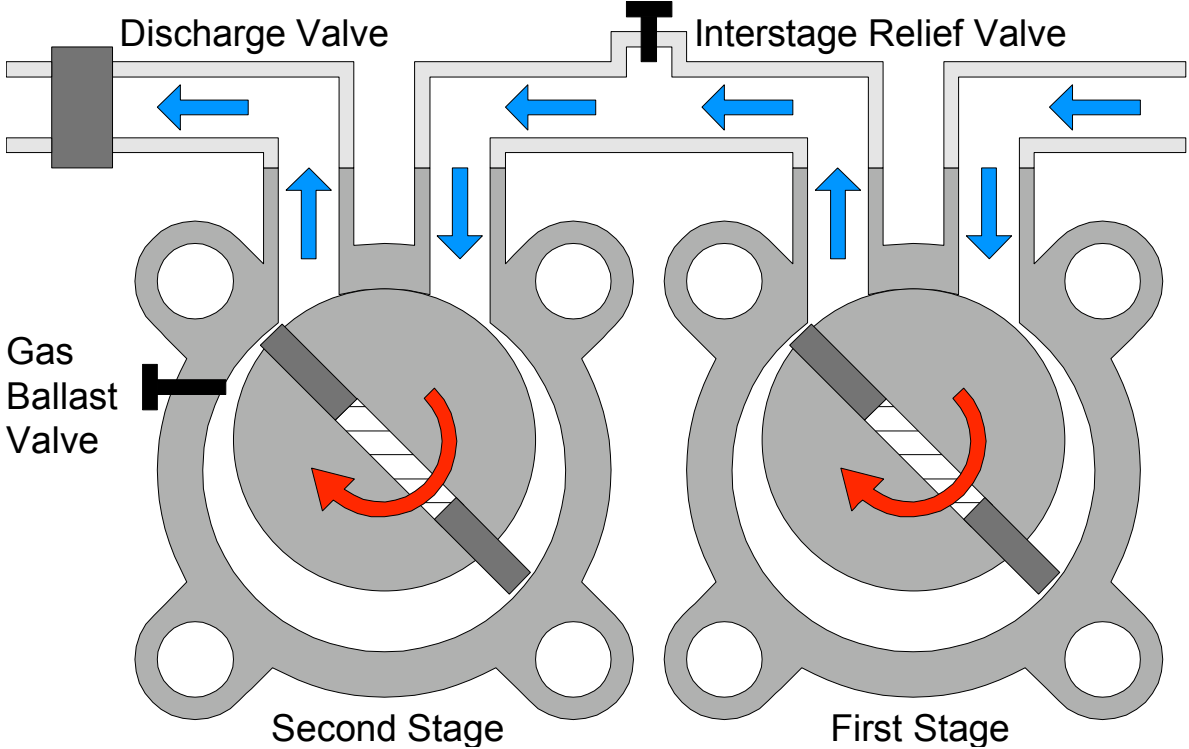
Vacuum Pumps

- Two fundamental types:
 - Concentration pumps
 - Gas entering the inlet is compressed and expelled out an outlet
 - Can run continuously
 - Entrainment pumps
 - Gas entering the inlet is trapped inside
 - Must be regenerated to empty the trapped gas

Rotary Vane Mechanical Pumps - 1



Rotary Vane Mechanical Pumps - 2



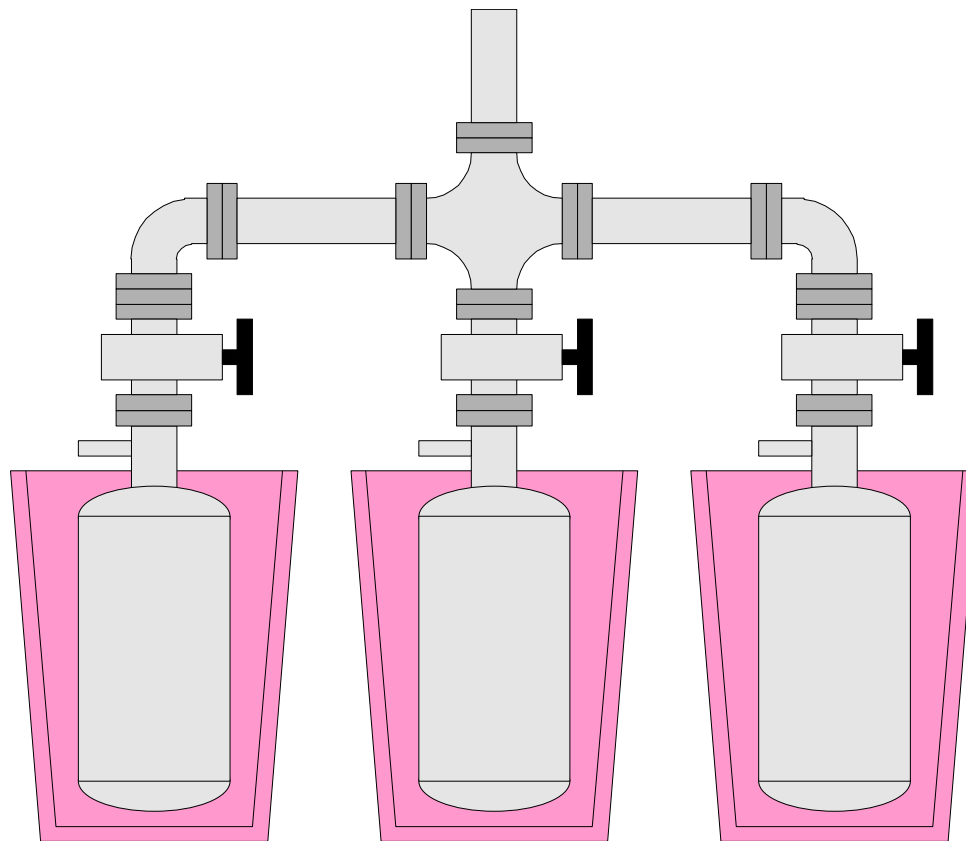
Rotary Vane Mechanical Pumps - 3

- Gases are removed by compressing them slightly above atmospheric pressure and then forcing them through a check valve.
- The rotary vane modules are immersed in an oil bath.
- The purpose of the oil is to:
 - cool the pump
 - lubricate the rotary vanes
 - provide a lip seal for the vanes
 - open the second stage exhaust valve at low inlet pressures
- They are powered by an electric motor:
 - Belt drive: 250 to 400 rpm
 - Direct drive: 1725 rpm (most common type)

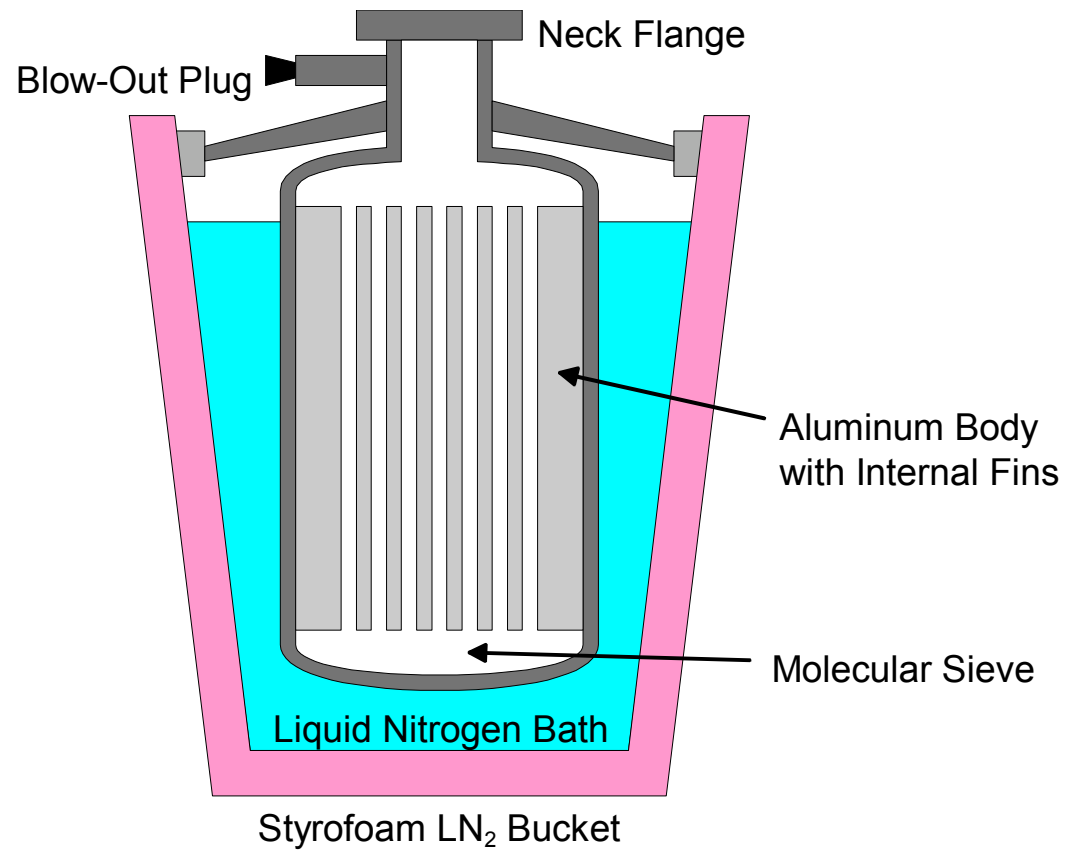
Rotary Vane Mechanical Pumps - 4

- Potential Problems:
 - Oil must have low vapor pressure to achieve desired performance
 - Water or dirt or impurities in the oil will raise the vapor pressure
 - Backstreaming of oil vapor can occur at low pressures
 - This can be trapped in a molecular sieve filter
 - Most often responsible for the oily smell in a vacuum chamber
 - Large gas loads can froth the oil and prevent sealing
 - Gas ballast can be opened to allow froth to settle
 - Roughing valves should be opened slowly (feathered) to prevent this
 - Belts can break on belt-drive pumps
 - Direct drive pumps eliminate this problem

Sorption Pumps - 1



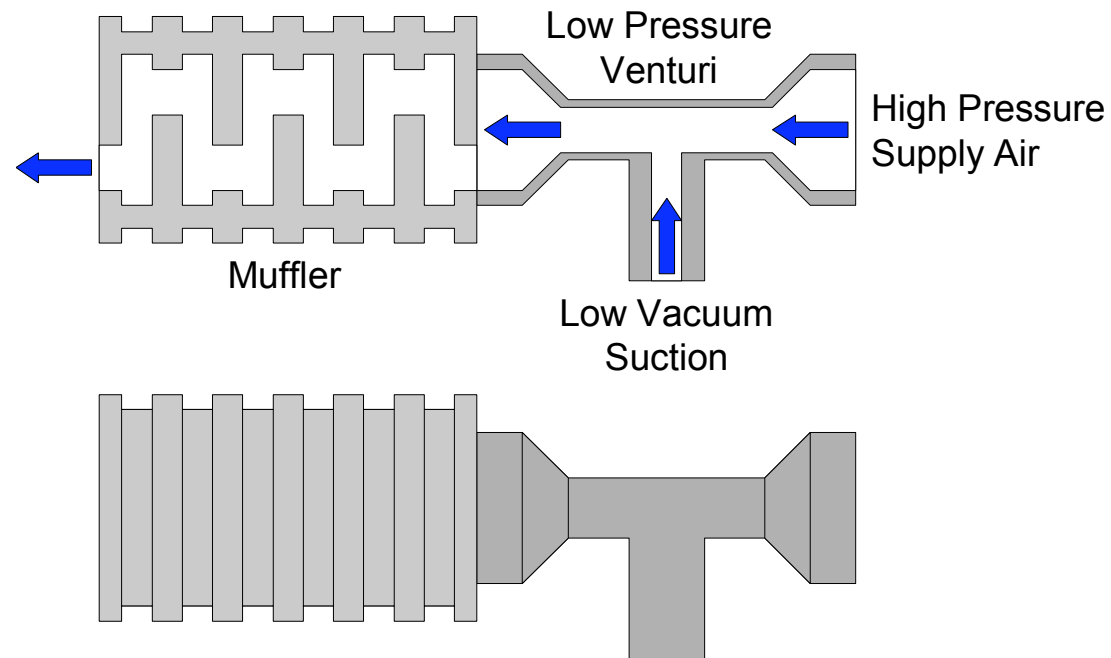
Sorption Pumps - 2



Sorption Pumps - 3

- Gases are pumped by
 - Cryocondensation: gases freeze into solid phase on cold surfaces
 - Cryosorption: gases are trapped in a porous molecular sieve
- Vessel is cooled by immersion in liquid nitrogen (LN2) which reaches -196°C , or 77°K .
- Pumping is completely oil free and has no moving parts.
- Each sorption pump requires about 2-3 gallons of LN2 and about 20 minutes to cool down.
- Several sorption pumps are often combined on a manifold.
- Pumps must be regenerated by heating to 250°C for 30 mins. to melt frost and degas the molecular sieve material.

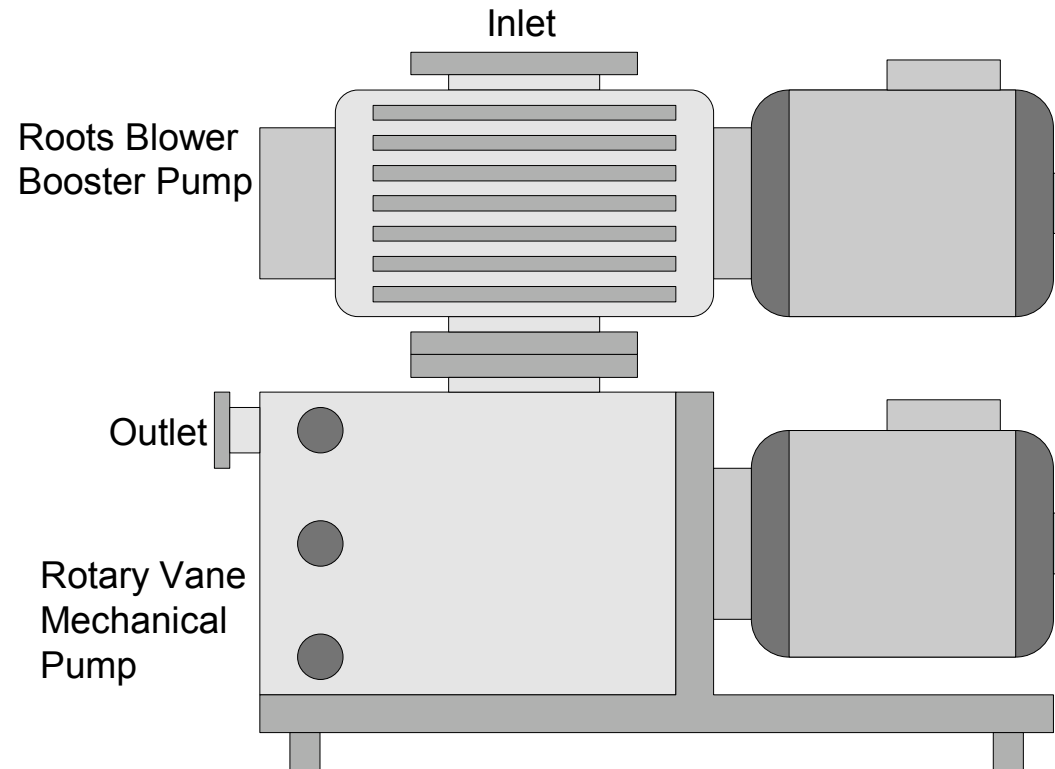
Venturi Pumps - 1



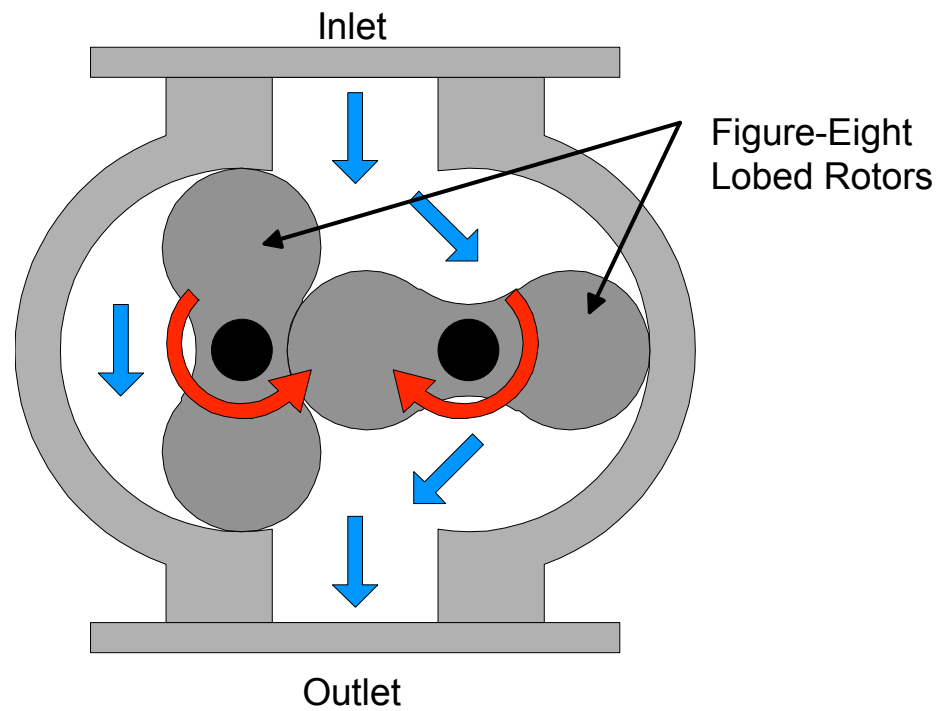
Venturi Pumps - 2

- Bernoulli's principle is used to pull vacuum from the pinched midsection of a flow restriction.
- Typically driven by 60 psi clean dry air.
- Venturi pumps can usually pump a chamber from 760 Torr to 60 Torr.
- Completely oil free and has no moving parts.
- Instant on and off.
- Venturi pumps can remove about 90 % of the air in a chamber, greatly reducing the capacity requirements of other pumps.
- Drawback is their noise; they usually need a muffler.

Roots Blowers / Booster Pumps - 1



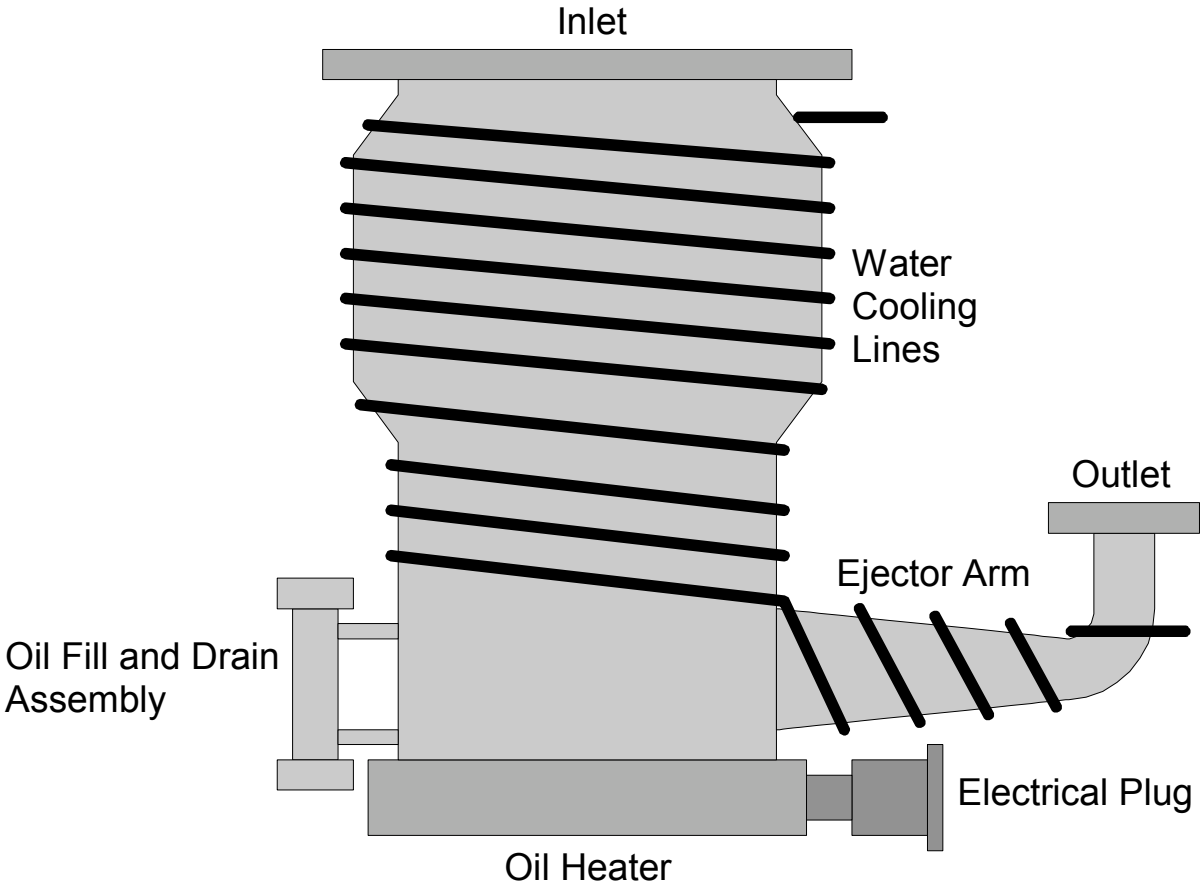
Roots Blowers / Booster Pumps - 2



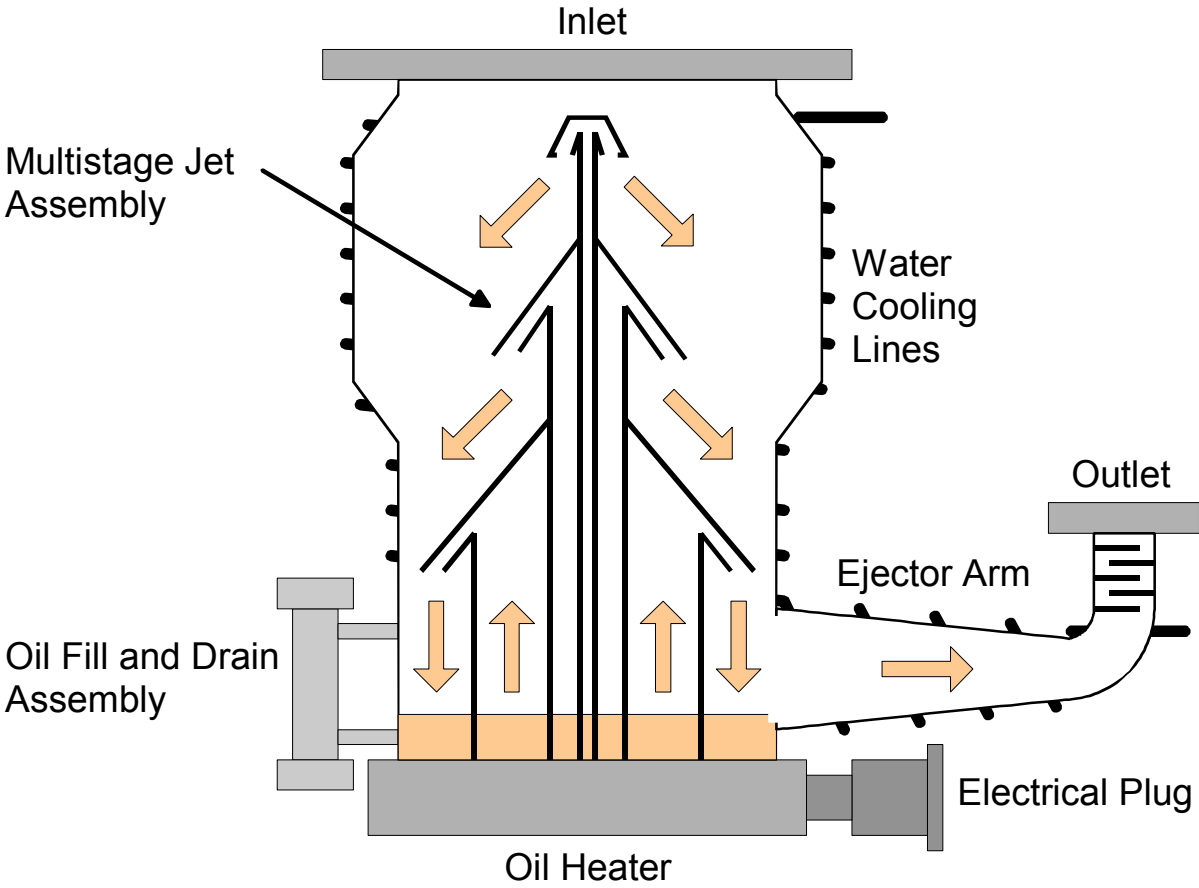
Roots Blowers / Booster Pumps - 3

- Precision shaped rotors mate to housing and to each other to within only a few thousandths of an inch.
- Rotors spin at 2500 to 3500 rpm.
- Gears synchronize the rotors.
- It is a high throughput, low compression pump that is used for moving large gas volumes.
- Must be below 10 Torr to operate.
- “Windmills” at atmospheric pressure, creating much heat.
- Requires a mechanical foreline pump.

Diffusion Pumps - 1



Diffusion Pumps - 2



Diffusion Pumps - 3

- Oil is vaporized and propelled downward by an internal boiler and multistage jet assembly.
- Oil vapor reaches speeds of 750 mph or more (supersonic).
- Oil vapor streams trap and compress gases into bottom of pump, which are then ejected out into the foreline arm.
- Oil vapor is condensed on sides of pump body which are water cooled.
- Can only operate at pressures of 100 mT or less.
- A mechanical foreline pump is required for operation.
- Multistage jet assembly is designed to fractionate the oil, using lighter weight fractions for higher vapor velocities.
- Typically 300 - 2800 L/s pumping speeds.

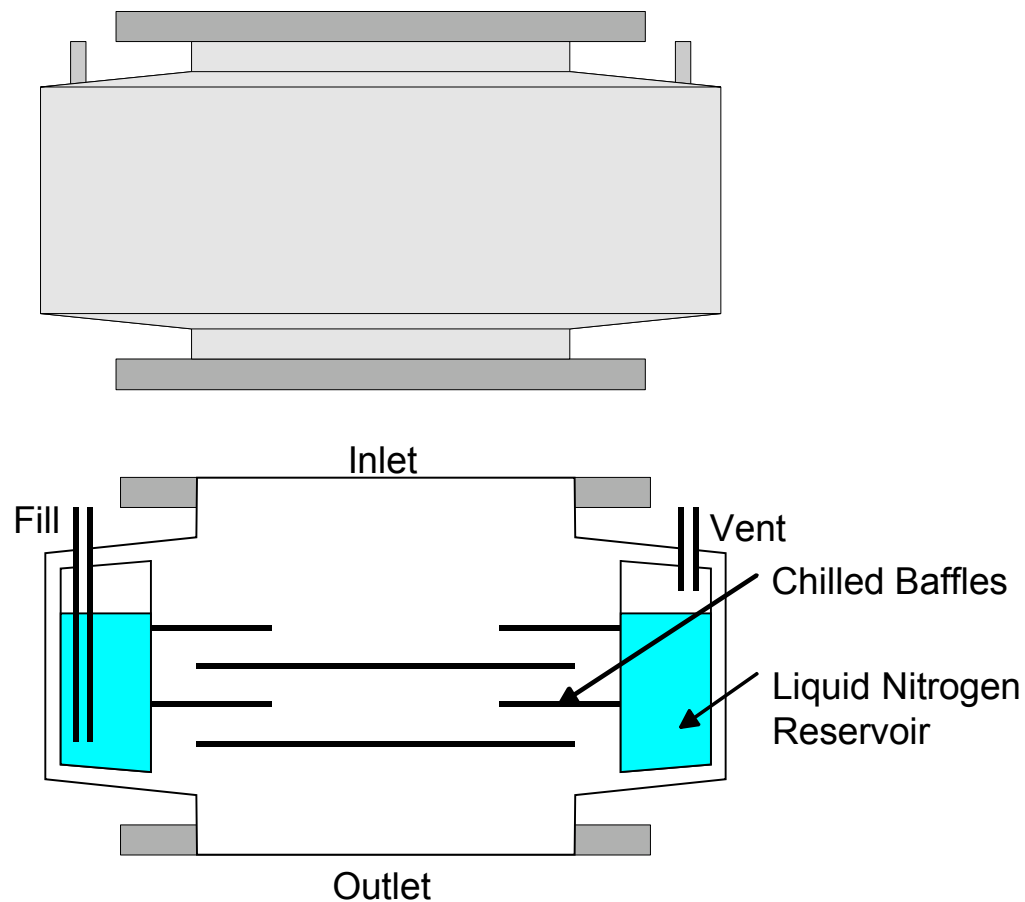
Diffusion Pumps - 4

- Potential Problems:
 - Backstreaming of oil vapor can occur if forepressure becomes too large.
 - Backstreaming occurs for pressures of 1 to 10 mTorr.
 - Cold cap on top of multistage jet assembly helps to reduce this.
 - Liquid nitrogen filled cryotrap also helps to reduce this.
 - Maximum tolerable foreline pressure (critical forepressure) must not be exceeded, or pump will “dump” or “blow-out”, sending oil up into the chamber.
 - Pump can overheat if cooling water fails
 - Most pumps have a thermal cutout switch.
 - Pumping requires low vapor pressure oil
 - Water, dirt, or other impurities will raise vapor pressure.
 - Only special oils are suitable for diffusion pump use.

Diffusion Pump Oils

- Diffusion pump oils have very low vapor pressure.
- Types
 - Hydrocarbon oils
 - Apiezon A, B, C, Litton Oil, Convoil-20
 - Silicone oils
 - DC-704, DC-705, Invoil 940
 - Polyphenyl ethers
 - Santovac 5, Convalex 10
 - Fatty esters
 - Octoil, Butyl Phthalate, Amoil, Invoil
 - Fluoroether polymers
 - Krytox, Fomblin

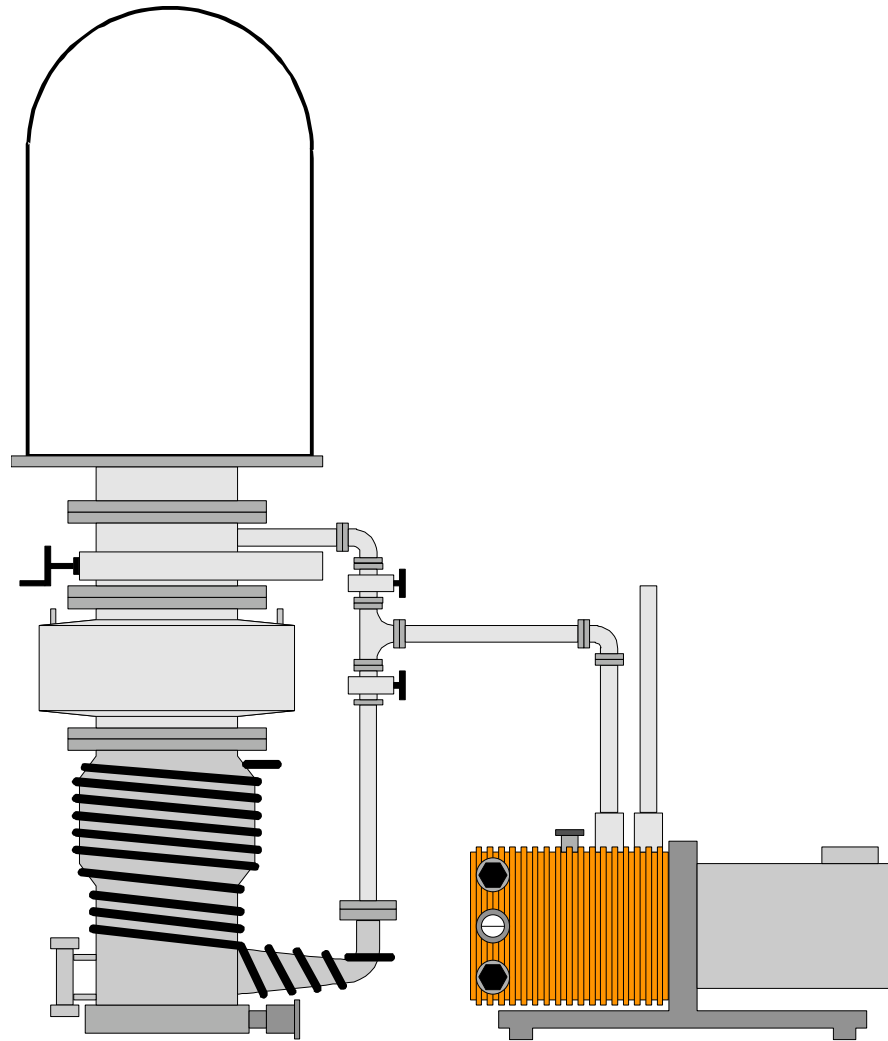
Liquid Nitrogen Traps / Baffles - 1



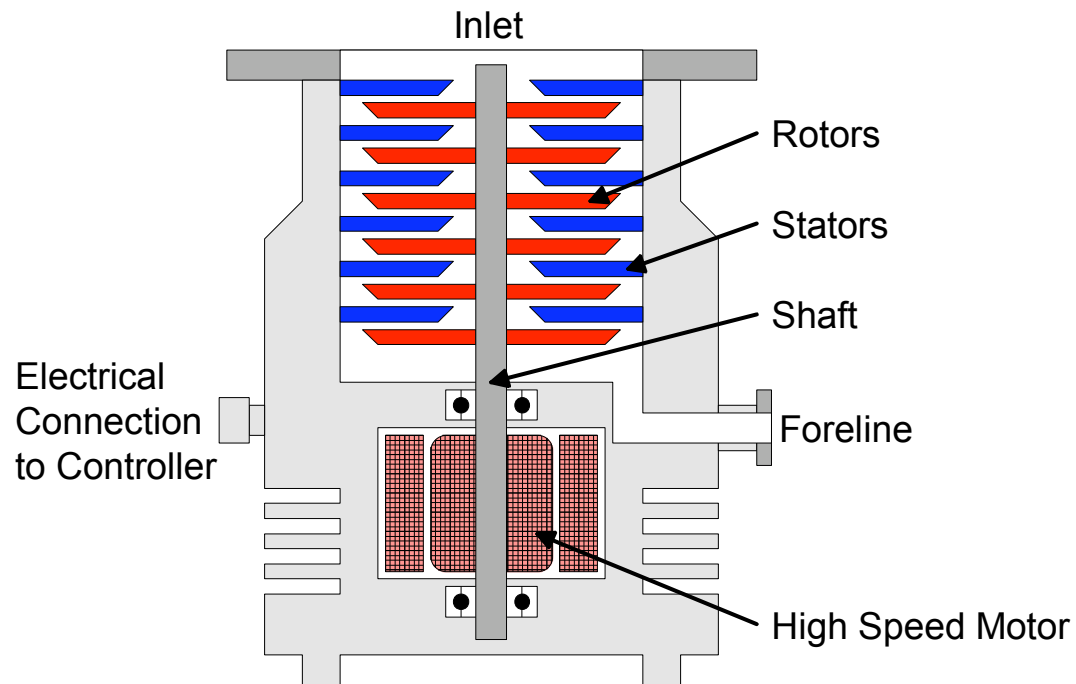
Liquid Nitrogen Traps / Baffles - 2

- Baffles and traps in the pumping lines can greatly help to reduce backstreaming:
 - low pressures in mechanical rough pumps (0.1 to 1.0 Torr)
 - high pressures in diffusion pumps (1 to 100 mTorr)
 - most important within the “cross-over” region.
- LN₂ cryotrap should not experience air pressure above 100 mTorr, or they will frost completely over.
- Residual water in a cryotrap can be frozen and cause trap to break, causing catastrophic failure of vacuum system.
 - Blow out any water vapor with dry N₂ before filling with LN₂.
- LN₂ cryotrap require constant refilling.
 - Expensive, but autofill valves are available.

Diffusion Pumped High Vacuum Bell Jar System



Turbomolecular Pumps - 1



Turbomolecular Pumps - 2

- Very clean mechanical compression pump
- Use high speed rotation blades to impart velocity and direction to gas molecules
- 9,000 to 90,000 rpm motor speeds!
- 20 to 60 blades per disk
- 10 to 40 compression stages per pump
- Requires a mechanical foreline pump
- Typically 100 to 800 L/sec pumping speeds
- Ideal for hydrocarbon free applications

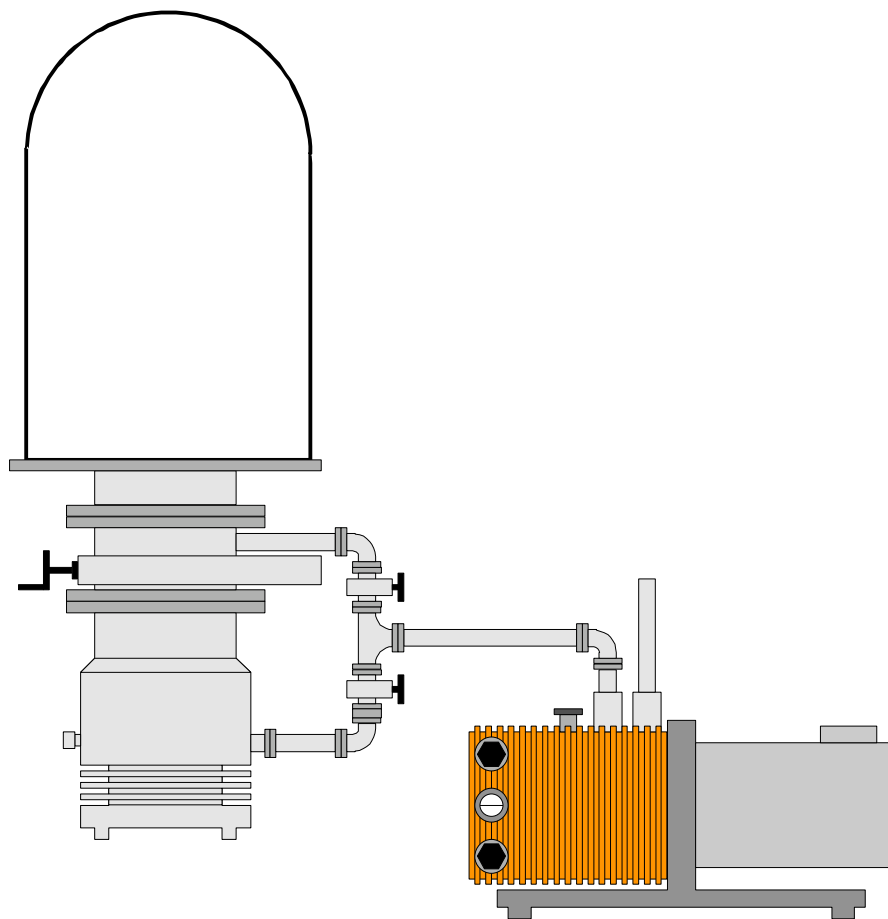
Turbomolecular Pumps - 3

- Pumping speed is proportional to the rotor speed.
- The compression ratio of the turbine establishes the base pressure.
- The compression ratio is higher for higher molecular weights:
 - Approximately: $\log_{10}K = 1.5 (M)^{1/2}$
 - For H_2 , $M = 1$, so $K = 10^{1.5} = 30 =$ very small
 - For hydrocarbons, $M = 100$, so $K = 10^{15} =$ very large
- Base pressure is usually limited by H_2 .

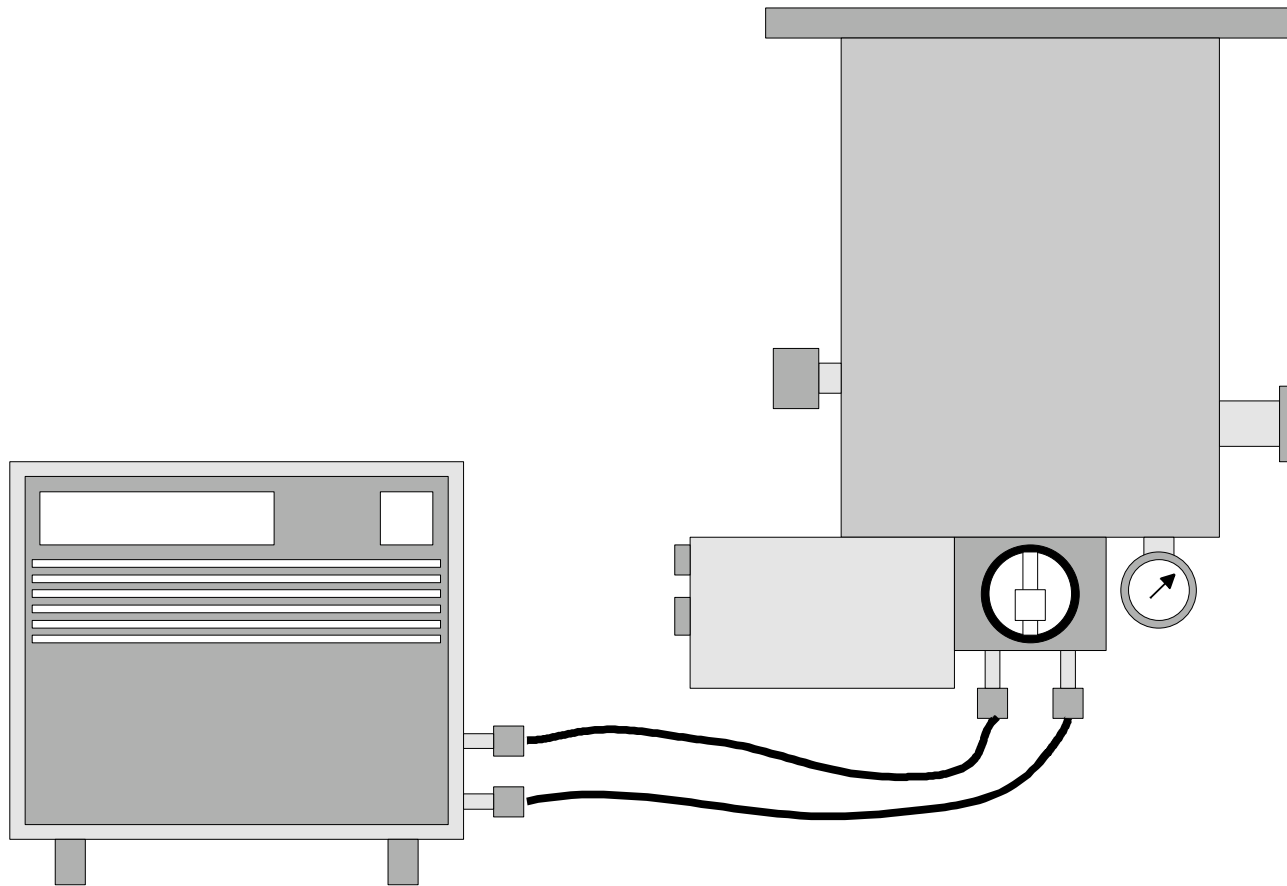
Turbomolecular Pumps - 4

- Potential Problems:
 - Very high speed rotor blades have close-mating stator blades.
 - Slight imbalances can cause vibration and bearing wear problems.
 - Sudden blast of atmospheric pressure can bend the blades down, causing catastrophic failure, “crashing the pump.”
 - Lubrication of the high speed rotor is an engineering problem.
 - Circulating oil is most reliable, but pump must be right-side-up.
 - Grease-lubricated bearings are less reliable, but allow pump to be placed at any orientation.
 - Too high of a pressure will cause aerodynamic lift and drag.
 - A mechanical foreline pump must be used
 - Aerodynamic lift can bend blades, causing catastrophic failure.

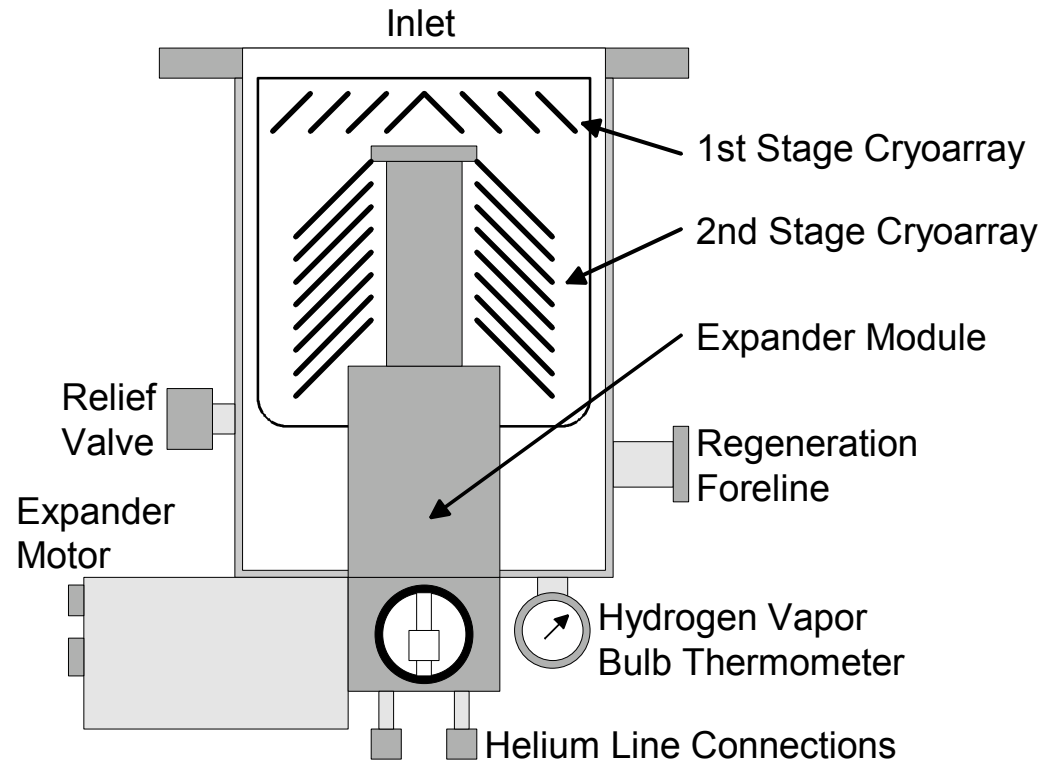
Turbo Pumped High Vacuum Bell Jar System



Cryopumps - 1



Cryopumps - 2



Cryopumps - 3

- Use a closed-loop helium cryogenic refrigerator.
- Primary parts are:
 - Compressor
 - Expander
 - Cold Head
- Gases are pumped by two processes:
 - Cryocondensation (H_2O , CO_2 , N_2 , O_2 , Ar, solvent vapors)
 - Gases are condensed into a solid phase on cryogenically cooled surfaces. (They become frost!)
 - Cryosorption (H_2 , He, Ne)
 - Non-condensable gases are adsorbed onto surfaces of cryogenically cooled porous media, usually activated charcoal or zeolites.
- Typically 100 - 1000 L/s pumping speeds.

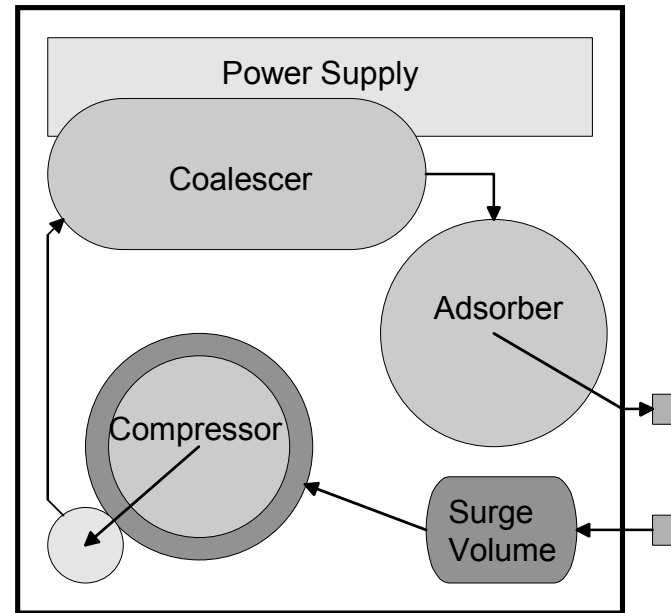
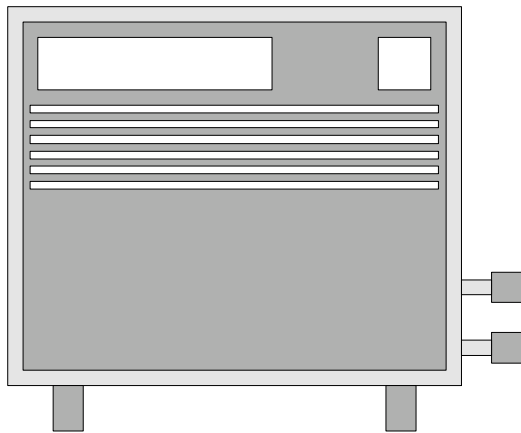
Cryopumps - 4

- First stage array operates at 50 to 80 K
 - Primarily used for pumping water vapor and carbon dioxide.
- Second stage array operates at 10 to 20 K
 - Primarily used for pumping other condensable gases.
- Activated charcoal in the second stage provides cryosorption.
 - Primarily used for pumping other non-condensable gases.
 - Charcoal and zeolites have about 8000 ft²/cm³ of surface area.
- Completely oil free operation.
- Can operate from any orientation.
- Very clean vacuum with high pumping speed.
- Very high impulsive pumping capacity.

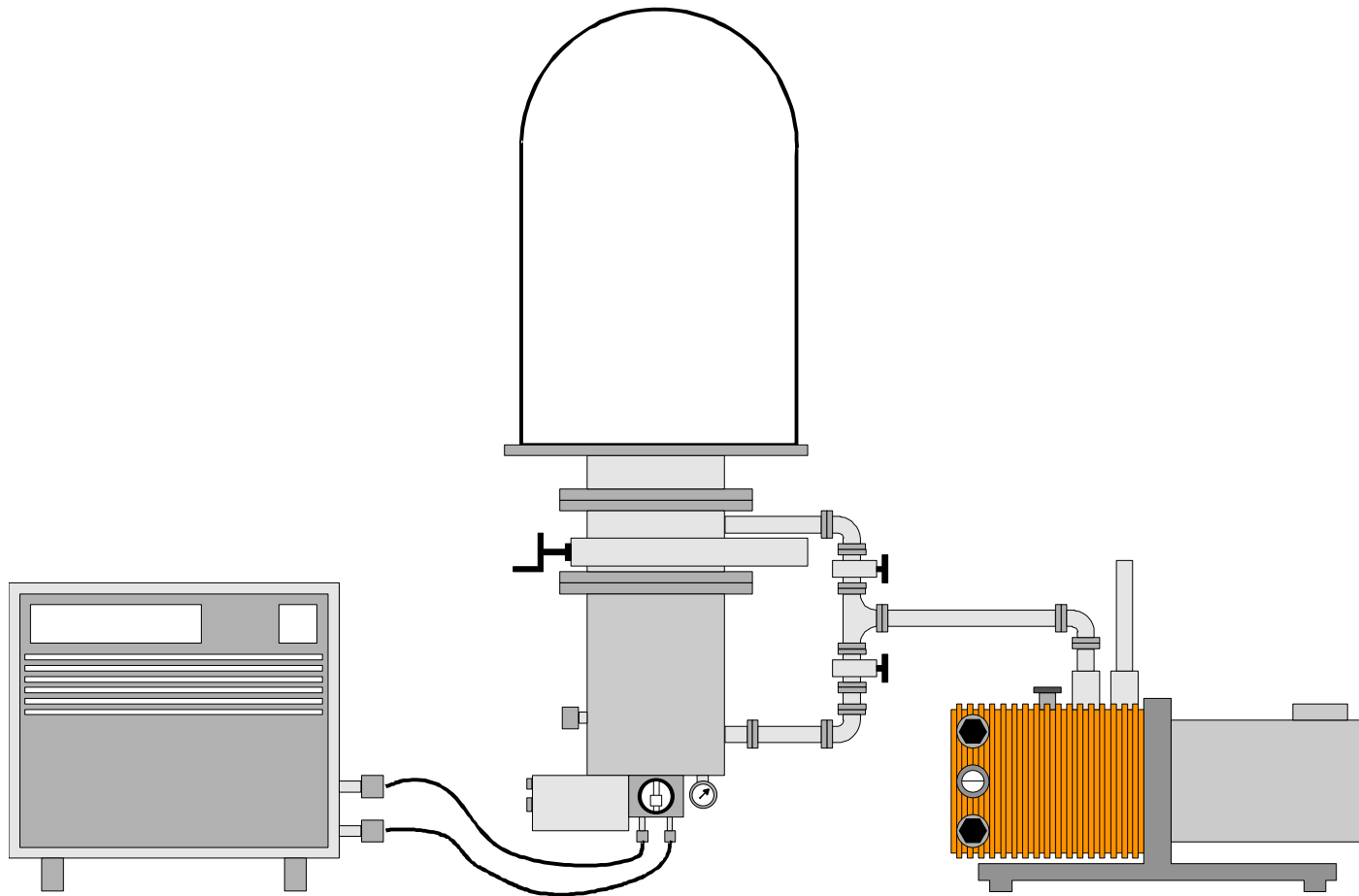
Cryopumps - 5

- Potential Problems:
 - Must be regenerated to extract the trapped gases
 - Allow to warm to room temperature (slow), or
 - Use a built-in heater to warm to 250 C and outgas (fast).
 - Regeneration takes the pump off-line for several hours.
 - Regeneration process can produce considerable pressure.
 - Pumps have a safety pressure relief valve on the bucket.
 - Must be started from below 100 mTorr
 - Use a mechanical roughing pump

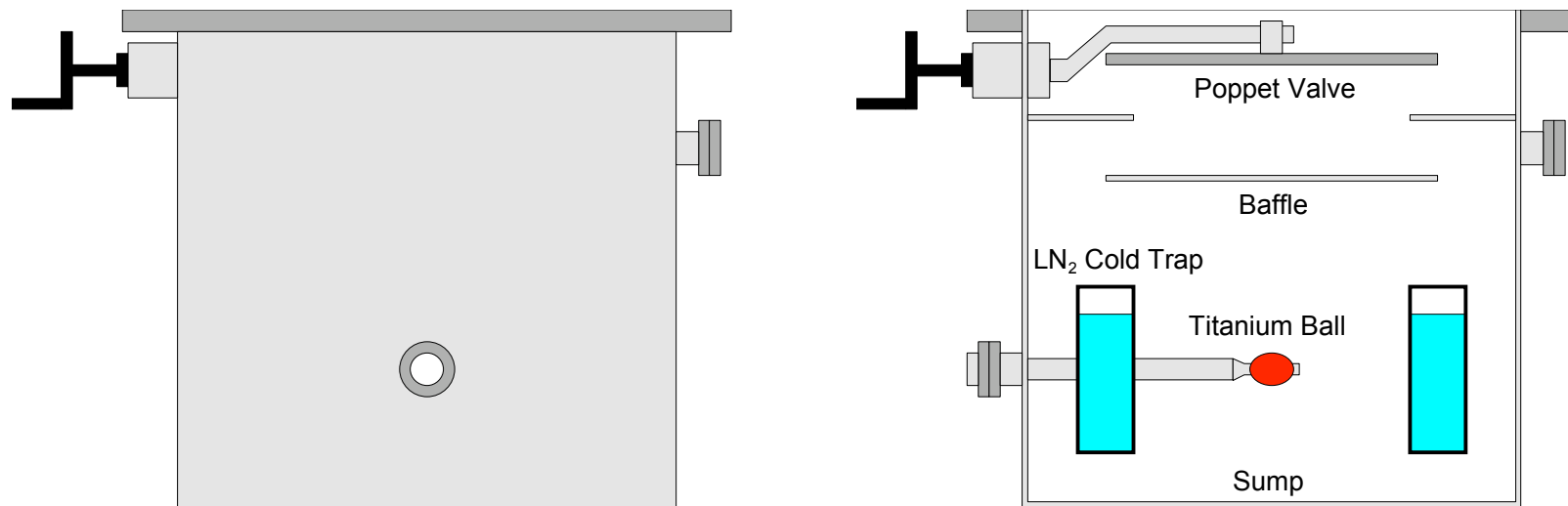
Cryopump Compressor Module



Cryo Pumped High Vacuum Bell Jar System



Titanium Sublimation Pumps - 1



Titanium Sublimation Pumps - 2

- “TSP”; a type of “getter pump”
- Titanium, which has been freshly evaporated onto the sides of a sump, will chemically combine with gas molecules.
- Titanium sublimes from a heated source and evaporates to coat the walls of the sump.
- Types of Ti sources:
 - 35 g Ti-ball; 750 W operating, 200 W standby
 - 15 g mini-Ti-ball; 380 W operating, 95 W standby
 - 4.5 g Ti filament; 380 W operating, zero standby

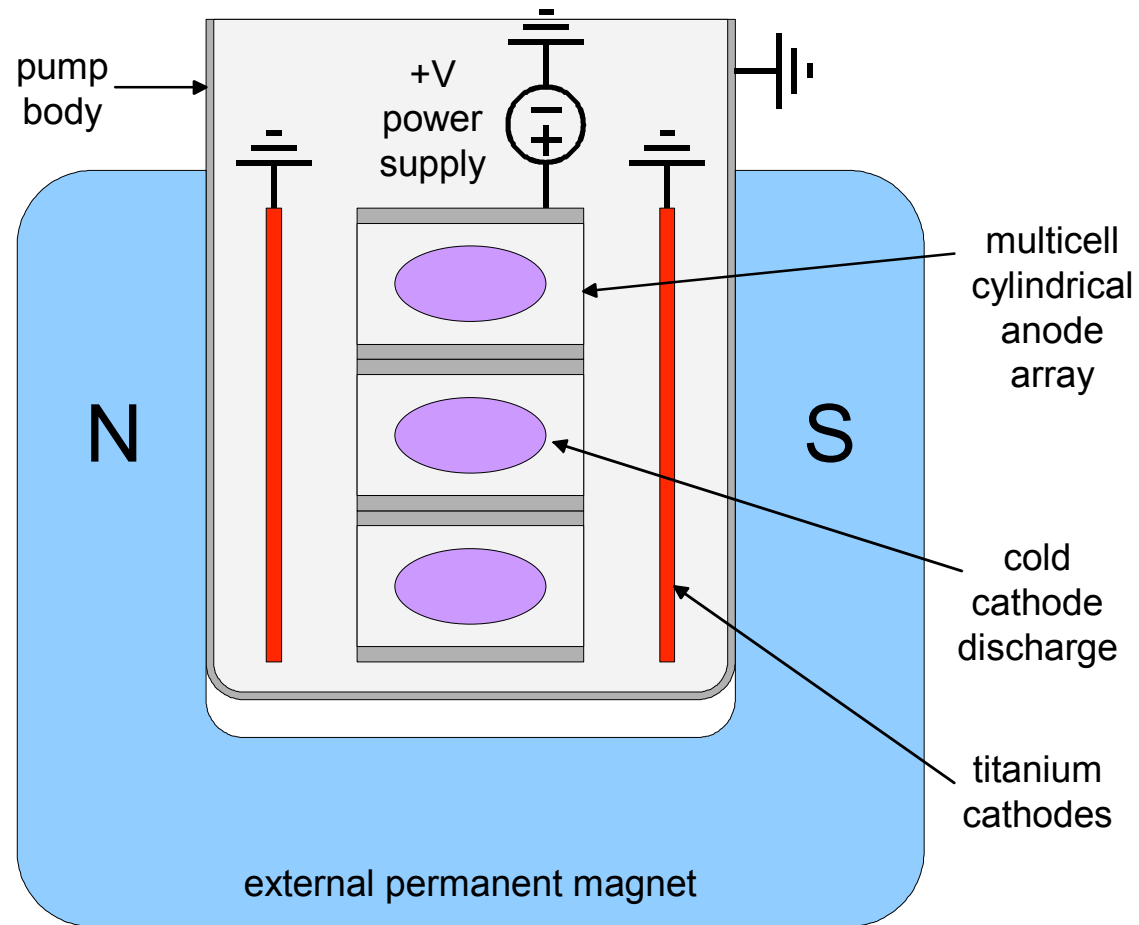
Typical pumping speeds for freshly coated Ti surfaces (L/sec-in²):

	H ₂	N ₂	O ₂	CO	CO ₂	H ₂ O
20°C:	20	30	60	60	50	20
-190°C:	65	65	70	70	60	90

Non-Evaporable Getter Pumps

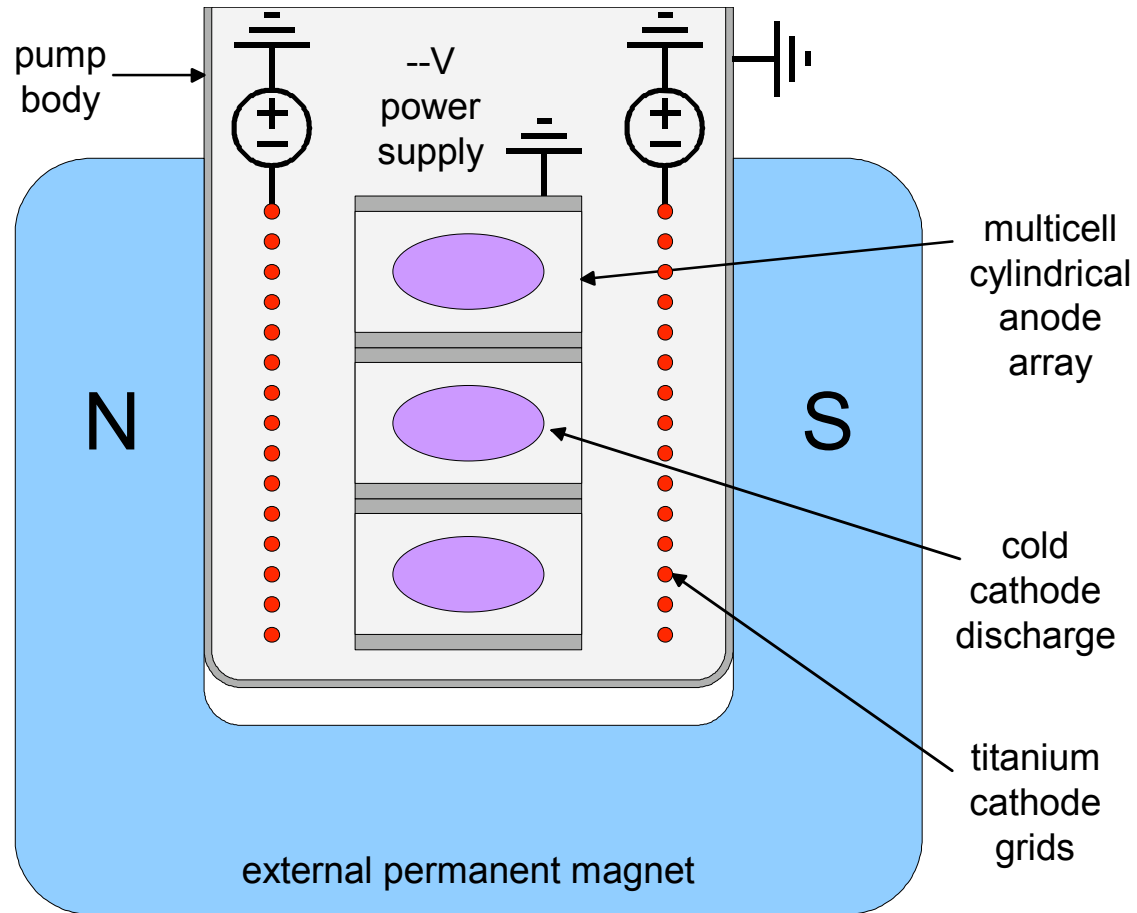
- “NEG” pumps.
- Zr-V-Fe alloy that is formed into a cartridge over a constantan strip heater.
- Pumps all of the time, until loaded with gas molecules.
- Regenerated by heating to $\sim 350^{\circ}\text{C}$ for 30 mins. to degas the alloy.
- Very simple in construction and operation.

Ion Pumps - 1



Diode Ion Pump

Ion Pumps - 2



Triode Ion Pump

Ion Pumps - 3

- Operation is based upon a rarefied gas electric discharge.
 - High electric field can ionize a gas molecule, forming a free electron and a gas ion.
 - Free electron is collected by the anode, while gas ion is collected by the cathode.
 - Fast electrons, accelerated by the E-field, will collide with and ionize other gas molecules.
 - A coaxial magnetic and electric field will produce spiral orbits for the free electrons; the larger paths greatly increase the ionization.
 - Higher ionization levels will sustain a cold cathode discharge.
 - Gas ions accelerated into the cathode can stick and therefore be pumped.

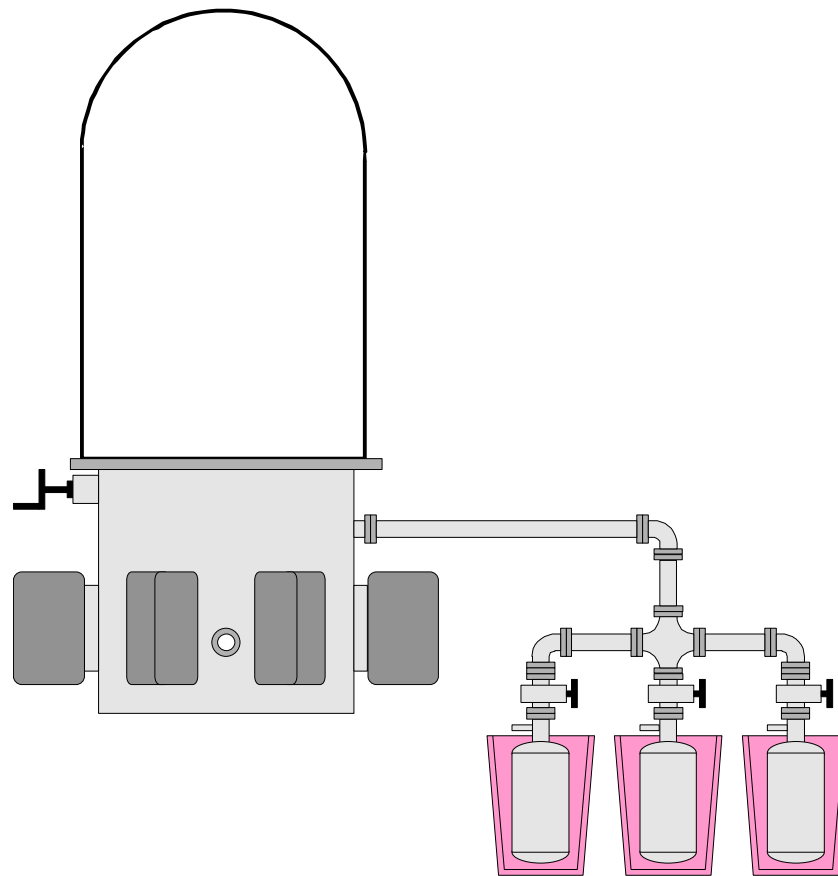
Ion Pumps - 4

- Cathode plates are made of titanium (Ti).
- Pumping mechanisms:
 - Incident gas ions may be implanted into the Ti cathode plates.
 - Incident gas ions may sputter Ti from the cathode plates into the cylindrical anode cells, thus providing additional getter pumping.
 - H₂ is directly absorbed by the fresh Ti surfaces.
 - Gas molecules may be trapped and buried by sputtered Ti.
 - Electric discharge cracks larger molecules into smaller ones that are more readily pumped.
- Ion pumps must be started at 10⁻⁵ torr or less.
- Intermediate pumping is usually provided by a sorption or a cryo pump.

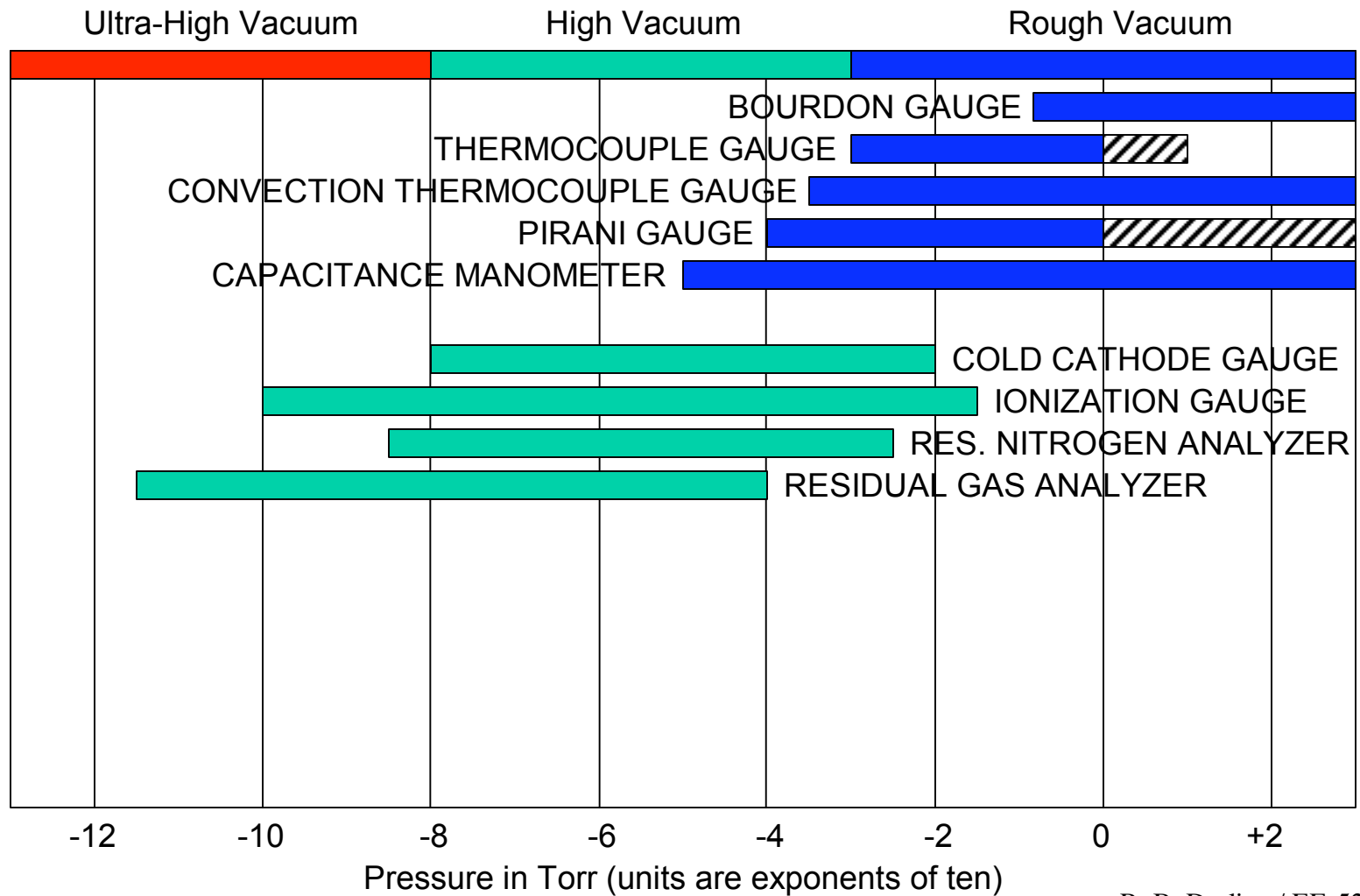
Ion Pumps - 5

- Diode pumps use a Ti plate as the cathode.
- Triode pumps use a Ti screen as a grid electrode and the pump body as the cathode.
- Typical triode pumps will operate for ~35,000 hours (about 4 years) at an inlet pressure of 10^{-6} torr of N_2 .
- The ion pump current is proportional to the gas pressure in the pump, so this can be used as a pressure gauge.
- Appendage ion pumps are often used to sustain high vacuum in long service devices such as microwave tubes.

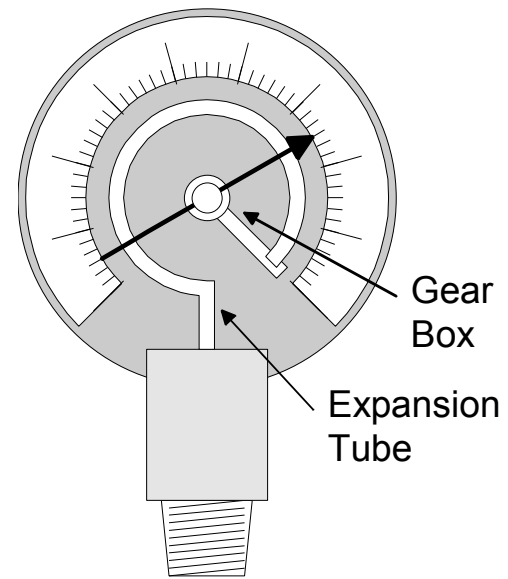
Ion / Ti-Sub. Pumped Ultra-High Vacuum System



Vacuum Gauge Pressure Ranges



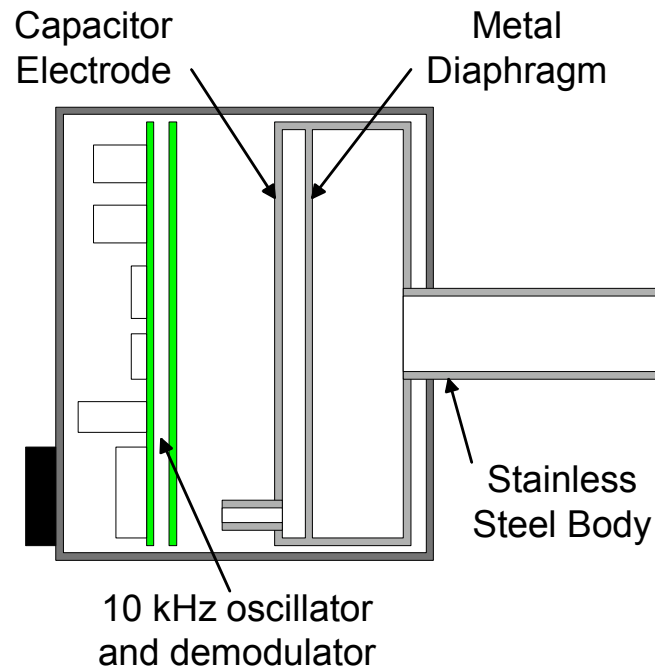
Bourdon Gauges - 1



Bourdon Gauges - 2

- Mechanical gas pressure flexes the Bourdon tube and causes the arc to unwind, which through a series of gears and levers moves a needle on the gauge's face.
- It is completely insensitive to the chemical composition of the gas.
- It can be used for measuring positive pressure and vacuum.
- Lower sensitivity for vacuum measurements is about 0.1 torr.
- Gauges are precision instruments and can be damaged by mechanical shock.

Capacitance Manometers - 1



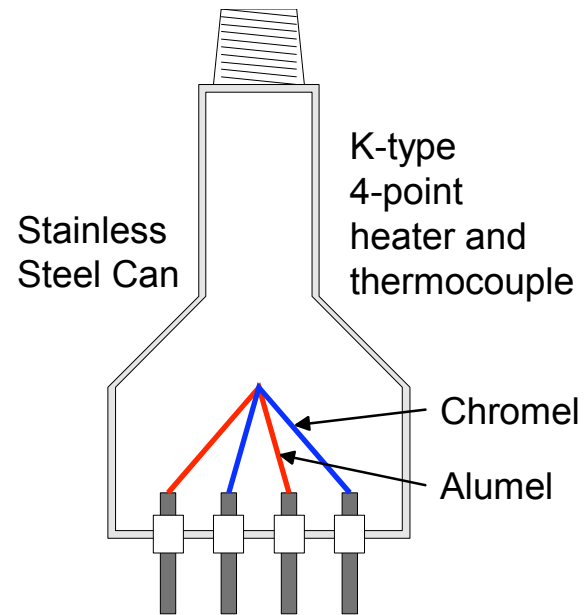
Capacitance Manometers - 2

- Mechanical gas pressure deforms a tensioned metal diaphragm.
- An air gap capacitor is formed between the diaphragm and a set of fixed electrodes.
- The capacitance thus varies with the pressure.
- The capacitance is measured by a demodulation and amplifier circuit that makes a 10 kHz oscillator with the diaphragm capacitor.
- Capacitance manometers are extremely linear and accurate.
 - Typically within 1% of full scale.
- They are insensitive to the chemical composition of the gas.

Capacitance Manometers - 3

- Can be used to measure pressure in all modes:
 - Gauge
 - Absolute
 - Differential
- A single capacitance manometer can only read over 3-4 decades of pressure.
- Capacitance manometers can be constructed to cover the range from atmospheric pressure down to $\sim 10^{-5}$ torr by using diaphragms of differing stiffness.
- Capacitance manometers are often used to accurately measure pressure in process reactors, and are often used in feedback control loops.

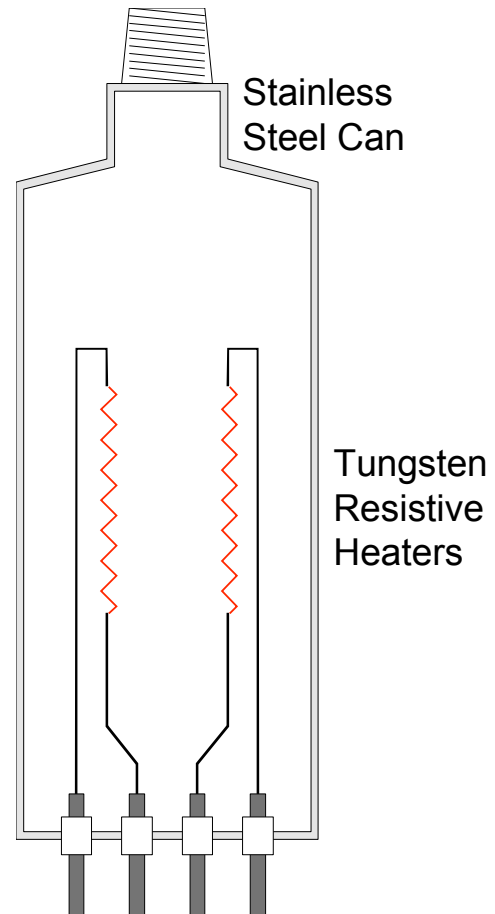
Thermocouple Gauges - 1



Thermocouple Gauges - 2

- Electric current passed through a filament heats up the filament to a temperature that depends upon how fast the surrounding gas conducts the heat away.
- The temperature is measured by a thermocouple, which is part of the filament assembly, and the temperature reading is converted into an approximate pressure on a meter.
- Since different gases have different thermal conductivities, thermocouple gauges read differently for different gases.
- Read from about 1 to 1000 mTorr.
- Very rugged, reliable, and inexpensive.

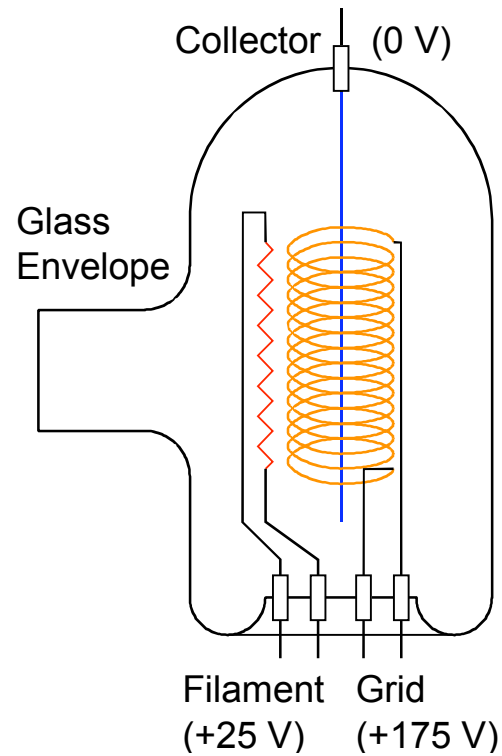
Pirani Gauges - 1



Pirani Gauges - 2

- Similar to a TC gauge, an electrically heated filament takes on a temperature that depends upon the rate of heat loss to the surrounding gas.
- The temperature of the filament is sensed by measuring the change in the resistance of the filament as it is heated.
 - For most metals, the TCR is about +200 ppm/°C.
- Pirani gauges require a more sophisticated controller, but are more accurate and faster responding than a TC gauge.
- Most use a Wheatstone bridge circuit to linearize the filament against a compensating filament that is held at atmospheric pressure.
- Pirani gauges are also sensitive to the gas composition.

Hot Filament Ionization Gauges - 1



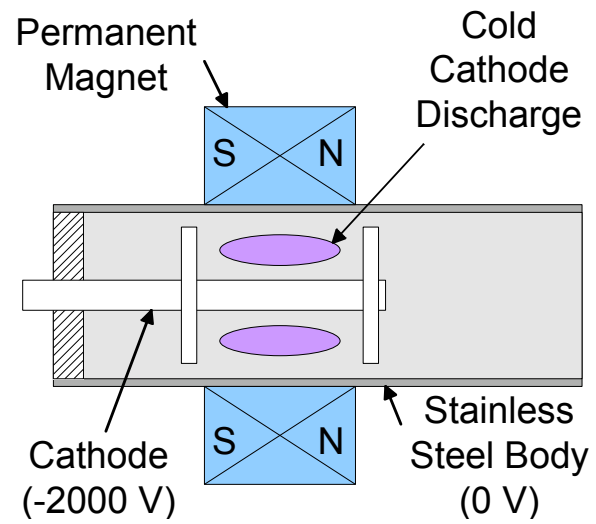
Hot Filament Ionization Gauges - 2

- Also known as “Bayard-Alpert” gauges.
- Electrons are thermionically emitted from a hot filament and then accelerated by a grid electrode.
- The accelerated electrons will ionize any gas molecules in the vicinity of the grid, and the positively charged gas ion will contribute to a current through the collector electrode.
- $I_P = I_E * S * P$, where
 - I_P = positive ion current through collector electrode
 - I_E = electron emission current through filament
 - S = gauge sensitivity parameter
 - P = gas pressure

Hot Filament Ionization Gauges - 3

- The ionization rate depends upon the gas species, so ion gauges are sensitive to the gas composition.
- Accuracy is about 10% of full scale, when calibrated.
- Ion gauges can work from 10^{-3} to 10^{-11} torr!
- Lower pressure limit is set by soft x-ray emission from electrons striking the grid.
- Hot filament requires some precautions:
 - Exposure to pressures above 10^{-3} torr will burn out filament.
 - Hot filament is an ignition source which can trigger explosions in the process chamber with combustible gases.

Cold Cathode Ionization Gauges - 1



Cold Cathode Ionization Gauges - 2

- A cold cathode discharge replaces the hot filament for producing ionizing electrons.
- Ionized gas molecules are collected by the negatively charged cathode, and the electric current is proportional to the gas pressure.
- Can operate from 10^{-2} to 10^{-8} torr.
- More rugged than a hot filament ion gauge, but less accurate, typically only about 50% of full scale.
- Cold cathode discharge is still a potential source of ignition for combustible process gases.

Cleanliness Inside a Vacuum Chamber

- At 10^{-6} torr:
 - there are 4×10^4 molecules/cm³
 - the mean free path is about 5×10^3 cm
 - the impingement rate is about 10^{15} molecules/cm²/sec
- Thus, at 10^{-6} torr, a monolayer of molecules will deposit on any surface in about 1 second.
- 10^{-6} torr is equivalent to a purity of 1 ppb!
 - (Relative to atmospheric pressure at $\sim 10^3$ torr)
- The matter in one fingerprint (1 cm x 1 cm x 20 μ m), when vaporized, will produce a pressure of 10^{-4} torr inside a 10 ft³ vacuum chamber!
- Thus: **ALWAYS WEAR GLOVES!!!**

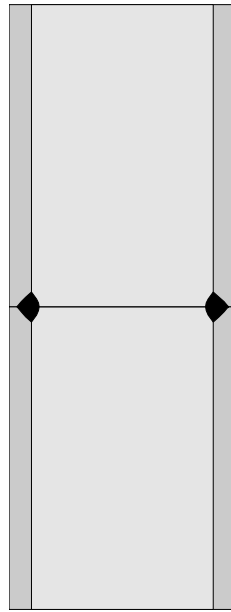
Vacuum Materials - 1

- **Stainless Steel**
 - Type 304 SS is most common.
 - Easy to machine.
 - Easy to fusion weld.
- **Copper**
 - Use Oxygen-Free High-Conductivity (OFHC) alloy.
 - Used for electrical conductors.
- **Ceramics**
 - Alumina (Al_2O_3) is very common.
 - Used for electrical insulators.
- **Kovar**
 - (54% Fe, 29% Ni, 17 % Co); used for glass-to-metal seals.

Vacuum Materials - 2

- Elastomers
 - Buna-N
 - Inexpensive, good to 80°C, rather impermeable to He.
 - Viton
 - Outgasses very little, good to 150°C.
 - Polyimide
 - Good to 200°C, stiffer than other elastomers, permeable to H₂O vapor.
 - Silicones
 - Can handle higher temperatures, but very permeable to H₂O and He.
 - Teflon
 - Very inert, but exhibits cold flow plasticity, making it a poor seal.
 - Very permeable to He, good to 150°C.

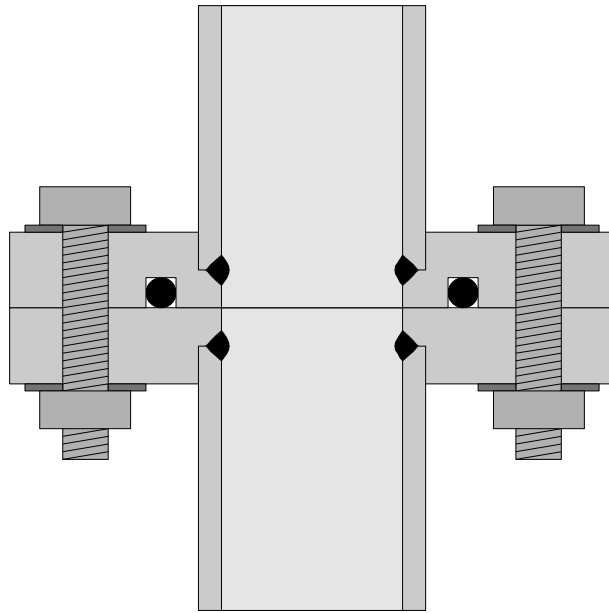
Vacuum Joining Techniques - 1



Internal continuous fusion welds are most commonly used for joining tubing, pipes, and chamber ports.

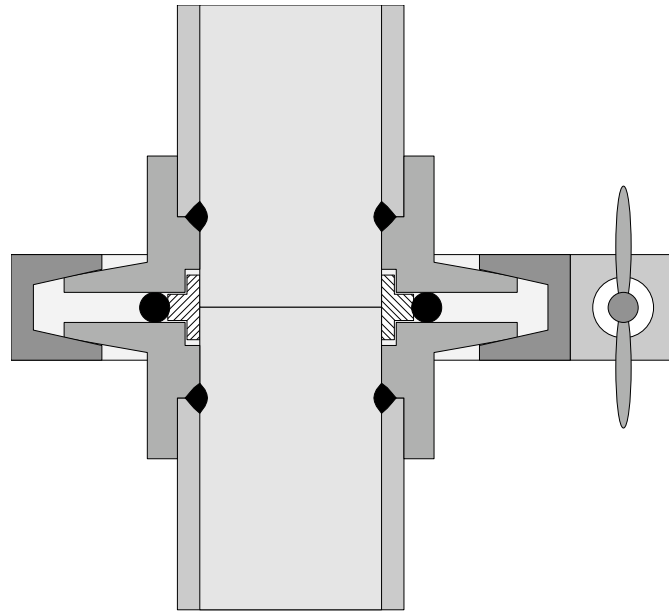
For small bore tubing, external orbital welding must produce complete penetration welds.

Vacuum Joining Techniques - 2



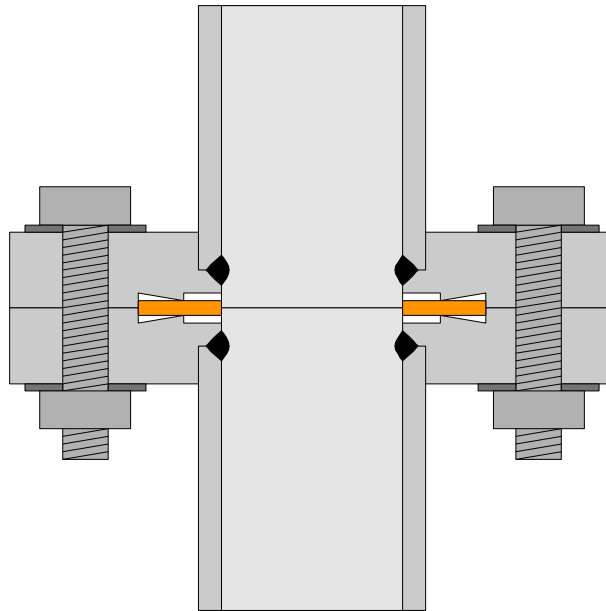
ASA flanges are a common standard that uses a captured O-ring to provide sealing.

Vacuum Joining Techniques - 3



KF or “Quick-Flanges” are a common standard for rough or high vacuum plumbing. They utilize an O-ring supported against flat flanges with an internal centering ring. Compression is supplied by a tapered clamp and wingnut. No tools are needed.

Vacuum Joining Techniques - 4



Metal-sealed, or “Con-Flat” flanges are used for ultra-high vacuum applications where elastomer sealed flanges would be too leaky.

A knife edge on each flange bites into and compresses a copper gasket. The extremely high pressure of the knife edge causes the copper to deform to match the surfaces of both flanges. These flanges are bakeable up to 350°C.

Things to Watch for in Vacuum Systems

- Real Leaks
- Virtual Leaks
- Water Leaks
- Oil Contamination
- Finger Prints
- Organic Materials that Outgas